







Article

A Comprehensive Review on the Ground Granulated Blast Furnace Slag (GGBS) in Concrete Production

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Citation: Ahmad, J.; Kontoleon, K.J.; Majdi, A.; Naqash, M.T.; Deifalla, A.F.; Ben Kahla, N.; Isleem, H.F.; Qaidi, S.M.A. A Comprehensive Review on the Ground Granulated Blast Furnace Slag (GGBS) in Concrete Production. *Sustainability* **2022**, *14*, 8783. <https://doi.org/10.3390/su14148783>

Academic Editor: José Ignacio Alvarez

Received: 17 June 2022

Accepted: 13 July 2022

Published: 18 July 2022

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Abstract: In the last few decades, the concrete industry has been massively expanded with the adoption of various kinds of binding materials. As a substitute to cement and in an effort to relieve ecofriendly difficulties linked with cement creation, the utilization of industrial waste as cementitious material can sharply reduce the amount of trash disposed of in lakes and landfills. With respect to the mechanical properties, durability and thermal behavior, ground-granulated blast-furnace slag (GGBS) delineates a rational way to develop sustainable cement and concrete. Apart from environmental benefits, the replacement of cement by GGBS illustrates an adequate way to mitigate the economic impact. Although many researchers concentrate on utilizing GGBS in concrete production, knowledge is scattered, and additional research is needed to better understand relationships among a wide spectrum of key questions and to more accurately determine these preliminary findings. This work aims to shed some light on the scientific literature focusing on the use and effectiveness of GGBS as an alternative to cement. First and foremost, basic information on GGBS manufacturing and its physical, chemical and hydraulic activity and heat of hydration are thoroughly discussed. In a following step, fresh concrete properties, such as flowability and mechanical strength, are examined. Furthermore, the durability of concrete, such as density, permeability, acid resistance, carbonation depth and dry shrinkage, are also reviewed and interpreted. It can be deduced that the chemical structure of GGBS is parallel to that of cement, as it shows the creditability of being partially integrated and overall suggests an alternative to Ordinary Portland Cement (OPC). On the basis of such adjustments, the mechanical strength of concrete with GGBS has shown an increase, to a certain degree; however, the flowability of concrete has been reduced. In addition, the durability of concrete containing GGBS cement is shown to be superior. The optimum percentage of GGBS is an essential aspect of better performance. Previous studies have suggested different optimum percentages of GGBS varying from 10 to 20%, depending on the source of GGBS, concrete mix design and particle size of GGBS. Finally, the review also presents some basic process improvement tips for future generations to use GGBS in concrete.

Keywords: industrial waste; sustainable concrete; GGBS; mechanical properties; durability

1. Introduction

Building manufacturing has played a significant part in the urbanization and industrialization that has occurred in recent decades. Approximately 5–10% of global employment is provided by the construction industry, which also accounts for 5–15% of national GDP [1]. About 40% of overall energy use and 30% of total natural resource depletion are attributed to the building industry. Furthermore, these construction industries are responsible for 40% of carbon dioxide emissions and around 30% of garbage output. Approximately 7–9% of global carbon dioxide emissions are attributed to the manufacturing process of this hydraulic cement [2]. Worldwide, the carbon dioxide released from cement factories now accounts for more than 5% of worldwide carbon dioxide emissions [3]. Cementation materials may be used to reduce carbon dioxide emissions by substituting OPC with other binding materials [4–6]. A variety of byproducts from the industry may be utilized in multicomponent binder materials for a variety of purposes [7]. Diverse studies have been performed on building concrete using supplemental components to decrease the price and scarcity of standard materials [8]. Concrete is the very often utilized man-made construction resource in the building business, and hydraulic cement is a vital component of this material. Worldwide, around 4 billion tons of hydraulic cement are manufactured annually, equating to over 30 billion tons of concrete produced in 2015 [9]. The World Cement Association Conference shows the global cement production rate in Figure 1 [10]. From 1990 to 2030, it can be noted that the demand for cement is growing steadily. A growing demand for cement in contemporary buildings and infrastructure, particularly in emerging countries, such as China, Russia and Japan, has led to considerable manufacturing growth [11]. Because of the assumption of prospective demand for growing infrastructure, cement production has created the ability to produce 59.5 million tons of cement annually. Within just 10 years, the price of cement has risen by about 150% [12]. As a result, it is critical to employ supplemental materials in place of cement wherever possible.

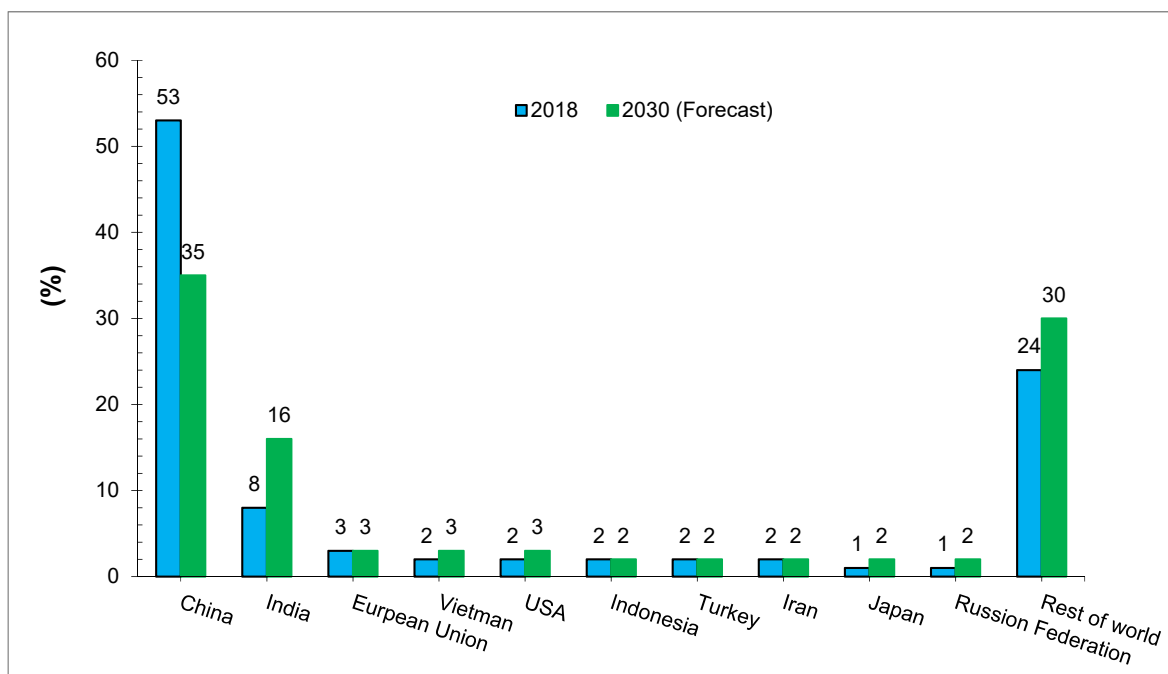


Figure 1. Global OPC manufacture 2018 and predicted 2030 [10].

During the last three decades, the construction sector has implemented a variety of steps to limit the release of harmful gases connected with cement manufacture, particularly in the United Kingdom. Alternative approaches include using organic gas as a gasoline substitute for coal for calcination, using chemicals to absorb carbon dioxide, developing a more efficient grinding process for clinker and incorporating sustainable cement manufacturing.

Implementing cementitious materials, on the other hand, may be a practical strategy for significantly reducing greenhouse gas emissions. Manufacturing wastes, such as GGBS, silica fume, metakaolin and fly ash, are used as a substitute for OPC and can potentially cut greenhouse gas emissions by a significant amount. Table 1 shows the chemical composition of different cementitious materials (GGBS, silica fume, metakaolin and fly ash) as in past literature on the topic. According to ASTM [13], pozzolanic materials may be formed by the accumulation of chemicals, such as silica, calcium, alumina, magnesia and iron, to a concentration of more than 70%. Silica, calcium, alumina, magnesia and iron are among the elements that have accumulated in GGBS at a concentration greater than 70%. As a result, GGBS silica fume, metakaolin and fly ash have the potential to be used (pozzolanic material) that may be utilized as an OPC substitute in concrete.

Table 1. Chemical Compositions of Different Cementitious Materials.

Chemical	Fly Ash	Silica Fume	Metakaolin	GGBS
SiO ₂	54.22	34.32	54	37.5
Al ₂ O ₃	31.18	15.57	43	6.4
Fe ₂ O ₃	2.63	0.58	1.2	0.51
MgO	0.47	6.89	0.4	8.6
CaO	1.24	37.52	0.4	34.6
Na ₂ O	0.49	0.31	0.3	0.38
K ₂ O	1.34	0.66	0.3	-
Reference	[14]	[15]	[16]	[17]

Considering that these wastes (GGBS, silica fume, metakaolin and fly ash) have binding properties, they have gained popularity among researchers as prospective candidates for being incorporated into cement blends to minimize the carbon footprint left behind in the environment. Many other kinds of industrial waste may be applied as well as binding material, including waste marble, foundry sand, fly ash, slag and rubber [18–24]. Most of these pozzolanic materials are the result of waste from the manufacturing procedure. Blast-furnace slag and its derivative GGBS are examples of industrial byproducts that are primarily utilized as supplemental cementitious products in cement and concrete production. Its self-hydration feature, in addition to its pozzolanic action, distinguishes it from other compounds, which might be due to the presence of 30–40% calcium oxide, which could explain its color. The significance of GGBS resides in the fact that it is a more environmentally friendly option for concrete material. Because GGBS is a byproduct, it must be disposed of appropriately. This waste material may thus be used to minimize the depletion of traditional concrete components, such as OPC, and fine and coarse aggregates, by mixing them into the concrete mix. Furthermore, several investigations have shown that the substitution of GGBS for concrete does not cause a reduction in the concrete capacity.

2. Environmental Assessment

Carbon dioxide emissions are caused by carbonate oxidizing in the cement clinker manufacturing process, which is the primary component of cement and the most significant source of noncombustion carbon dioxide emissions from industrial production, accounting for approximately 4.8% of total global emissions in 2013. The carbon dioxide emissions from fuel combustion associated with cement manufacturing are roughly the same; cement manufacturing accounts for approximately 9.5% of worldwide carbon dioxide emissions [25]. Energy savings, reduced greenhouse gas emissions and decreased pure raw resources are only a few benefits associated with the use of slag cement [26]. It is also implied that the use of GGBS will result in a significant reduction in carbon dioxide emissions per ton of cementitious materials and the consumption of byproducts of industrial production processes [27].

The average global emission factor for producing a ton of cement, which includes transporting the cement to ready-mixed concrete facilities, was 0.91 t CO₂-e/ton. However,

this value falls to 0.143 t CO₂-e/ton for GGBS [28]. High temperatures are required to burn natural raw materials and impart particular features to the clinker. The manufacture of cement emits carbon dioxide. Carbon dioxide is created primarily from three sources: (1) the decarburization of limestone in the furnace, which produces about 525 kg of carbon dioxide per ton of clinker; (2) the fuel combustion in the furnace produces approximately 335 kg carbon dioxide per ton of cement; (3) electrical energy usage produces about 50 kg of carbon dioxide per ton of cement. GGBS is produced as a byproduct from another manufacturing process, and its utilization is an example of industrial ecology. It may be used as a coarse aggregate or as a mineral additive in concrete where it can replace up to 80% of the cement and reduce carbon dioxide emissions per ton of concrete by as much as 60% or 70%. GGBS is often used in concrete to replace 35–65% of the Portland cement. The substitution of 50% GGBS with Portland cement in concrete might reduce about 0.5 tons of carbon dioxide being released into the atmosphere. A study was conducted to calculate the carbon dioxide emissions associated with the production and placement of concrete as well as the emissions associated with coarse and fine aggregate, cement, fly ash, GGBS, admixtures, concrete batching, transportation and placement processes. According to the findings of that research, replacing 40% of GGBS with Portland cement in 25 or 32 MPa concrete outputs results in a 22% reduction in carbon dioxide emissions [29]. It is predicted that the globe generated 260–330 million tons of GGBS and 150–220 million tons of steel slag last year [30].

3. Ground-Granulated Blast-Furnace Slag (GGBS)

GGBS is a principal byproduct produced by steel and iron productions. The furnace is typically run at a temperature of 1500 degrees Celsius. The blast furnace is supplied with a carefully regulated combination of limestone, iron ore and coke. When limestone, iron ore and coke are melted together in a blast furnace, iron and slag are created in the molten state. When the slag from the blast furnace is molten, it is swiftly cooled with strong water jets, which transform it into GGBS, a fine, granular and glassy substance. Figure 2 depicts the GGBS manufacturing process.

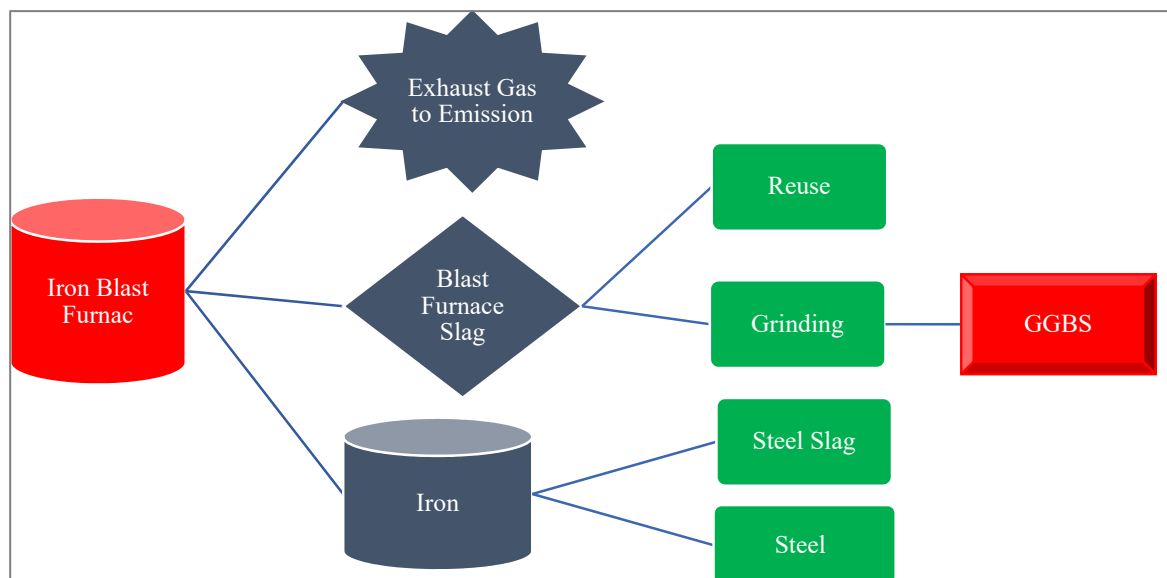


Figure 2. Manufacturing Process of GGBS.

