Review Article

A Review of the Hardened Properties of Eco-Friendly Concrete Containing Ground Granulated Blast-furnace Slag

ABSTRACT

Cement manufacture depletes natural resources, requires significant energy usage, and emits large quantities of greenhouse gases. Roughly one tonne of carbon dioxide is released by ordinary Portland cement, which is roughly 7% of global carbon dioxide generation. In concrete production GGBS can be a partial alternative of cement. GGBS is produced by finely grinding of molten slag generated by the process of extraction of iron from ore. In this study the concrete properties incorporating GGBS is reviewed. The hardened properties of concrete incorporating GGBS are discussed. The cement replacement of about 35-40% by GGBS in concrete demonstrates various advantages like less heat of hydration, increase in ductility, increase in strength, reduction in carbon emission and better aesthetics.GGBS improves the durability properties of concrete, such as higher resistance to sulphate attack, increased resistance to alkali-silica reaction, reduced chloride ion penetration which enhances corrosion resistance. Denser microstructure and lower porosity due to the addition of GGBS, which in turn enhances the durability of concrete.With the use of GGBS in concrete, cementcontent can be reduced, which turns into an eco-friendly solution.

Keywords: *Ground granulated blastfurnace slag; Mechanical property; Durability property; Green concrete.*

1.INTRODUCTION

After China, India isthe largest cement manufacturer. By the year 2025, the cement demand of India is estimatedat 550000000 to 600000000 tonnes per year [1]. The manufacturing process of cement contributes to a huge proportion of greenhouse gases that are released into the atmosphere. The incorporation of alternative pozzolanic materials like fly-ash, GGBS, micro-silica, etc. in concrete can be used as analternativefor cement [2].

The molten slag formed duringthe extraction of metal is quickly quenched and grounded which leads to the formation of GGBS [3]. In the future, more GGBS will be used as a partial replacement for cement [4]. In Britain, GGBS use is noted about 10% of all the cementitious materials used in the year 2000 [5]. The trend of using GGBS cement was first started in the year 1960 in the Soviet Union and Poland [6]. Various European countries like Finland and France adopted GGBS cement in the manufacturing of precast construction products [7]. Various researches demonstrated the increase in strength of the structures made with cement incorporated with GGBS [8].

The reduction in cement consumption will result in a decrease in carbon dioxide emission [9-12]. The concrete properties are improved bythe substitution of mineral admixtures in concrete. This is mainly due to their pozzolanic activity and particle size distribution [13,14]. Both cement and slag contain lime, alumina and silica but in different proportions [15,16]. By finely grinding molten slag the GGBS is obtained [17]. It was found from various researches that the slagreacts with$Ca(OH)_2$ and results in the generation of C-S-H [18-20].

When GGBS is incorporated in concrete it reduces the porosity of the concrete and hence improves its durability by reducing the intrusion of sulphates[21]. The decrease in depth of chloride penetration due to GGBS is noted by various researchers [22-26]. Research carried out by Deja and Malotepsy [27] showed that there is a subsequent decrease in penetration depth of chlorides and sulphates in concrete. Pu et al. [28] and Wu et al. [29] find out the strength of concrete with GGBS by placing the samples in $MgSO_4$ solution, HCl and H_2SO_4 for 1 year. They found that after a year, the concrete samples made with GGBS hadimproved strength, while the samples made with OPC degraded in just six months. Byfores et al. [30] carried out a carbonation test on concrete samples incorporating GGBS. They observedthe carbonation resistance of GGBS and OPC concrete samples ata constant water binder ratio and found out that the carbonation resistanceof GGBS is greater.

Chloride ion penetration test on concrete samples with GGBS was conducted by Douglas et al. [31]. They reported that the GGBS concrete has high chloride ion resistance than conventional concrete. But some researchers [19, 20, 32] reported that the GGBS incorporated concrete has higher carbonation depth in lean concrete. Carbonation of hydration materials like C-S-H gel may be the possible cause for increased carbonation depth [34-38].

ASTM C 989 categorized the GGBS into three categories based on their compressive strength namely 80 Grade, 100 Grade and 120 Grade [39-41]. Hwang and Lin [42] researched the mortar’s compressive strength incorporating GGBS. They reported that the samples containing GGBS have more compressive strength than the control specimens. Papakadis [43] reported that GGBS concrete has better compressive strength than standard concrete. The higher compressive strength of GGBS concrete islikely because of its smaller particle size [44-47].

Many researchers studied the corrosion mechanism and preventions to control corrosion [48-50]. Various studies imply that reinforced concrete is corroded mainly because of cracks [51-55]. They found out that the more the crack width faster will be the rate of corrosion [56]. With the incorporation of GGBS in concrete,the microstructure of concrete densifies by filling capillary pores with C-S-H