According to research, the worldwide output of GGBS is about 530 million tonnes, with just 65% of it being used by the building sector [31]. GGBS is a byproduct of the iron manufacture process in the blast furnace. It mostly consists of silicate and aluminosilicate of molten calcium that had to be taken from the blast furnace regularly, according to the manufacturer. GGBS has a large quantity of amorphous calcium, silica and alumina, making it

an excellent binder for cement concrete manufacture [32]. GGBS is a cement substitute extensively employed in various civil engineering tasks, including concrete manufacture [33]. GGBS is a byproduct of steel production commonly used as a cementitious material as it improves the strength and reduces penetrability by increasing the boundary with the aggregate. In addition to providing financial and environmental advantages in power and supply reductions, employing GGBS as a binding ingredient in concrete manufacturing may also result in significant cost savings [34]. For more than a century, GGBS was the primary supplemental cementing material used in the construction industry. Cementitious and pozzolanic characteristics may be found in GGBS material. Various research has been performed on the impact of GGBS on the performance of various kinds of concrete and mortars [35–39]. The substitution of OPC decreases the discharge of harmful gases and the use of superfluous electricity [40]. In addition to its cost-effectiveness and being ecofriendly, its strength and durability characteristics are equivalent to those of cement.

Scholars have devised an attractive aim for GGBS-based geopolymer concrete, which may be utilized as an alternate binding material to OPC in manufacturing concrete [41]. GGBS particle size variation did not cause a substantial change in its chemical composition or particle shape. However, the study also demonstrated that the change in water requirement increased rapidly as GGBS particle size varied [42]. High strength concrete (HSC) was subjected to tests to determine its compressive capacity, penetrability and opposition to chloride ion infiltration. The result shows that when the ground nano slag (NS) replacement percentage was 10%, the strength and durability aspects of HSC were excellent. A lower fraction (5%) of NS is also not evenly distributed and is insufficient to provide greater strength. In the presence of a high proportion (15%) of NS, the ultrafine particle is increased, as the inappropriate filling of pores results in increased concrete performance [43]. The compressive tensile capacity, elasticity, chloride ion penetration and resistivity were investigated experimentally. After three days of curing, it was discovered that concrete mixed with UFS had higher early compressive strength, lower permeability and better durability than conventional concrete [44].

Although a lot of researchers concentrate on GGBS to utilize in concrete production, knowledge is scattered, and a compressive review is required. This work evaluates the literature on the use and effectiveness of GGBS as an alternative to cement. First and foremost, basic information on GGBS manufacture, as well as its physical, chemical and hydraulic activity and heat of hydration are discussed. Then, fresh concrete properties, such as flowability and mechanical strength, are discussed. Furthermore, the durability of concrete, such as density, permeability, acid resistance, carbonation depth and dry shrinkage are also discussed.

4. Physical Properties of GGBS

The physical properties of industrial wastes, including specific gravity, absorption, grain size, fineness modulus, moisture content, bulk density specific surface and unit weight, support establishing their applicability and capability to apply in concrete. Table 2 shows the physical properties of GGBS as per past studies.

Table 2. Physical Properties of GGBS.

Reference	[45]	[46]	[47]	[48]	[49]	[50]	[51]
Specific gravity	2.54	2.82	2.56	2.9	2.85	2.75	2.85
Absorption (%)	-	-	1.2	-	-	-	-
Fineness modulus (cm ² /g)	2.76	5000	-	-	4000	-	-
Bulk density (kg/m ³)	1668	-	1394	1200	-	1165	1200
Specific surface area, cm ² /g	-	-	-	4250–4700	-	-	-
Unit weight (kg/m ³)	-	-	-	1555	-	-	-

The specific gravity of GGBS ranges from 2.5 to 2.9, approximately equal to the specific gravity of cement. The absorption capacity of GGBS was reported at 1.2%, which adversely affects the flowability of concrete. GGBS has a grain size range of 1.18 mm to 0.10 mm, with 62% of the material falling between these two sizes [52]. The bulk density of GGBS ranges from 1200 to 1670 kg/m³, roughly equal to that of cement at 1440 kg/m³. The surface area of GGBS ranges from 4250 to 4700 cm²/g, which is considerably more than the surface area of cement at 3310 cm²/g. The larger surface area of GGBS needs more mortar to cover it, leading to less paste being accessible for lubrication, which ultimately decreases the flowability of concrete. However, other research reported different physical properties of GGBS. The different properties of GGBS may be due to the various location sources of GGBS.

In addition, a scanning electron microscope (SEM) of GGBS is shown in Figure 3. SEM is one of the microscopic methods used to investigate the surface morphology of GGBS. Additionally, it was seen that the fragments were angular in form and that the surface of the GGBS was rough. The angular form and surface roughness enhanced the internal friction between concrete materials, which in turn had a harmful influence on the flowability.

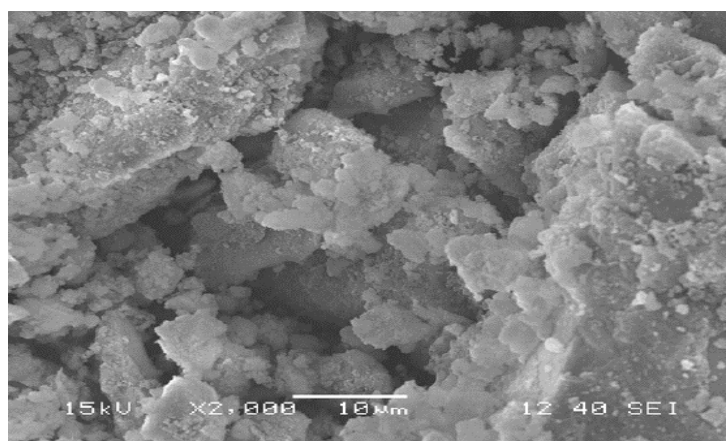


Figure 3. SEM of GGBS [47].

5. Chemical Composition

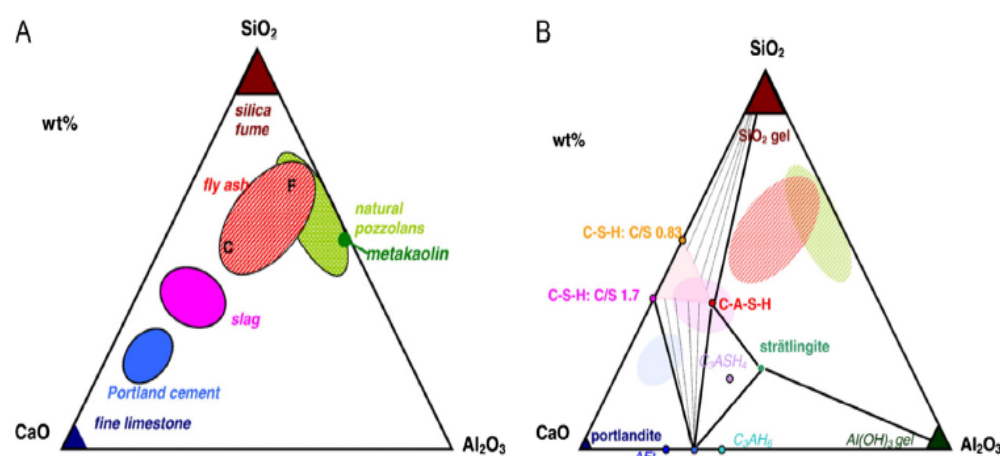
The arrangement of blast furnace slag changes depending on the ore, fluxing stone and contaminations in the coke supply in the blast furnace. GGBS is typically composed of silica, calcium, aluminum, magnesium and oxygen, with silica accounting for more than 95% of the total composition. Table 3 lists various typical chemical compositions of GGBS utilized in concrete. When it comes to the relationship between basicity and hydraulic activity in GGBS, the more basic the GGBS, the better the hydraulic activity of the GGBS in the existence of alkaline activators. Maintaining steady basicity improves the alumina content, which enhances the strength, and a shortage in calcium can be compensated for by increasing the quantity of alumina used in the formulation of magnesia oxide. The impact of magnesia oxide as a calcium oxide replacement seems to be affected by both the basicity of the GGBS and the amount of magnesia oxide present in it. Up to roughly 8–10% variations in magnesia oxide concentration may have only a little influence on strength growth. However, more than 10% magnesia oxide may have a detrimental effect on strength development [53]. However, as indicated in Table 3, the majority of researchers observed that MgO concentrations in GGBS are less than 10%. According to ASTM [13], pozzolanic materials may be formed by the accumulation of chemicals, such as silica, calcium, alumina, magnesia and iron to a concentration of more than 70%. Silica, calcium, alumina, magnesia and iron are among the elements that have accumulated in GGBS to a concentration greater than 70%. As a result, GGBS is a credible pozzolanic material that may be utilized as an OPC substitute in concrete.

Table 3. Chemical Compounds of GGBS.

Authors	Topcu et al. [54]	Yazıcı et al. [55]	Majhi et al. [46]	Patra et al. [47]	Ramakrishnan et al. [49]
SiO ₂	39.41	39.66	34	35.6	91
Al ₂ O ₃	11.63	12.94	14	11.74	-
Fe ₂ O ₃	3.35	1.58	4	0.8	-
MgO	5.52	6.94	7	10.7	7.73
CaO	36.56	34.20	23	41.7	-
Na ₂ O	0.32	0.20	-	-	0.12
K ₂ O	1.21	1.44	-	-	-

6. Hydraulic Activity of Slag

The chemical composition of slag is essential for its hydraulic activity. Slags may be classed based on their basicity index, which is determined by their chemical composition. The ratio of calcium to siliceous oxide must be more than one to be effective [56]. When it comes to the relationship between basicity and hydraulic activity in slag, the more basic the slag, the higher the hydraulic activity of the slag in the existence of alkaline activators. Holding the basicity steady, raising the alumina trioxide concentration, which enhances the strength, and a shortfall in calcium oxide may be compensated for by increasing the quantity of alumina used in the formulation of magnesia oxide. The impact of magnesium oxide as a calcium oxide replacement seems to be controlled by the basicity of the slag as well as the magnesium oxide concentration of the slag. Up to roughly 8–10% variations in magnesia oxide concentration may have only a little influence on strength growth. However, more than 10% magnesium oxide may negatively affect strength development [53]. Furthermore, the hydraulic activity increases with rising calcium, aluminum and magnesium oxide levels and is reduced with improving silica dioxide content in the water. The mass ratio of calcium and magnesium oxide is required to exceed 1.0 following TS EN 197-1 and the British Standards Institute (British Standards). This percentage ensures greater alkalinity, not including slag that could be hydraulically inactive [53]. Figure 4 depicts the chemistry of GGBS and the hydration phases that have been produced [57].

**Figure 4.** (A) Ternary of Cementitious and (B) Hydrated Phase [57]. Used as per Elsevier Permission.

The primary hydration product of GGBS in the presence of cement and water is C–S–H, which the researchers acknowledge and are in agreement on. Since the initial hydration of GGBS occurs substantially more sluggishly than in cement, it is necessary to add an activator, such as Portland cement, alkalis or lime, to speed up the hydration process. In most cases, the hydration of slag cement with cement is dependent on the break and dissolution of the vitreous slag structure caused by the extrication of OH ions from the vitreous slag structure caused by the hydration of the cement. It is generated by the effect of sodium and potassium alkalis with calcium hydroxide when slag cement hydrates,

producing additional CSH. In addition, when slag cement is combined with water, a little and immediate reaction occurs, which positively frees calcium and aluminum ions into the solution, according to one study. It is impossible to proceed with the reaction until more alkali or calcium hydroxide or sulphate is introduced into the mixture [58]. During typical temperature conditions, the hydration of slag cement blended with Portland cement occurs in the form of a two-phase reaction. Most of the reaction occurs with alkali hydroxide in the beginning and throughout the early hydration, whereas the subsequent reaction is mostly with calcium hydroxide [26].

Slags must be given mechanical and thermal treatments in order to activate them and enhance their hydraulic capabilities [59]. Additionally, there are different approaches to achieving the same results such as adding nano- or microparticles or additional cementing ingredients such as silica fume [60]. Furthermore, only the early-age lime-slag reaction and compressive strength improve when the hydration temperature is increased to 100 °C (up to 1 day). However, the long-term hydration reaction rates of slags are not significantly affected by a reaction at 100 °C. As a result, it seems that diffusional processes control the response rate. At 100 °C, calcium aluminum oxide hydroxide hydrate (C_4AH_{13}) was not found [61].

Chemical activation is a fairly easy procedure that may be used to accelerate hydration processes and boost mechanical strengths, particularly in young materials. It doesn't need any additional energy or equipment. Because the composition of different forms of slags varies based on raw materials and industrial process, the best chemical activator may vary from one type of slag to another. When the slag is being ground or later when it has been dissolved in water, chemical activators may be added to the mixture [62].

7. Heat of Hydration

A substantial temperature differential and thermally induced stress cracking are caused by the interior cement of a mass concrete structure's incapacity to promptly release its hydration heat [63]. In order to lessen the danger of cracking in large concrete constructions, high percentages of mineral admixtures are employed to reduce the hydration heat of cement and the adiabatic temperature increase in the concrete [64].

The results of the adiabatic calorimeter experiments performed on the GGBS are shown in Figure 5. The results contain the information taken for the first 100 t_{20} h of assessment, and heat amounts are indicated in Joules per maturity second per kilogram of the cement. Detailed information on the maximum heat rates (q_{max}) as calculated from the data given in Figure 3 is included in Table 4. Figure 5 depicts the ultimate hydration heat percentage falls when the amount of GGBS is enhanced. According to similar research, the pozzolanic reaction continues gradually and is associated with the hydration of cement, which ultimately causes a decline in the heat, especially in the early days of hydration [11].

When utilized as a mineral ingredient, slag may significantly reduce the heat required for cement to hydrate and the adiabatic temperature rise of concrete [65]. The large slag particles, however, are lacking in many cementitious properties, and their interfaces with calcium silicate hydrate gels are potential failure points [66]. Furthermore, the presence of a lot of slag tends to give the hardened paste a coarser pore structure [67], which reduces the strength and longevity of the concrete [68]. In some studies, it has been demonstrated that using a composite mineral admixture known as ground-granulated blast-furnace slag-steel slag composite binder can increase the fluidity of fresh concrete, lengthen the cement's setting time, improve the pore structure of hardened paste and create concrete with a satisfactory compressive strength [69]. It is important to remember that the composite binder has a bigger effect on lowering cement hydration heat and adiabatic temperature rise in concrete than fly ash [70].

Table 4 demonstrates that increasing the fraction of GGBS to 60% results in a minor reduction in the time necessary to attain this highest hydration rate. The decrease in the time to peak heat amount becomes more substantial when the fraction of GGBS is raised from 60% to 80% of the total heat rate.

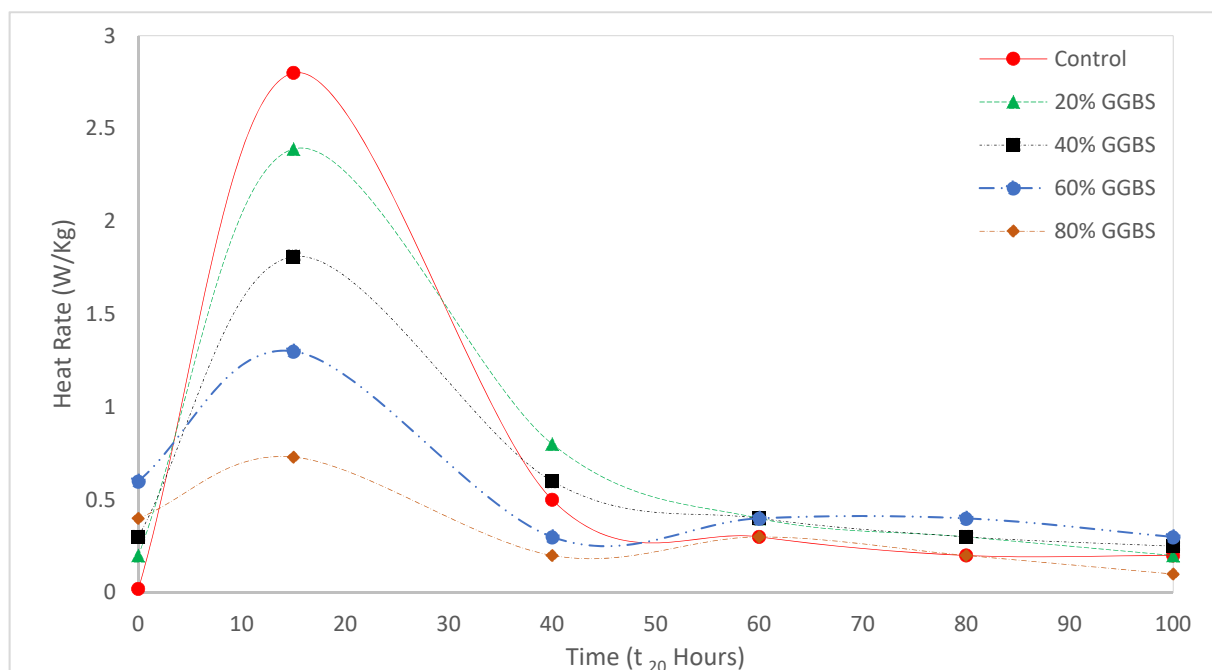


Figure 5. Heat Rate of Concrete with and without GGBS: Data Source [71].

Table 4. Peak Heat Characteristics of GGBS [71].

Mix Composition	Time to q_{\max} (t_{20} h)	q_{\max} (W/kg)	to 100% CEM I (W/kg)
100-OPC	17.6	2.80	2.80
20-GGBS	15.3	2.39	2.99
40-GGBS	15.7	1.81	3.02
60-GGBS	14.2	1.30	3.25
80-GGBS	10.7	0.73	3.65

According to Table 4, the stabilized peak heat rates of blended concrete are more significant than the stabilized peak heat rates for the plain OPC concrete. GGBS hydration contributes to heat formation at initial ages, indicating that the concrete is generating heat due to its hydration. Experimental data from Wu et al. [72] reveal that the GGBS concretes responded similarly.

8. Workability

The flowability of concrete with GGBS is presented in Figure 6. It should be mentioned that the slump value improved when GGBS was used instead of Portland cement. More cement paste resources are accessible to minimize internal friction among concrete components due to micro filling spaces within the concrete aggregate, resulting in more flowable concrete [73]. A researcher also claims that the increased slump is due to better GGBS particle dispersion [74]. A study concluded that the inclusion of slag (30–50%) increased the workability of concrete mixes; although a higher slag concentration led to larger improvements [75]. Higher slag fineness had no discernible impact on workability, and the authors of [76] found that the workability of mortar decreased as GGBS surface area increased.

According to research, an enhancement in the substitution ratio of OPC by GGBS leads to considerable improvements in the flowability of the ultra-high performance concrete (UHPC) mix. It may be extrapolated that the enhancement in flow is significant up to a 40% substitution ratio of GGBS and that the improvement in flowability is not considered beyond a 40% substitution ratio of GGBS [1]. In contrast, the flowability of concrete mixes

reduces as the quantity of GGBS is enhanced. This decrease in the flowability of concrete might be ascribed to increased water absorption. In addition, the findings of the slump test show that the workability of the concrete decreases as GGBS concentration increases. This could be a result of the GGBS's increased water absorption capacity when compared to natural fine aggregate. Therefore, when using more than 40% GGBS in concrete, the use of superplasticizers is advised to produce the necessary slump value. Furthermore, the harsh surface texture and increased water absorption of GGBS are two of the most important factors that influence the flowability of concrete [47].

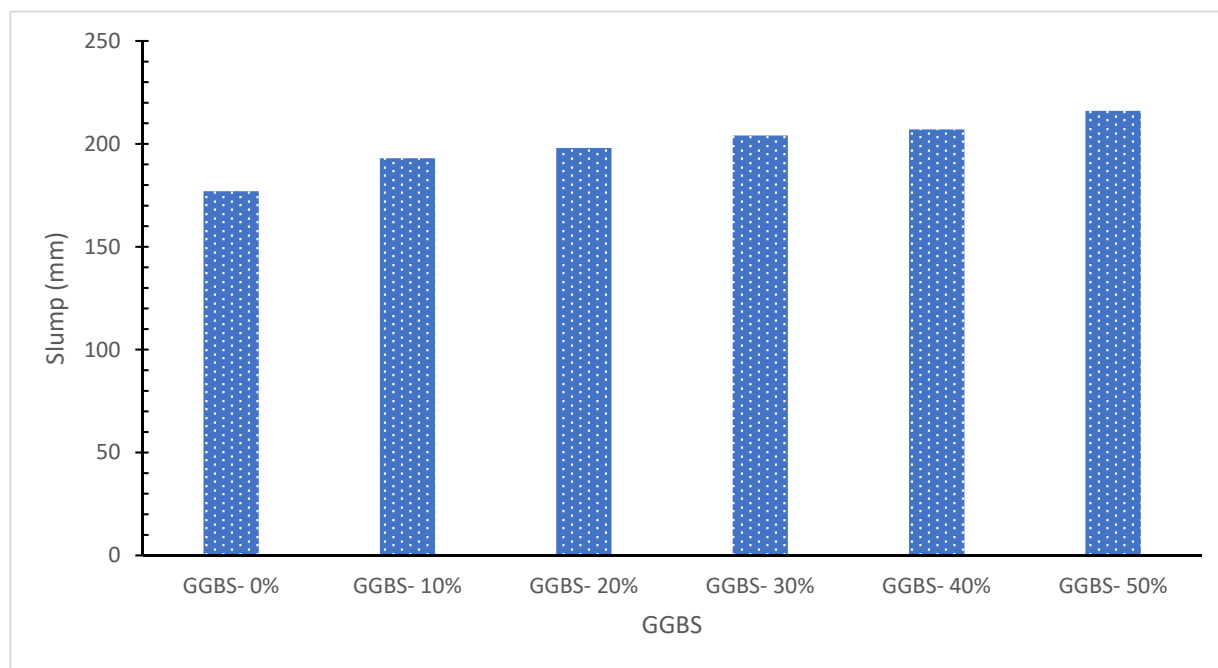


Figure 6. Slump Flow [77].

Similarly, the SEM of GGBS shown in Figure 3 shows a greater surface area and a rough surface for the GGBS material. To cover the increased surface area of GGBS with cement paste, more cement paste was necessary, causing less cement paste to be accessible for lubrication, resulting in decreased flowability. Plasticizers are necessary to apply to meet the water requirement while also improving flowability. The slump value of concrete with varying amounts of GGBS is displayed in Table 5 below and is based on previous research.

Table 5. The slump of concrete made with GGBS as per past research.

Author	(GGBS) Replacement Ratio	Slump (mm)
Erdogon et al. [78]	0%, 15% and 30%	260, 270 and 260
Majhi et al. [46]	0%, 25%, 50% and 100%	70, 75, 85 and 95
Majhi et al. [79]	GGBS (kg) 0 and 234	70 and 80
Rakesh et al. [47]	0%, 20%, 40% and 60%	100, 80, 60 and 40
Suda et al. [80]	0 g, 97.2 g, 129.6 g and 162 g	111, 119, 113 and 105
Vediyappan et al. [81]	GGBS (kg/m ³) 364.5, 324, 284, 243 and 0	147, 122, 146, 165 and 173
Soni et al. [82]	0%, 30%, 40% and 50%	100, 85, 110 and 130
Nath et al. [83]	GGBS (kg/m ³) 0, 73, 146 and 219	250, 230, 235 and 205

9. Mechanical Properties

9.1. Compressive Strength (CPS)

The CPS of concrete with varied replacement ratios of GGBS is shown in Figure 7. At all curing ages, it can be noticed that CPS enhanced with GGBS up to a 20% replacement fell progressively, reaching its maximum strength at 20% of GGBS substitution. Strength declined significantly after 20% replacement of GGBS with an 80% substitution of GGBS, showing significantly lower CPS than concrete that had been substituted with GGBS with a 20% substitution [1]. According to another study, the CPS of concrete increased up to 20% when substituted with GGBS but the further addition of GGBS dropped owing to a lack of flowability [73]. The pozzolanic interaction of silica dioxide in GGBS with the calcium hydrate of cement caused the development of additional binding compounds, such as CSH, which was responsible for the favorable influence on CPS [3,19]. With the addition of the extra binder formed by the GGBS reaction with accessible lime, concrete is able to continue to develop strength as time passes. However, at higher dosages (greater than 20% by weight of cement), strength decreases as a result of the dilution effect, which causes the alkali–silica reaction as a result of a larger quantity of unreactive silica being available due to the higher percentage of GGBS being utilized in concrete [4].

Additionally, GGBS fills in the spaces in the aggregate resulting in denser concrete, which increases the CPS of concrete [73]. However, at larger doses of GGBS (more than 20%), a drop in CPS was found owing to deficient flowability, which enhanced compaction efforts resulting in more pores in the concrete, ultimately lowering the CPS of the concrete. According to research [84], the strength advantage of concrete containing 20–60% GGBS did not appear until 28 days of curing, at which point comparable or greater long-term strength was attained as compared to conventional concrete. A study [76] reported that the strength of mortar containing GGBS is related to both the particle size distribution and surface area of GGBS. The early strength of the mortar rose according to the quantity of fine GGBS particles even if GGBS had the same surface area. The strength of the mortars over time increased with the amount of GGBS particles present.

Furthermore, since the pozzolanic reaction occurs slowly, the CPS of concrete containing GGBS also depends on curing days. According to the research findings, the CPS of the concrete using GGBS as fine aggregate is comparable to that of the reference concrete at early ages. However, owing to the reactivity of slag, the higher the amount of slag replaced by sand, the greater the CPS of the concrete is likely to be at 365 days [85]. Based on previous research, the CPS of concrete with varying amounts of GGBS is shown in Table 6 below.

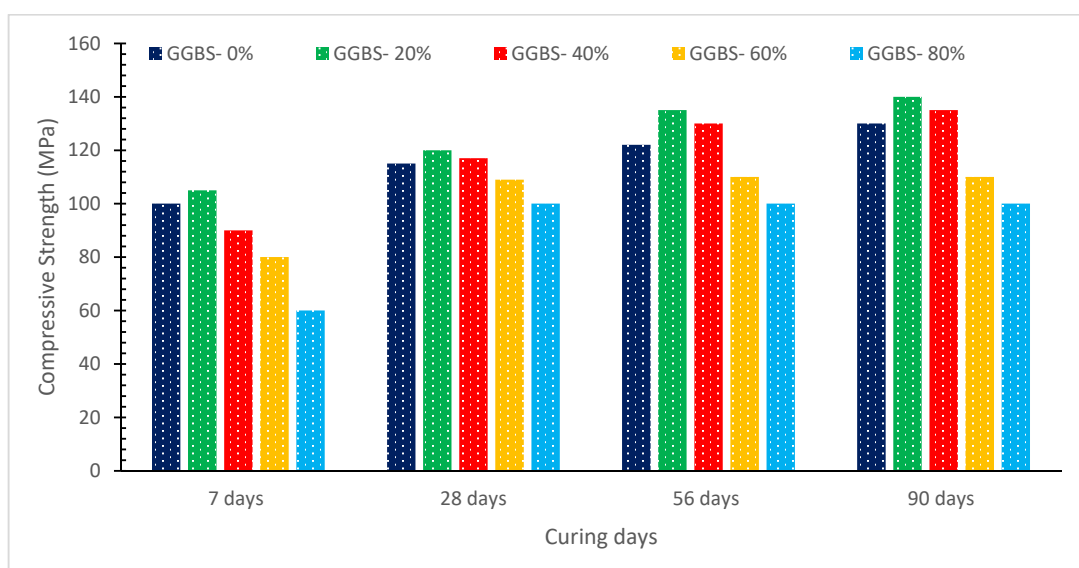


Figure 7. Compressive Strength: Data Source [1].

Table 6. Compressive strength of concrete made with GGBS as per past research.

Author	(GGBS) Replacement Ratio	Compression Strength (MPa)
Erdogon et al. [78]	0%, 15% and 30%	35, 45 and 40
Arash et al. [86]	0%, 20%, 40% and 60%	45, 45, 48 and 38
Topçu et al. [54]	0%, 25% and 50%	28 days 35, 49 and 43 90 days 37, 53 and 44
Ganesh et al. [1]	GGBS (kg/m ³) 0, 192, 384, 576 and 768	115.67, 129.90, 117.98, 109.81 and 101.16
Majhi et al. [46]	0%, 25%, 50% and 100%	40, 32, 35 and 15
Majhi et al. [79]	GGBS (kg) 0 and 234	35 and 30
Rakesh et al. [47]	0%, 20%, 40% and 60%	36.42, 39.1, 41.0 and 43.6
Suda et al. [80]	0 g, 97.2 g, 129.6 g and 162 g	36.50, 40.32, 42.95 and 39.30
Siddique et al. [48]	0% 20% 40% 60% 80%	7 days 43.4, 35.6, 42.5, 35.2 and 35 28 days 54.3, 55.4, 63.6, 58.4 and 56
Ramakrishnan et al. [49]	(C + GP + GGBS)% 50 + 40 + 10, 50 + 30 + 20, 50 + 20 + 30, 50 + 10 + 40 and 100 + 0 + 0	20.45, 18.16, 26.14, 31.26 and 29.05
Raafidiani et al. [87]	0%, 40%, 50% and 60%	14 days 26.06, 22.99, 25.25 and 22.40 28 days 26.50, 23.03, 26.65 and 22.02
Ramani et al. [88]	GGBS (kg/m ³) 394, 355, 315 and 276	7 days 66.5, 67.6, 46.32 and 20.48 28 days 69.28, 70.72, 51.46 and 24.52
Vignesh et al. [45]	FLYASH + GGBS 100 + 0, 90 + 10, 80 + 20, 70 + 30, 60 + 40 and 0 + 0	16.30, 21.11, 34.32, 42.48, 45.55 and 36.84
Vediyappan et al. [81]	GGBS (kg/m ³) 364.5, 324, 284, 243 and 0	45.51, 54.64, 62.39, 58.78 and 58.14
Makhdoom et al. [89]	0%, 25%, 50% and 75%	10.73, 5.88, 3.96 and 3.4
Nazari et al. [90]	0%, 15%, 30%, 45% and 60%	31.5, 35.4, 38.9, 43.7 and 40.6
Nath et al. [83]	GGBS (kg/m ³) 0, 73, 146 and 219	10, 25, 35 and 40

(RCA) = Recycled coarse aggregate. (GGBS) = Ground-granulated blast-furnace slag. (CM) = Control mix.

The compressive strength (CPS) age relationship is displayed in Figure 8 in which 28 days CPS was selected as the reference strength from which another dose of GGBS is compared at various days of curing. CPS (7 days) of concrete with a 20% substitution of GGBS is only 9% less than the reference concrete (28 days control concrete CPS), while CPS (28 days) with a 20% substitution of GGBS is only 5% more than the reference concrete. The same dose of GGBS (20%) shows a CPS of 17% and 21% more than the reference concrete at 56 and 90 days curing. It can be noted that GGBS does not improve CPS up to 28 days considerably. However, dramatically improved CPS was indicated at 56 and 90 days of curing. The considerable improvement in CPS at 56 and 90 days is due to the pozzolanic reaction of GGBS as it continues gradually as assessed by the hydration of OPC. Similarly,

studies reported that pozzolanic reaction continues gradually as compared to the hydration of OPC [91–93].

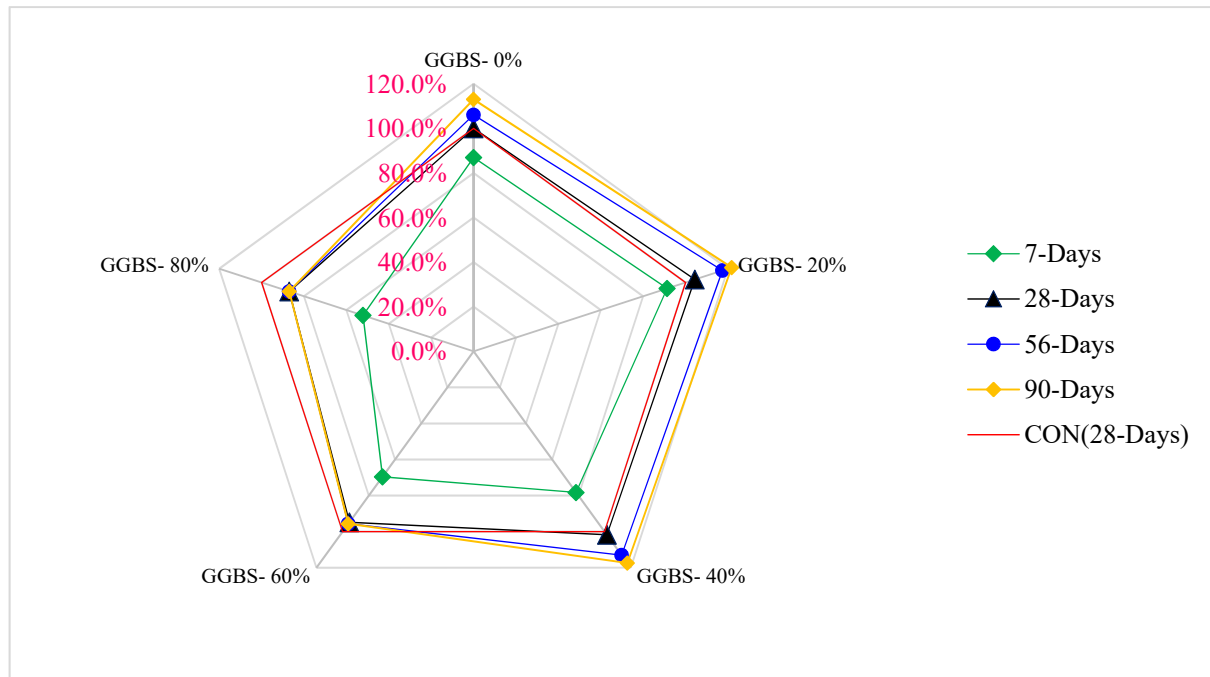


Figure 8. Compressive Strength Gain Age Analysis: Data Source [1].

9.2. Split Tensile Strength (STS)

The direct tensile strength of concrete is not often tested because of the production of secondary stresses caused by sample holding mechanisms, which must be considered. As a result, there are many indirect ways of determining the STS. The STS of concrete with varied replacement ratios of GGBS is shown in Figure 9.

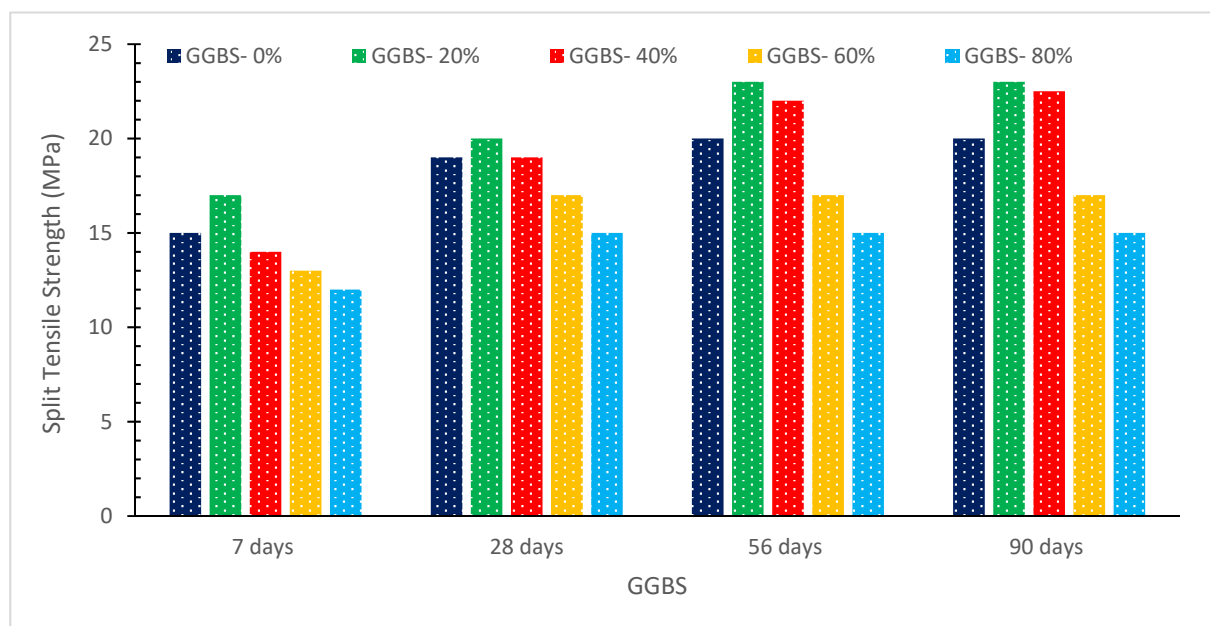


Figure 9. Tensile Strength (STS) [1].

The STS of concrete increased with a GGBS replacement up to 20% and then fell progressively with the maximum STS at 20% of GGBS substitution at all ages of curing,

similar to the CPS. However, the STS reduced significantly beyond a 20% replacement of GGBS, and even after an 80% substitution of GGBS, the STS is much lower when compared to concrete without the substitution of GGBS (control concrete) [1]. Research also found that the STS of concrete increased with up to a 20% substitution of GGBS, but the STS reduced owing to a lack of flowability after the further addition of GGBS, i. e., beyond 20% [73]. A possible explanation for the improvement in STS might be traced to the pozzolanic activity of GGBS, which helps to minimize the presence of holes and enhance the interface properties. According to another study, the STS findings of high-volume GGBS at 56 and 90 days demonstrate that the primary stage strength of the concrete does not exhibit any substantial enhancement when associated with the later age results at 56 and 90 days. One possible explanation is that GGBS does not respond readily when exposed to conventional water curing conditions at an initial stage. However, curing at a high temperature improved STS considerably [1].

In contrast, when the amount of GGBS was increased by over 20%, the STS fell due to the dilution impact, which led to an alkali–silica reaction. When a higher dosage of GGBS is used, unreactive silicon dioxide is found to be readily accessible, which reacts with alkali, resulting in the alkali–silica reaction (ASR) [73]. The ASR exerts stress on concrete to expand, which eventually cracks the concrete structure. Research also discovered that the STS falls as the rate of GGBS replacements increases, and there is no difference in the STS up to a 10% substitution of GGBS. In the case of a replacement with GGBS up to 30%, the STS is reduced by 12% [94]. Based on previous publications, the STS of concrete with fluctuating proportions of GGBS is shown in Table 7 below.

Table 7. Split Tensile strength of concrete made with GGBS as per past research.

Author	(GGBS) Replacement Ratio	Split Tensile Strength (MPa)
Topçu et al. [54]	0%, 25% and 50%	28 days 3.3, 3.5 and 3.3 90 days 3.7, 4.2 and 3.3
Ganesh et al. [1]	GGBS (kg/m ³) 0, 192, 384, 576 and 768	19.48, 20.37, 19.24, 17.71 and 14.96
Majhi et al. [46]	0%, 25%, 50% and 100%	3.1, 3.2, 3 and 2.9
Rakesh et al. [47]	0%, 20%, 40% and 60%	2.9, 3, 3.3 and 3.5
Suda et al. [80]	0 g, 97.2 g, 129.6 g and 162 g	3.27, 3.52, 3.77 and 3.44
Ramakrishnan et al. [49]	(C + GP + GGBS)% 50 + 40 + 10, 50 + 30 + 20, 50 + 20 + 30, 50 + 10 + 40 and 100 + 0 + 0	2.14, 1.58, 1.84, 2.31 and 2.03
Ramani et al. [88]	GGBS (kg/m ³) 394, 355, 315 and 276	7 days 6.43, 6.69, 3.94 and 0.89 28 days 6.74, 6.92, 4.26 and 1.12
Vignesh et al. [45]	FLYASH + GGBS 100 + 0, 90 + 10, 80 + 20, 70 + 30, 60 + 40 and 0 + 0	1.92, 3.15, 3.91, 4.37, 5.94 and 4.20
Vediyappan et al. [81]	GGBS (kg/m ³) 364.5, 324, 284, 243 and 0	3.055, 4.108, 4.621, 3.983 and 4.063
Soni et al. [82]	0%, 30%, 40% and 50%	4.20, 4.33, 4.67 and 4.47
Nazari et al. [90]	0%, 15%, 30%, 45% and 60%	1.6, 1.9, 1.9, 2.1 and 2.0

Figure 10 shows the correlation between CPS and STS with varying percentages of GGBS. It is well known that CPS and STS are correlated with each other; i.e., the STS of concrete is 9 to 10% of CPS [95]. Therefore, a strong correlation between CPS and STS

occurs with an R^2 value greater than 0.90. The following expression has been established based on various GGBS percentages.

$$f_{sp} = 0.224 \times f_c^{0.90}, \quad (1)$$

where f_{sp} = STS and f_c = CPS.

However, codes suggested various equations to calculate STS from CPS, which are listed below. ACI-318.11 [96] Equation (2), Eurocode [97] Equation (3) and JSCE-07 [98] Equation (4). Table 8 shows the predicted STS from CPS based on different proposed equations.

$$f_{sp} = 0.53 \times \sqrt{f_c} \quad (2)$$

$$f_{sp} = 0.3 \times \sqrt{f_c} \quad (3)$$

$$f_{sp} = 0.44 \times \sqrt{f_c} \quad (4)$$

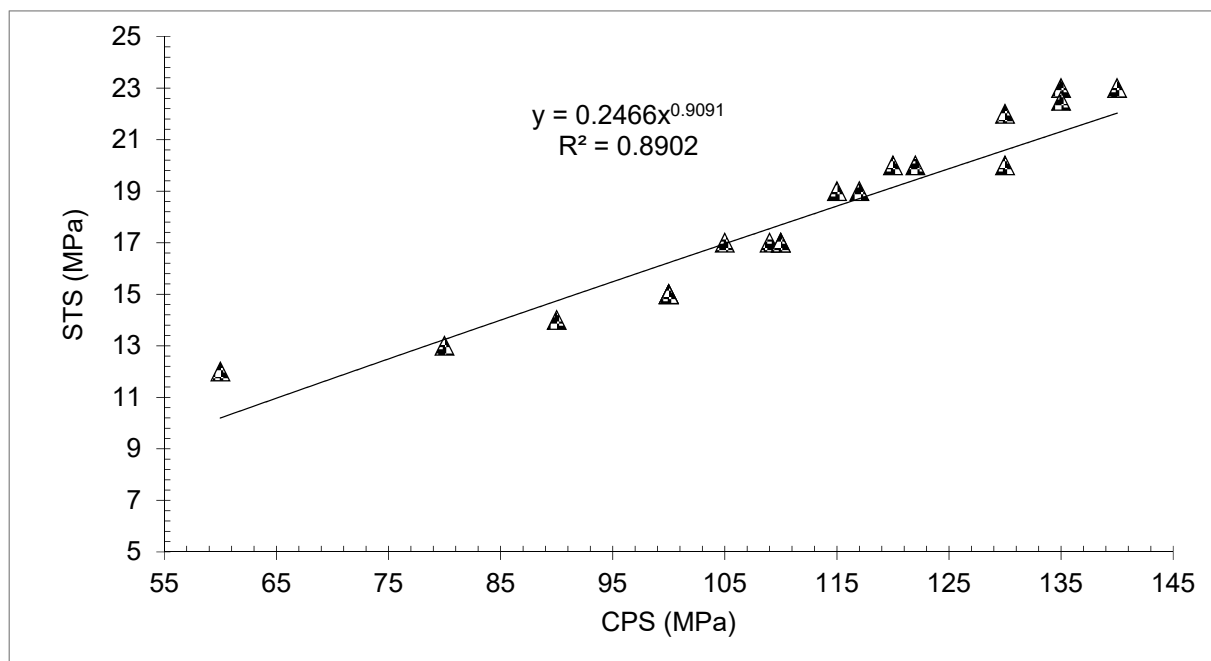


Figure 10. Correlation between CPS and STS: Data Source [1].

Table 8. Experimental and Calculated STS.

Experimental CPS (MPa)	Experimental STS (MPa)	Equation (1)	ACI-318.11 [96]	Eurocode [97]	JSCE-07 [98]
100	15	14.13	5.3	3	4.4
105	17	14.76	5.43	3.07	4.50
90	14	12.85	5.02	2.84	4.17
80	13	11.56	4.74	2.68	3.93
60	12	8.92	4.10	2.32	3.40
115	19	16.02	5.68	3.21	4.71
120	20	16.65	5.80	3.28	4.81
117	19	16.27	5.73	3.24	4.75
109	17	15.27	5.53	3.13	4.59
100	15	14.13	5.3	3	4.4
122	20	16.90	5.85	3.31	4.85
135	23	18.51	6.15	3.48	5.11
130	22	17.89	6.04	3.42	5.01
110	17	15.39	5.55	3.14	4.61
100	15	14.13	5.3	3	4.4

Table 8. Cont.

Experimental CPS (MPa)	Experimental STS (MPa)	Equation (1)	ACI-318.11 [96]	Eurocode [97]	JSCE-07 [98]
130	20	17.89	6.04	3.42	5.01
140	23	19.13	6.27	3.54	5.20
135	22.5	18.51	6.15	3.48	5.11
110	17	15.39	5.55	3.14	4.61
100	15	14.13	5.3	3	4.4

Figure 11 shows the correlation among predicted STS from Equation (1), ACI-318.11 [96] Equation (2), Eurocode [97] Equation (3) and JSCE-07 [98] Equation (4). It can be observed that the STS calculated from Equation (2) gives results closer to experimental split tensile strength. However, the findings obtained from various codes, i.e., ACI-318.11 [96] Equation (2), Eurocode [97] Equation (3) and JSCE-07 [98] Equation (4) are much lower than the actual experimental results of split tensile strength. It might be because ACI-318.11 [96] Equation (2), Eurocode [97] Equation (3) and JSCE-07 [98] Equation (4) are proposed for conventional concrete, while Equation (2) is developed for concrete with different percentages of GGBS. Furthermore, the STS mainly depends on cement paste strength. During tensile load, the aggregate tries to elongate while cement paste holds them. With the substitution of GGBS, the binding properties of cement paste improved paste due to the pozzolanic reaction, which forms secondary cementitious compounds, such as calcium silicate hydrate gel (CSH). A study also claimed that mineral admixture improved tensile capacity more effectively than compressive strength [99]. Therefore, this study suggests that Equation (2) could be used to calculate the STS from the CPS of concrete, particularly concrete with different doses of GGBS.

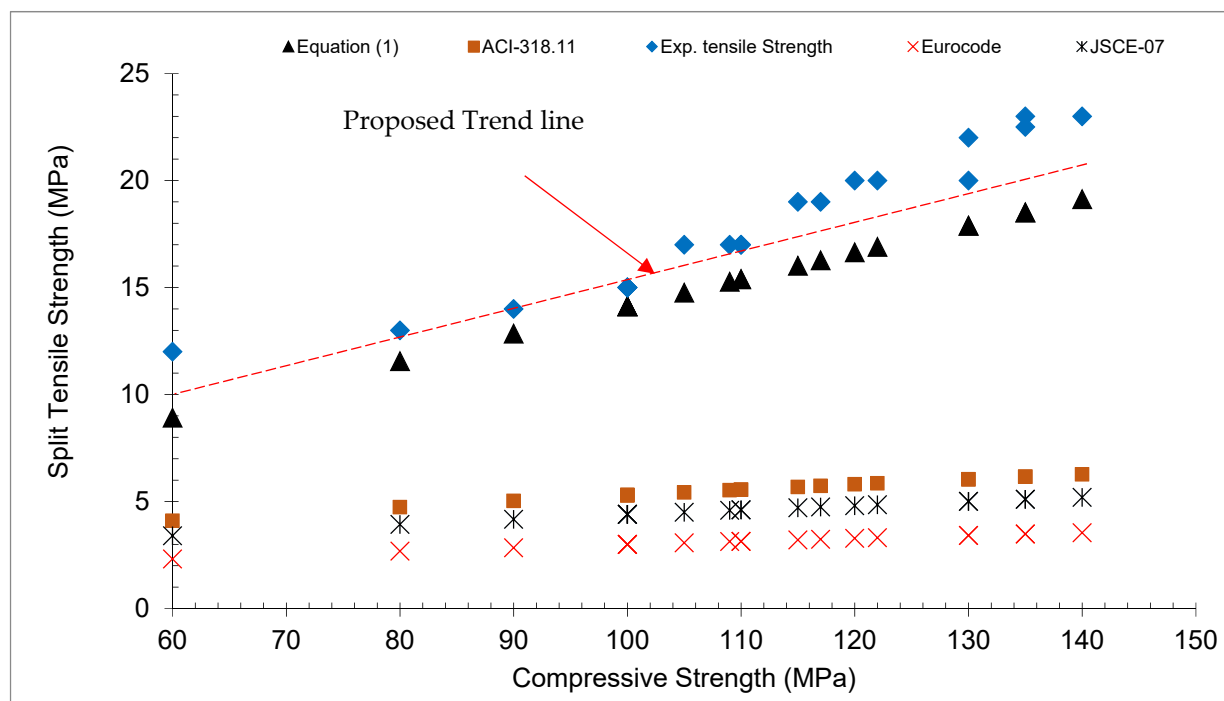


Figure 11. Correlation between Calculated and Experimental STS.

9.3. Flexure Strength (FS)

The FS of concrete with GGBS and metakaolin (MK) replacement is shown in Figure 12. Flexure strength was enhanced when the proportion of GGBS and MK was increased. The pozzolanic interaction of silica in GGBS with calcium hydrate in cement results in the formation of a supplemental cementitious gel, i.e., calcium silicate hydrate (CSH) [73],

which has a beneficial influence on FS. According to previous work, FS is mainly affected by the strength of the binder. When subjected to tensile tension, aggregates attempt to migrate apart. The resistance is increased because of the extra binder formed by the GGBS [99]. In contrast, when the amount of GGBS was increased by over 20%, the FS dropped because of the dilution effect, which led to an alkali–silica reaction. When a greater dosage of GGBS is used, unreactive silica is found to be readily accessible, which reacts with alkali resulting in the alkali–silica reaction [73]. Furthermore, according to the findings of one study, the FS of concrete mixes increases as the amount of GGBS in the mix increases. The FS of concrete at a water to binder ratio of 0.45 is 4.216 MPa for a control mix that does not include GGBS. In addition, the FS is increased to 4.367 MPa, 4.47 MPa and 4.61 MPa, which is 3.58 percent higher, 6.02 percent higher and 9.34 percent higher than the control mix when GBS is replaced at 20%, 40% and 60%. The pozzolanic activity of GGBS in the concrete is strengthened by the neutralizing of calcium hydroxide crystals. As a result, the FS of the concrete is increased [47]. Research also discovered that when GGBS was substituted for 10%, FS increases by 10% compared to the control mix [94]. According to previous research, the FS of concrete with various percentages of GGBS is shown in Table 9.

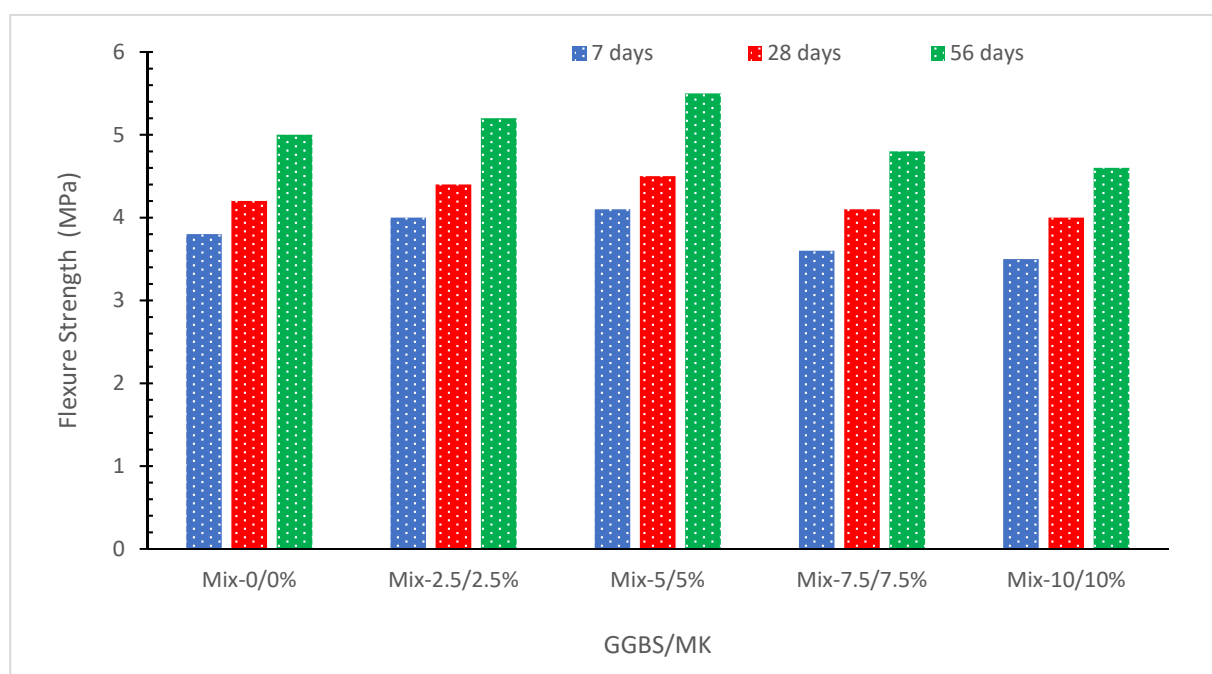


Figure 12. Flexure Strength [100].

Table 9. Flexure Strength of Concrete with GGBS as per past research.

Author	(GGBS) Replacement Ratio	Flexure Strength (MPa)
Erdogon et al. [78]	0%, 15% and 30%	4, 6 and 8
Majhi et al. [46]	0%, 25%, 50% and 100%	5, 4.9, 4.8 and 4.8
Rakesh et al. [47]	0%, 20%, 40% and 60%	4.2, 4.3, 4.5 and 4.6
Suda et al. [80]	0 g, 97.2 g, 129.6 g and 162 g	4.74, 5.14, 5.56 and 5
Ramakrishnan et al. [49]	(C + GP + GGBS)%	21.07
	50 + 40 + 10, 50 + 30 + 20,	-
	50 + 20 + 30, 50 + 10 + 40	-
	and 100 + 0 + 0	21.42
		-

Table 9. Cont.

Author	(GGBS) Replacement Ratio	Flexure Strength (MPa)
Ramani et al. [88]	GGBS (kg/m ³) 394, 355, 315 and 276	7 days 5.75, 6.26, 3.57 and 1.05
		28 days 6.06, 6.98, 4.12 and 1.27
Vignesh et al. [45]	FLYASH + GGBS 100 + 0, 90 + 10, 80 + 20, 70 + 30, 60 + 40 and 0 + 0	2.40, 3.58, 4.16, 4.68, 5.97 and 4.45
Vediyappan et al. [81]	GGBS (kg/m ³) 364.5, 324, 284, 243 and 0	3.296, 3.913, 4.217, 4.103 and 4.109
Nazari et al. [90]	0%, 15%, 30%, 45% and 60%	4.2, 4.6, 4.9, 5.4 and 5.1

10. Durability

10.1. Density

Density is an important parameter that detects the quality of concrete, particularly its durability of concrete. Denser concrete has stronger strength and fewer voids and less porosity than less dense concrete. As the number of spaces in concrete decreases, the material becomes less permeable to water and soluble components, which causes a reduction in water absorption, and the durability of concrete will be improved. Water contains a harmful chemical that causes the degradation of concrete. Figure 13 demonstrates concrete density at 28 days with GGBS and metakaolin (MK) substitution. It can be noted that the density of concrete is reduced with the substitution of GGBS. The decrease in concrete density caused by the addition of GGBS and MK is because the specific gravity of cement is larger than the particular gravity of metakaolin and GGBS combined [100]. A study suggests that the concrete mix incorporating GGBS could be helpful in lightweight construction owing to the lower density of GBS [47].

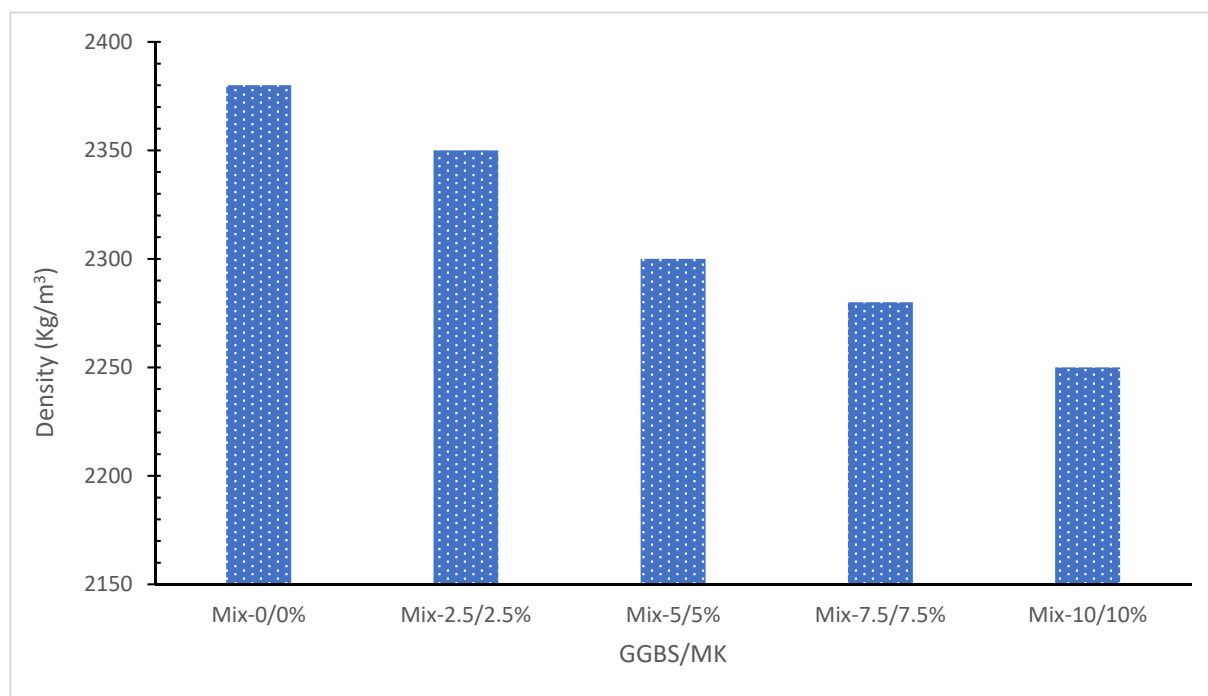


Figure 13. Density of Concrete [100].

In contrast, the research described that concrete density increased with GGBS. The increase in density with GGBS is due to the micro filling effects of GGBS, which fills the voids between concrete ingredients, leading to a more compact mass that ultimately

increases the concrete density [73]. Although the density is one of the most critical factors that define the characteristic of concrete, few researchers consider density in their research, and more studies are recommended in this regard.

10.2. Rapid Chloride Ion Penetration (RCPT)

The RCPT test was performed to measure the material's resistance to chloride ions penetrating the sample. The depth to which chloride ions from the surrounding environment permeate into the concrete is called chloride penetration. RCC structures can corrode as a result of chloride penetration. Therefore, chloride permeability is an essential component that influences the durability of the concrete. The capacity to keep the concrete's permeability at the lowest possible levels is one of the most essential criteria for the long-term durability of concrete structures that are sensitive to reinforcing corrosion. The measured chloride ion penetration value of ultra-high performance concrete with a large amount of GGBS is shown in Figure 14. For G-0, G-20, G-40, G-60 and G-80, the average charge passed is 139, 101, 75, 76 and 82 Coulombs, with the average charge passing being 139, 101, 75, 76 and 82 Coulombs. In this study, it was discovered that increasing the replacement amount of GGBS results in a decrease in chloride penetration. According to ASTM C1202 [101], the mixtures G-0 and G-20 have a permeability class of extremely low, which means a low rate of chloride penetration. Forms G-40, G-60 and G-80 blend. On the other hand, chloride penetration is almost nonexistent. According to the findings, increasing the dose of GGBS in the UHPC mix leads to increased resistance to chloride penetration of the mixture. The chloride resistivity of UHPC increases due to the physical densification of the pore structure caused by the action of GGBS replacement. Additionally, according to one study, concrete incorporating glassy ground-granulated blast-furnace slag has enhanced resistance to chloride penetration when compared to conventional concrete [102]. According to the findings [103], calcium sulfate had a different impact on chloride binding and the chemistry of the pore solution than sodium sulfate. As a straightforward replacement for OPC, the slag cement had higher chloride-binding capacities. However, at the same sulfate content, the slag cement did not exhibit the anticipated higher binding capacities, indicating that the difference in sulphate content between the two cements may be the primary factor influencing their divergent chloride-binding behavior.

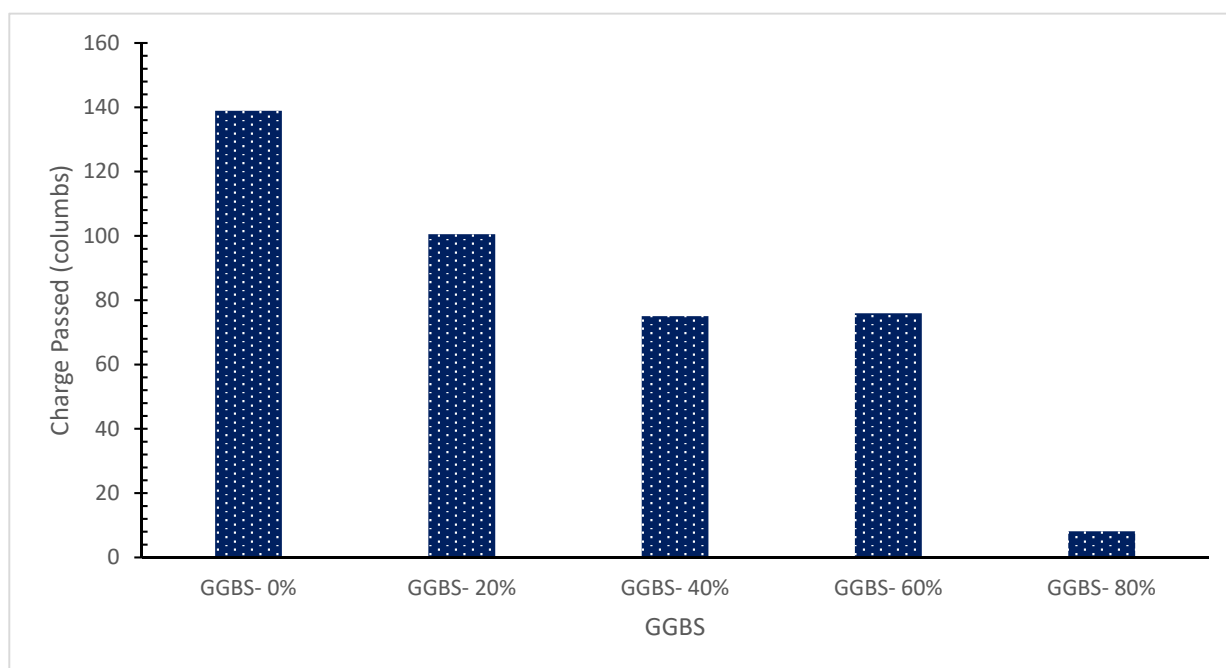


Figure 14. Rapid Chloride Penetration [1].

10.3. Permeability

The permeability of concrete impacts the durability of concrete because it regulates the pace at which moisture may include an aggressive chemical penetration. Concrete with a lower permeability is more resistant to cracking. The permeability of concrete with GBBS and metakaolin (MK) substitutions is shown in Figure 15. It can be noted that the permeability of concrete decreased with the GBBS substitution. In concrete, after 28 days, the maximum permeability was determined to be 19.5 mm at 0% of GBBS, while the lowest permeability was calculated to be 9 mm with 10% GBBS and 10% MK.

Furthermore, the permeability of concrete is an important characteristic of durable concrete, and concrete with a reduced water penetration depth shows significant resistance to chemical assaults [104]. The decrease in permeability of concrete with GBBS is due to the pozzolanic reaction with secondary cementitious materials (CSH), which improved the binding property of mortar, leading to lower permeability. Furthermore, the micro filling effect of GBBS, which fills the voids in aggregate, leads to a more compact mass, ultimately decreasing the concrete's permeability. The combined pozzolanic reaction and micro filling voids positively impact the concrete's permeability. However, one study suggests that a higher dose of GBBS (beyond 20%) results in more voids in concrete due to a lack of workability [73]. More voids tend to cause an increase in the permeability of concrete.

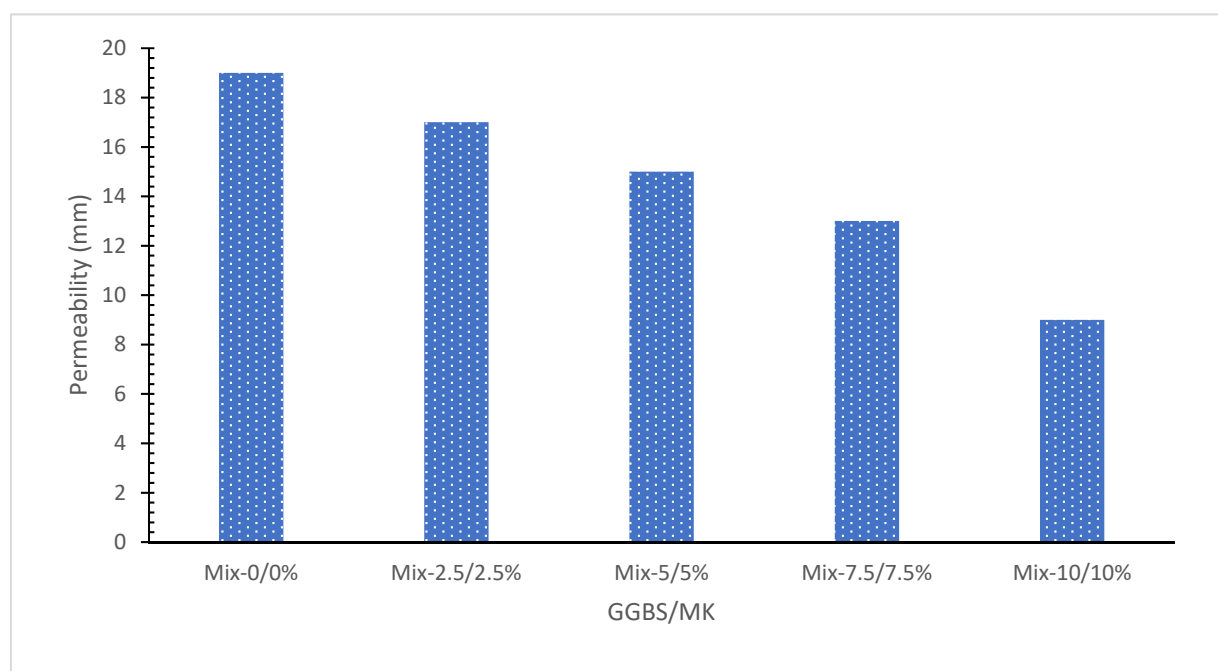


Figure 15. Permeability of Concrete [100].

10.4. Chloride Attack

The long-term durability of concrete, chloride attack is the most severe aspect that must be considered. Chloride attack is responsible for about 40% of the failures of concrete buildings. Because of the presence of oxygen and water, a chloride attack corrodes the steel, significantly lowering the structural strength of the structure. Corrosion occurs when chloride ions come into contact with steel and passive materials in the surrounding area, resulting in a chemical reaction that produces hydrochloric acid. The hydrochloric acid eats the steel reinforcement, resulting in cracking, spalling and finally the collapse of the concrete structure [105]. Figure 16 shows the residual CPS of concrete exposed to a chloride attack with and without GBBS and metakaolin (MK) substitution. It can be noticed that the residual CPS of concrete subjected to a chloride attack increases when the replacement ratio of GBBS was increased. Improvement in residual CPS of concrete exposed to a chloride attack is due to the pozzolanic reaction of GBBS, which increased the cement paste's

binding properties, resulting in a denser mass and decreased chloride penetration into the concrete. This ultimately reduces the degradation of concrete when a chloride attack occurs. Additionally, the micro filling of spaces in the concrete aggregate of GGBS results in denser concrete, reducing chloride penetration into the concrete.

Consequently, the residual CPS of concrete subjected to a chloride attack increases. According to the research findings, concrete mixed with groundnut shell ash has more resistance to a chloride attack than control mix concrete [106]. Although the chloride attack test is one of the most critical factors related to the corrosion of reinforcement, few researchers consider the chloride attack test in their research, and more studies are recommended in this regard.

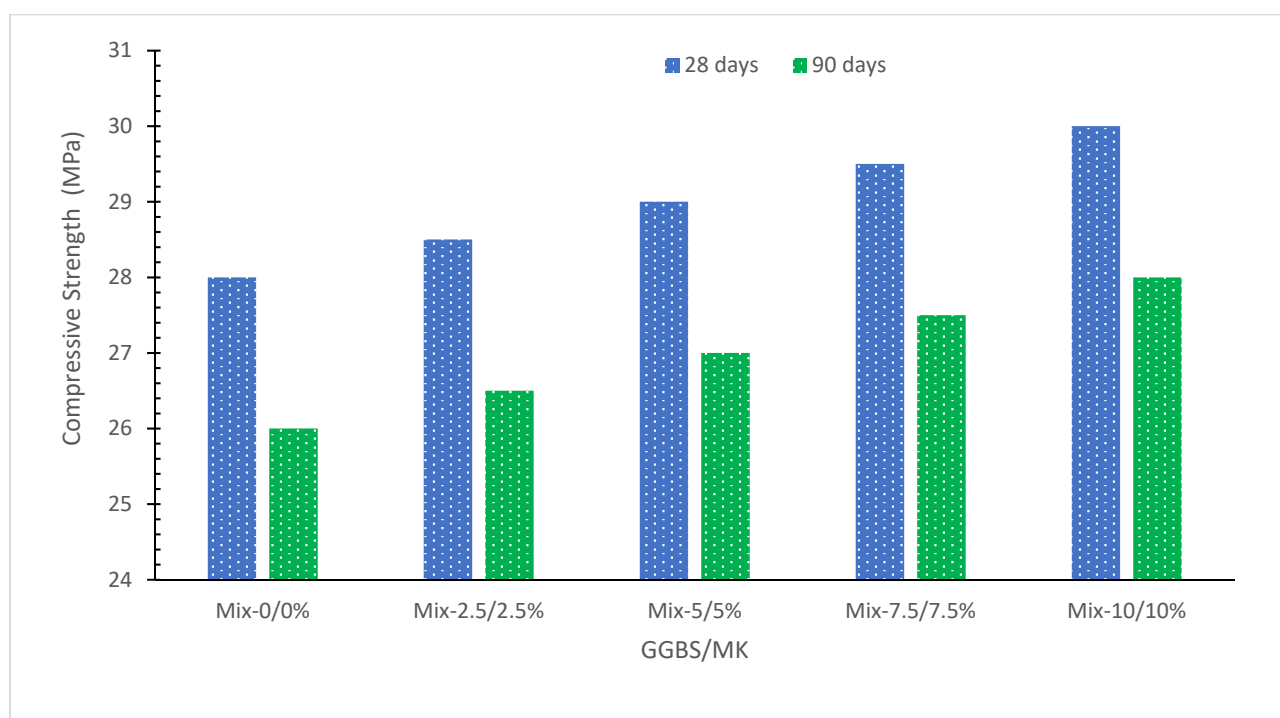


Figure 16. Chloride Attack Test Results [100].

10.5. Dry Shrinkage

Dry shrinkage is an essential feature of cementitious composites that significantly impacts their long-term durability. Dry shrinkage occurs due to the loss of capillary water from the concrete mixture resulting in contraction, and cracks development inside the concrete structure. The dry shrinkage of concrete with and without the GGBS and metakaolin (MK) replacement is shown in Figure 17.

The drying shrinkage of concrete decreased as the proportion of GGBS in the concrete increased. There is reduced cement content in cement pastes, which decreases the drying shrinkage of cement pastes [100]. In addition, the research found that the mineral additive lowered the heat of hydration, preventing the quick evaporation of water from the concrete surface, which caused the formation of dry shrinkage cracks [107]. The pozzolanic reaction produces CSH, which results in compact (denser) concrete, which may help reduce dry shrinkage. It has also been observed that fly ash may significantly minimize drying shrinkage in concrete by plugging micropores in the concrete and hence increasing the internal compactness of the concrete mix [19]. The dry shrinkage is mainly due to the change of volume mortar, while coarse aggregate prevents the change of cement paste. The combined pozzolanic reaction and micro filling of mineral admixture improved the cement paste's binding properties and density, ultimately decreasing the concrete's dry shrinkage [99].

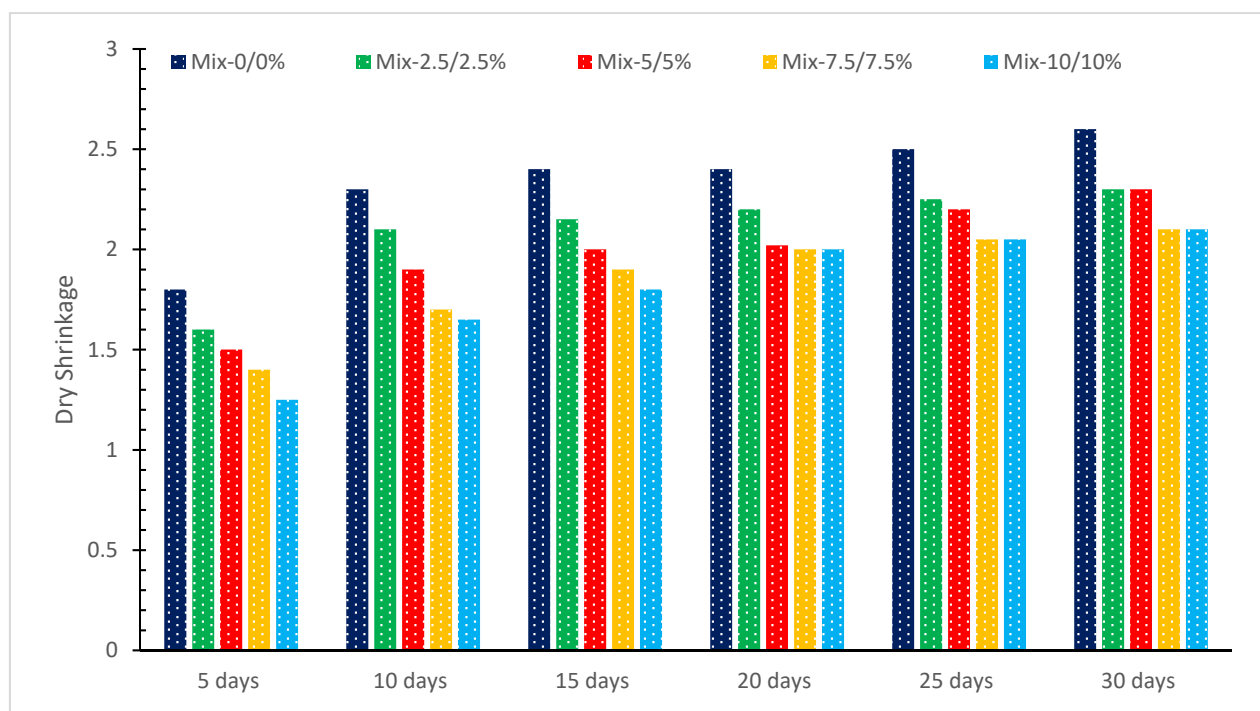


Figure 17. Dry Shrinkage of Concrete [100].

11. Conclusions

In this review, newly published articles on the use and efficiency of GGBS on the characteristics of concrete are examined. There was a thorough discussion of the manufacturing method, physical and chemical composition of GGBS and hydration reaction of GGBS, as well as the influence of GGBS use on the fresh-, mechanical-, permeability- and durability-associated qualities. This paper aimed to create awareness of the usage of GGBS in terms of possible environmental consequences and technical advantages for sustainable building. The following are some general benefits of using GGBS in concrete:

- Physical assets of GGBS, such as specific gravity and bulk density of concrete, are approximately equal to the cement. However, the surface area of GGBS is larger than cement. Furthermore, the SEM of GGBS shows the angular and rough surface texture of GGBS particles.
- The chemical composition of GGBS shows that it can be used as a cement replacement up to a certain extent.
- The heat of hydration decreased with the substitution of GGBS as the pozzolanic reaction proceeds slowly as compared to the hydration of cement.
- The workability of concrete is reduced by replacing OPC with GGBS due to the larger surface area and rough surface texture of GGBS particles. Therefore, plasticizer was recommended particularly for the higher dose of GGBS.
- Mechanical performance of concrete, such as compressive strength, split tensile strength and flexure, improved with GGBS due to the pozzolanic reaction and micro filling voids. However, a higher dose caused a decrease in the mechanical and durability of concrete due to lack of workability.
- Increased durability performance, such as dry shrinkage, permeability, chloride penetration and acid attack, was observed with GGBS. The combined micro filling and the pozzolanic reaction of GGBS results in more durable concrete.
- The optimum dose is important for better mechanical and durability aspects of concrete. Different researchers reported different values of optimum quantity of GGBS due to varying sources of GGBS. However, most researchers reported a 20% optimum dose of GGBS.

- Environmental assessments show the reduction of carbon dioxide emissions and the conservation of natural resources have a significant impact on environmental protection.

Author Contributions: Conceptualization, J.A. and K.J.K.; Data curation, J.A.; Formal analysis, A.F.D. and H.F.I.; Funding acquisition, K.J.K. and N.B.K.; Investigation, A.M. and H.F.I.; Methodology, J.A. and N.B.K.; Project administration, A.M.; Resources, M.T.N.; Software, A.F.D. and S.M.A.Q.; Supervision, M.T.N. and S.M.A.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is funded by the deanship of King Khalid University under grant number RGP.RGP.2/104/43.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data are available in manuscript.

Acknowledgments: The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Large Groups Project under grant number is on RGP.2/104/43.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ganesh, P.; Murthy, A.R. Tensile Behaviour and Durability Aspects of Sustainable Ultra-High Performance Concrete Incorporated with GGBS as Cementitious Material. *Constr. Build. Mater.* **2019**, *197*, 667–680. [CrossRef]
2. Monteiro, P.J.M.; Miller, S.A.; Horvath, A. Towards Sustainable Concrete. *Nat. Mater.* **2017**, *16*, 698–699. [CrossRef]
3. Oh, D.-Y.; Noguchi, T.; Kitagaki, R.; Park, W.-J. CO₂ Emission Reduction by Reuse of Building Material Waste in the Japanese Cement Industry. *Renew. Sustain. Energy Rev.* **2014**, *38*, 796–810. [CrossRef]
4. Mehta, P.K. Greening of the Concrete Industry for Sustainable Development. *Concr. Int.* **2002**, *24*, 23–28.
5. Kurad, R.; Silvestre, J.D.; de Brito, J.; Ahmed, H. Effect of Incorporation of High Volume of Recycled Concrete Aggregates and Fly Ash on the Strength and Global Warming Potential of Concrete. *J. Clean. Prod.* **2017**, *166*, 485–502. [CrossRef]
6. Mohseni, E.; Ranjbar, M.M.; Yazdi, M.A.; Hosseiny, S.S.; Roshandel, E. The Effects of Silicon Dioxide, Iron(III) Oxide and Copper Oxide Nanomaterials on the Properties of Self-Compacting Mortar Containing Fly Ash. *Mag. Concr. Res.* **2015**, *67*, 1112–1124. [CrossRef]
7. Smirnova, O. Compatibility of Shungisite Microfillers with Polycarboxylate Admixtures in Cement Compositions. *ARPN J. Eng. Appl. Sci.* **2019**, *14*, 600–610.
8. Vigneshpandian, G.V.; Shruthi, E.A.; Venkatasubramanian, C.; Muthu, D. Utilisation of Waste Marble Dust as Fine Aggregate in Concrete. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *80*, 012007. [CrossRef]
9. Yang, K.-H.; Jung, Y.-B.; Cho, M.-S.; Tae, S.-H. Effect of Supplementary Cementitious Materials on Reduction of CO₂ Emissions from Concrete. *J. Clean. Prod.* **2015**, *103*, 774–783. [CrossRef]
10. Oyak Cement. World Cement Association. Available online: <https://www.worldcementassociation.org/images/info-graphics/001-World-Wide-Cement-Production.pdf> (accessed on 16 June 2022).
11. Ahmad, J.; Zaid, O.; Shahzaib, M.; Abdullah, M.U.; Ullah, A.; Ullah, R. Mechanical Properties of Sustainable Concrete Modified by Adding Marble Slurry as Cement Substitution. *AIMS Mater. Sci.* **2021**, *8*, 343–358. [CrossRef]
12. Mirza, J.; Riaz, M.; Naseer, A.; Rehman, F.; Khan, A.N.; Ali, Q. Pakistani Bentonite in Mortars and Concrete as Low Cost Construction Material. *Appl. Clay Sci.* **2009**, *45*, 220–226. [CrossRef]
13. ASTM D6868; Standard Specification for Biodegradable Plastics Used as Coatings on Paper and Other Compostable Substrates. ASTM International: West Conshohocken, PA, USA, 2017.
14. Karimipour, A.; de Brito, J. Influence of Polypropylene Fibres and Silica Fume on the Mechanical and Fracture Properties of Ultra-High-Performance Geopolymer Concrete. *Constr. Build. Mater.* **2021**, *283*, 122753. [CrossRef]
15. Zhang, P.; Wang, K.; Wang, J.; Guo, J.; Ling, Y. Macroscopic and Microscopic Analyses on Mechanical Performance of Metakaolin/Fly Ash Based Geopolymer Mortar. *J. Clean. Prod.* **2021**, *294*, 126193. [CrossRef]
16. Nazarpour, H.; Jamali, M. Mechanical and Freezing Cycles Properties of Geopolymer Concrete with Recycled Aggregate. *Struct. Concr.* **2020**, *21*, 1004–1012. [CrossRef]
17. Liu, Y.; Shi, C.; Zhang, Z.; Li, N.; Shi, D. Mechanical and Fracture Properties of Ultra-High Performance Geopolymer Concrete: Effects of Steel Fiber and Silica Fume. *Cem. Concr. Compos.* **2020**, *112*, 103665. [CrossRef]
18. Bakharev, T. Thermal Behaviour of Geopolymers Prepared Using Class F Fly Ash and Elevated Temperature Curing. *Cem. Concr. Res.* **2006**, *36*, 1134–1147. [CrossRef]
19. Mwiti, M.J.; Karanja, T.J.; Muthengia, W.J. Thermal Resistivity of Chemically Activated Calcined Clays-Based Cements. In *RILEM Bookseries*; Springer: Dordrecht, The Netherlands, 2018; Volume 16, pp. 327–333, ISBN 9789402412062.

20. Imbabi, M.S.; Carrigan, C.; McKenna, S. Trends and Developments in Green Cement and Concrete Technology. *Int. J. Sustain. Built Environ.* **2012**, *1*, 194–216. [\[CrossRef\]](#)
21. Smirnova, O.M.; Potyomkin, D.A. Influence of Ground Granulated Blast Furnace Slag Properties on the Superplasticizers Effect. *Int. J. Civ. Eng. Technol.* **2018**, *9*, 874–880.
22. Smirnova, O.M.; Menéndez Pidal de Navascués, I.; Mikhailevskii, V.R.; Kolosov, O.I.; Skolota, N.S. Sound-Absorbing Composites with Rubber Crumb from Used Tires. *Appl. Sci.* **2021**, *11*, 7347. [\[CrossRef\]](#)
23. Rondi, L.; Bregoli, G.; Sorlini, S.; Cominoli, L.; Collivignarelli, C.; Plizzari, G. Concrete with EAF Steel Slag as Aggregate: A Comprehensive Technical and Environmental Characterisation. *Compos. Part B Eng.* **2016**, *90*, 195–202. [\[CrossRef\]](#)
24. De Domenico, D.; Faleschini, F.; Pellegrino, C.; Ricciardi, G. Structural Behavior of RC Beams Containing EAF Slag as Recycled Aggregate: Numerical versus Experimental Results. *Constr. Build. Mater.* **2018**, *171*, 321–337. [\[CrossRef\]](#)
25. Olivier, J.G.J.; Schure, K.M.; Peters, J. Trends in Global CO₂ and Total Greenhouse Gas Emissions. *PBL Neth. Environ. Assess. Agency* **2017**, *5*, 1–11.
26. Hogan, F.J. Ground Granulated Blast Furnace Slag As A Cementitious Material. In *Acimanual of Concrete Practice, Part 1*; American Concrete Institute: Farmington Hills, MI, USA, 1982; pp. 299–316.
27. Thomas, M.D.A.; Hooton, R.D.; Scott, A.; Zibara, H. The Effect of Supplementary Cementitious Materials on Chloride Binding in Hardened Cement Paste. *Cem. Concr. Res.* **2012**, *42*, 1–7. [\[CrossRef\]](#)
28. Şanal, İ. Fresh-state Performance Design of Green Concrete Mixes with Reduced Carbon Dioxide Emissions. *Greenh. Gases Sci. Technol.* **2018**, *8*, 1134–1145. [\[CrossRef\]](#)
29. Flower, D.J.M.; Sanjayan, J.G. Green House Gas Emissions Due to Concrete Manufacture. *Int. J. Life Cycle Assess.* **2007**, *12*, 282–288. [\[CrossRef\]](#)
30. Piatak, N.M.; Parsons, M.B.; Seal, R.R., II. Characteristics and Environmental Aspects of Slag: A Review. *Appl. Geochem.* **2015**, *57*, 236–266. [\[CrossRef\]](#)
31. Sharma, A.K.; Sivapullaiah, P. V Ground Granulated Blast Furnace Slag Amended Fly Ash as an Expansive Soil Stabilizer. *Soils Found.* **2016**, *56*, 205–212. [\[CrossRef\]](#)
32. Aydın, S.; Baradan, B. Effect of Activator Type and Content on Properties of Alkali-Activated Slag Mortars. *Compos. Part B Eng.* **2014**, *57*, 166–172. [\[CrossRef\]](#)
33. Flynn, R.T.; Grisinger, T.J.; Mather, B.; Hooton, R.D.; Dewey, G.R.; Luther, M.D.; Thomas, M.A.D. *Slag Cement in Concrete and Mortar*; American Concrete Institute: Farmington Hills, MI, USA, 2003.
34. Wang, X.-Y.; Lee, H.-S. Modeling the Hydration of Concrete Incorporating Fly Ash or Slag. *Cem. Concr. Res.* **2010**, *40*, 984–996. [\[CrossRef\]](#)
35. Dinakar, P.; Sethy, K.P.; Sahoo, U.C. Design of Self-Compacting Concrete with Ground Granulated Blast Furnace Slag. *Mater. Des.* **2013**, *43*, 161–169. [\[CrossRef\]](#)
36. Dhir, R.K.; Dyer, T.D.; Tang, M.C. Alkali-Silica Reaction in Concrete Containing Glass. *Mater. Struct.* **2009**, *42*, 1451–1462. [\[CrossRef\]](#)
37. Abbass, M.; Singh, D.; Singh, G. Properties of Hybrid Geopolymer Concrete Prepared Using Rice Husk Ash, Fly Ash and GGBS with Coconut Fiber. *Mater. Today Proc.* **2021**, *45*, 4964–4970. [\[CrossRef\]](#)
38. Du, H.; Tan, K.H. Use of Waste Glass as Sand in Mortar: Part II—Alkali-Silica Reaction and Mitigation Methods. *Cem. Concr. Compos.* **2013**, *35*, 118–126. [\[CrossRef\]](#)
39. Sumitha, Y.; Abraham, R. Experimental Study on Bentonite Clay Powder with Silica Fume and GGBS as Partial Replacement of Cement in M40 Grade Concrete. *Int. J. Eng. Res. Technol.* **2016**, *5*, 339–343. [\[CrossRef\]](#)
40. Naik, T.R. Sustainability of Concrete Construction. *Pract. Period. Struct. Des. Constr.* **2008**, *13*, 98–103. [\[CrossRef\]](#)
41. Sumajouw, D.M.J.; Hardjito, D.; Wallah, S.E.; Rangan, B.V. Fly Ash-Based Geopolymer Concrete: Study of Slender Reinforced Columns. *J. Mater. Sci.* **2007**, *42*, 3124–3130. [\[CrossRef\]](#)
42. Zhang, T.-S.; Yu, Q.-J.; Wei, J.-X.; Zhang, P.-P.; Li, S. Effect of Size Fraction of Ground Granulated Blast Furnace Slag on Its Strength Contribution and Hydraulic Activity. *Adv. Sci. Lett.* **2011**, *4*, 1286–1291. [\[CrossRef\]](#)
43. Sharmila, P.; Dhinakaran, G. Compressive Strength, Porosity and Sorptivity of Ultra Fine Slag Based High Strength Concrete. *Constr. Build. Mater.* **2016**, *120*, 48–53. [\[CrossRef\]](#)
44. Teng, S.; Lim, T.Y.D.; Divsholi, B.S. Durability and Mechanical Properties of High Strength Concrete Incorporating Ultra Fine Ground Granulated Blast-Furnace Slag. *Constr. Build. Mater.* **2013**, *40*, 875–881. [\[CrossRef\]](#)
45. Vignesh, P.; Vivek, K. An Experimental Investigation on Strength Parameters of Flyash Based Geopolymer Concrete with GGBS. *Int. Res. J. Eng. Technol.* **2015**, *2*, 135–142.
46. Majhi, R.K.; Nayak, A.N.; Mukharjee, B.B. Development of Sustainable Concrete Using Recycled Coarse Aggregate and Ground Granulated Blast Furnace Slag. *Constr. Build. Mater.* **2018**, *159*, 417–430. [\[CrossRef\]](#)
47. Patra, R.K.; Mukharjee, B.B. Influence of Incorporation of Granulated Blast Furnace Slag as Replacement of Fine Aggregate on Properties of Concrete. *J. Clean. Prod.* **2017**, *165*, 468–476. [\[CrossRef\]](#)
48. Siddique, R.; Bennacer, R. Use of Iron and Steel Industry By-Product (GGBS) in Cement Paste and Mortar. *Resour. Conserv. Recycl.* **2012**, *69*, 29–34. [\[CrossRef\]](#)

49. Ramakrishnan, K.; Pugazhmani, G.; Sripragadeesh, R.; Muthu, D.; Venkatasubramanian, C. Experimental Study on the Mechanical and Durability Properties of Concrete with Waste Glass Powder and Ground Granulated Blast Furnace Slag as Supplementary Cementitious Materials. *Constr. Build. Mater.* **2017**, *156*, 739–749. [\[CrossRef\]](#)
50. Rathod, S.; Hombal, G. A Comparative Study on Strength and Durability Aspects of Fly Ash-GGBS Based Geopolymer Concrete over Conventional Concrete. *Int. J. Eng. Res. Technol.* **2017**, *6*, 1062–1067.
51. MohanKumar, R.; Raju, R.S.; Ramesh, V. Strength and Durability Studies on Concrete with Partial Replacement of Cement by GGBS. *J. Impact Factor* **2017**, *2*, 23.
52. Bilir, T. Effects of Non-Ground Slag and Bottom Ash as Fine Aggregate on Concrete Permeability Properties. *Constr. Build. Mater.* **2012**, *26*, 730–734. [\[CrossRef\]](#)
53. Pal, S.C.; Mukherjee, A.; Pathak, S.R. Investigation of Hydraulic Activity of Ground Granulated Blast Furnace Slag in Concrete. *Cem. Concr. Res.* **2003**, *33*, 1481–1486. [\[CrossRef\]](#)
54. Topçu, İ.B.; Boğa, A.R. Effect of Ground Granulate Blast-Furnace Slag on Corrosion Performance of Steel Embedded in Concrete. *Mater. Des.* **2010**, *31*, 3358–3365. [\[CrossRef\]](#)
55. Yazıcı, H.; Yiğiter, H.; Karabulut, A.S.; Baradan, B. Utilization of Fly Ash and Ground Granulated Blast Furnace Slag as an Alternative Silica Source in Reactive Powder Concrete. *Fuel* **2008**, *87*, 2401–2407. [\[CrossRef\]](#)
56. Nkinamubanzi, P.C.; Baalbaki, M.; Bickley, J.; Aitcin, P.C. The Use of Slag for Making High Performance Concrete. In Proceedings of the 6th NCB International Seminar on Cement and Building Materials, New Delhi, India, 24–27 November 1998.
57. Lothenbach, B.; Scrivener, K.; Hooton, R.D. Supplementary Cementitious Materials. *Cem. Concr. Res.* **2011**, *41*, 1244–1256. [\[CrossRef\]](#)
58. Regourd, M. Characterization and Thermal Activation of Slag Cements. In *Proceedings of the 7th International Congress on the Chemistry of Cement*; Cement Research Institute: Paris, France, 1980; Volume 3, pp. 105–111.
59. Sajedi, F.; Razak, H.A. Effects of Thermal and Mechanical Activation Methods on Compressive Strength of Ordinary Portland Cement–Slag Mortar. *Mater. Des.* **2011**, *32*, 984–995. [\[CrossRef\]](#)
60. Zhang, M.-H.; Islam, J.; Peethamparan, S. Use of Nano-Silica to Increase Early Strength and Reduce Setting Time of Concretes with High Volumes of Slag. *Cem. Concr. Compos.* **2012**, *34*, 650–662. [\[CrossRef\]](#)
61. Mostafa, N.Y.; El-Hemaly, S.A.S.; Al-Wakeel, E.I.; El-Korashy, S.A.; Brown, P.W. Hydraulic Activity of Water-Cooled Slag and Air-Cooled Slag at Different Temperatures. *Cem. Concr. Res.* **2001**, *31*, 475–484. [\[CrossRef\]](#)
62. Sajedi, F.; Razak, H.A. The Effect of Chemical Activators on Early Strength of Ordinary Portland Cement-Slag Mortars. *Constr. Build. Mater.* **2010**, *24*, 1944–1951. [\[CrossRef\]](#)
63. Shabab, M.E.; Shahzada, K.; Gencturk, B.; Ashraf, M.; Fahad, M. Synergistic Effect of Fly Ash and Bentonite as Partial Replacement of Cement in Mass Concrete. *KSCE J. Civ. Eng.* **2016**, *20*, 1987–1995. [\[CrossRef\]](#)
64. Batog, M.; Giergiczny, Z. Influence of Mass Concrete Constituents on Its Properties. *Constr. Build. Mater.* **2017**, *146*, 221–230. [\[CrossRef\]](#)
65. Mengxiao, S.; Qiang, W.; Zhikai, Z. Comparison of the Properties between High-Volume Fly Ash Concrete and High-Volume Steel Slag Concrete under Temperature Matching Curing Condition. *Constr. Build. Mater.* **2015**, *98*, 649–655. [\[CrossRef\]](#)
66. Wang, Q.; Yan, P. Hydration Properties of Basic Oxygen Furnace Steel Slag. *Constr. Build. Mater.* **2010**, *24*, 1134–1140. [\[CrossRef\]](#)
67. Zhang, T.; Yu, Q.; Wei, J.; Li, J. Investigation on Mechanical Properties, Durability and Micro-Structural Development of Steel Slag Blended Cements. *J. Therm. Anal. Calorim.* **2012**, *110*, 633–639. [\[CrossRef\]](#)
68. Hu, J. Comparison between the Effects of Superfine Steel Slag and Superfine Phosphorus Slag on the Long-Term Performances and Durability of Concrete. *J. Therm. Anal. Calorim.* **2017**, *128*, 1251–1263. [\[CrossRef\]](#)
69. Zhao, J.; Wang, D.; Yan, P. Design and Experimental Study of a Ternary Blended Cement Containing High Volume Steel Slag and Blast-Furnace Slag Based on Fuller Distribution Model. *Constr. Build. Mater.* **2017**, *140*, 248–256. [\[CrossRef\]](#)
70. Wang, Q.; Yan, P.; Mi, G. Effect of Blended Steel Slag–GBFS Mineral Admixture on Hydration and Strength of Cement. *Constr. Build. Mater.* **2012**, *35*, 8–14. [\[CrossRef\]](#)
71. Ballim, Y.; Graham, P.C. The Effects of Supplementary Cementing Materials in Modifying the Heat of Hydration of Concrete. *Mater. Struct.* **2009**, *42*, 803–811. [\[CrossRef\]](#)
72. Wu, X.; Roy, D.M.; Langton, C.A. Early Stage Hydration of Slag-Cement. *Cem. Concr. Res.* **1983**, *13*, 277–286. [\[CrossRef\]](#)
73. Ahmad, J.; Martínez-García, R.; Szelag, M.; de-Prado-Gil, J.; Marzouki, R.; Alqurashi, M.; Hussein, E.E. Effects of Steel Fibers (SF) and Ground Granulated Blast Furnace Slag (GGBS) on Recycled Aggregate Concrete. *Materials* **2021**, *14*, 7497. [\[CrossRef\]](#)
74. Lenka, B.P.; Majhi, R.K.; Singh, S.; Nayak, A.N. Eco-Friendly and Cost-Effective Concrete Utilizing High-Volume Blast Furnace Slag and Demolition Waste with Lime. *Eur. J. Environ. Civ. Eng.* **2021**, 1–23. [\[CrossRef\]](#)
75. Meusel, J.W.; Rose, J.H. Production of Granulated Blast Furnace Slag at Sparrows Point, and the Workability and Strength Potential of Concrete Incorporating the Slag. *Spec. Publ.* **1983**, *79*, 867–890.
76. Wan, H.; Shui, Z.; Lin, Z. Analysis of Geometric Characteristics of GGBS Particles and Their Influences on Cement Properties. *Cem. Concr. Res.* **2004**, *34*, 133–137. [\[CrossRef\]](#)
77. Prakash, S.; Kumar, S.; Biswas, R.; Rai, B. Influence of Silica Fume and Ground Granulated Blast Furnace Slag on the Engineering Properties of Ultra-High-Performance Concrete. *Innov. Infrastruct. Solut.* **2022**, *7*, 117. [\[CrossRef\]](#)
78. Özbay, E.; Erdemir, M.; Durmuş, H.İ. Utilization and Efficiency of Ground Granulated Blast Furnace Slag on Concrete Properties—A Review. *Constr. Build. Mater.* **2016**, *105*, 423–434. [\[CrossRef\]](#)

79. Majhi, R.K.; Nayak, A.N.; Mukharjee, B.B. Characterization of Lime Activated Recycled Aggregate Concrete with High-Volume Ground Granulated Blast Furnace Slag. *Constr. Build. Mater.* **2020**, *259*, 119882. [\[CrossRef\]](#)
80. Suda, V.B.R.; Rao, P.S. Experimental Investigation on Optimum Usage of Micro Silica and GGBS for the Strength Characteristics of Concrete. *Mater. Today Proc.* **2020**, *27*, 805–811. [\[CrossRef\]](#)
81. VEDIYAPPAN, S.; CHINNARAJ, P.K.; HANUMANTRAYA, B.B.; SUBRAMANIAN, S.K. An Experimental Investigation on Geopolymer Concrete Utilising Micronized Biomass Silica and GGBS. *KSCE J. Civ. Eng.* **2021**, *25*, 2134–2142. [\[CrossRef\]](#)
82. Soni, Y.; Gupta, N. Experimental Investigation on Workability of Concrete with Partial Replacement of Cement by Ground Granulated Blast Furnace and Sand by Quarry Dust. Available online: https://www.academia.edu/29390523/Experimental_Investigation_on_Workability_of_Concrete_with_Partial_Replacement_of_Cement_by_Ground_Granulated_Blast_Furnace_and_Sand_by_Quarry_Dust (accessed on 16 June 2022).
83. Nath, P.; Sarker, P.K. Effect of GGBFS on Setting, Workability and Early Strength Properties of Fly Ash Geopolymer Concrete Cured in Ambient Condition. *Constr. Build. Mater.* **2014**, *66*, 163–171. [\[CrossRef\]](#)
84. Roy, D.M. Hydration, Structure, and Properties of Blast Furnace Slag Cements, Mortars, and Concrete. *J. Proc.* **1982**, *79*, 444–457.
85. Valcuende, M.; Benito, F.; Parra, C.; Miñano, I. Shrinkage of Self-Compacting Concrete Made with Blast Furnace Slag as Fine Aggregate. *Constr. Build. Mater.* **2015**, *76*, 1–9. [\[CrossRef\]](#)
86. Aghaeipour, A.; Madhkan, M. Effect of Ground Granulated Blast Furnace Slag (GGBFS) on RCCP Durability. *Constr. Build. Mater.* **2017**, *141*, 533–541. [\[CrossRef\]](#)
87. Raafidiani, R.; Sumargo, S.; Permana, R. The Influence of Ground Granulated Blast Furnace Slag (GGBFS) as Portland Composite Cement (PCC) Substitution in Improving Compressive Strength of Concrete. In Proceedings of the 5th Annual Applied Science and Engineering Conference (AASEC 2020), Bandung, Indonesia, 20–21 April 2020; Volume 1098, p. 22035.
88. Ramani, P.V.; Chinnaraj, P.K. Geopolymer Concrete with Ground Granulated Blast Furnace Slag and Black Rice Husk Ash. *Gradevinar* **2015**, *67*, 741–748.
89. Makhdoom, O.; Makhdoom, I. Effect of Components Fineness of Ground Granulated Blast Furnace Slag (GGBFS) on Its Strength Efficiency in Roller Compact Concrete Mixes. *Asian J. Nat. Appl. Sci.* **2013**, *2*, 82–89.
90. Nazari, A.; Riahi, S. Effects of Al₂O₃ Nanoparticles on Properties of Self Compacting Concrete with Ground Granulated Blast Furnace Slag (GGBFS) as Binder. *Sci. China Technol. Sci.* **2011**, *9*, 2327–2338. [\[CrossRef\]](#)
91. Ahmad, J.; Martínez-García, R.; De-Prado-Gil, J.; Irshad, K.; El-Shorbagy, M.A.; Fediuk, R.; Vatin, N.I. Concrete with Partial Substitution of Waste Glass and Recycled Concrete Aggregate. *Materials* **2022**, *15*, 430. [\[CrossRef\]](#) [\[PubMed\]](#)
92. Ahmad, J.; Aslam, F.; Martínez-García, R.; De-Prado-Gil, J.; Qaidi, S.M.A.; Brahmia, A. Effects of Waste Glass and Waste Marble on Mechanical and Durability Performance of Concrete. *Sci. Rep.* **2021**, *11*, 21525. [\[CrossRef\]](#)
93. Ahmad, J.; Tufail, R.F.; Aslam, F.; Mosavi, A.; Alyousef, R.; Faisal Javed, M.; Zaid, O.; Khan Niazi, M.S. A Step towards Sustainable Self-Compacting Concrete by Using Partial Substitution of Wheat Straw Ash and Bentonite Clay Instead of Cement. *Sustainability* **2021**, *13*, 824. [\[CrossRef\]](#)
94. Yuksel, I.; Genç, A. Properties of Concrete Containing Nonground Ash and Slag as Fine Aggregate. *ACI Mater. J.* **2007**, *104*, 397.
95. Basar, H.M.; Aksoy, N.D. The Effect of Waste Foundry Sand (WFS) as Partial Replacement of Sand on the Mechanical, Leaching and Micro-Structural Characteristics of Ready-Mixed Concrete. *Constr. Build. Mater.* **2012**, *35*, 508–515. [\[CrossRef\]](#)
96. ACI 318-11; Building Code Requirements for Structural Concrete. American Concrete Institute (ACI): Farmington Hills, MI, USA, 2011.
97. EN 1992-1-1:2004; 1-1. Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings. European Committee for Standardisation: Brussels, Belgium, 2004.
98. Sato, R.; Sogo, S.; Kanazu, T.; Kishi, T.; Noguchi, T.; Mizobuchi, T.; Miyazawa, S. JCI Guidelines for Control of Cracking of Mass Concrete 2008. In Proceedings of the Third International Conference on Sustainable Construction Materials and Technologies, Kyoto, Japan, 19–21 August 2013.
99. Ahmad, J.; Aslam, F.; Martínez-García, R.; El Ouni, M.H.; Khedher, K.M. Performance of Sustainable Self-Compacting Fiber Reinforced Concrete with Substitution of Marble Waste (MW) and Coconut Fibers (CFs). *Sci. Rep.* **2021**, *11*, 23184. [\[CrossRef\]](#)
100. Bheel, N.; Abbasi, S.A.; Awoyera, P.; Olalusi, O.B.; Sohu, S.; Rondon, C.; Echeverría, A.M. Fresh and Hardened Properties of Concrete Incorporating Binary Blend of Metakaolin and Ground Granulated Blast Furnace Slag as Supplementary Cementitious Material. *Adv. Civ. Eng.* **2020**, *2020*, 8851030. [\[CrossRef\]](#)
101. Bassuoni, M.T.; Nehdi, M.L.; Greenough, T.R. *Enhancing the Reliability of Evaluating Chloride Ingress in Concrete Using the ASTM C 1202 Rapid Chloride Penetrability Test*; ASTM International: West Conshohocken, PA, USA, 2006.
102. Thomas, M.D.A.; Bamforth, P.B. Modelling Chloride Diffusion in Concrete: Effect of Fly Ash and Slag. *Cem. Concr. Res.* **1999**, *29*, 487–495. [\[CrossRef\]](#)
103. Xu, Y. The Influence of Sulphates on Chloride Binding and Pore Solution Chemistry. *Cem. Concr. Res.* **1997**, *27*, 1841–1850. [\[CrossRef\]](#)
104. Ramezaniapour, A.A.; Pilvar, A.; Mahdikhani, M.; Moodi, F. Practical Evaluation of Relationship between Concrete Resistivity, Water Penetration, Rapid Chloride Penetration and Compressive Strength. *Constr. Build. Mater.* **2011**, *25*, 2472–2479. [\[CrossRef\]](#)
105. Shi, X.; Xie, N.; Fortune, K.; Gong, J. Durability of Steel Reinforced Concrete in Chloride Environments: An Overview. *Constr. Build. Mater.* **2012**, *30*, 125–138. [\[CrossRef\]](#)

-
106. Dharani, D.; iravida Selvan, V.A. Durability Studies on Concrete by Using Groundnut Shell Ash as Mineral Admixture. *Int. J. Innov. Res. Sci. Technol.* **2017**, *3*, 168–172.
 107. Ahmad, J.; Zaid, O.; Siddique, M.S.; Aslam, F.; Alabduljabbar, H.; Khedher, K.M. Mechanical and Durability Characteristics of Sustainable Coconut Fibers Reinforced Concrete with Incorporation of Marble Powder. *Mater. Res. Express* **2021**, *8*, 075505. [[CrossRef](#)]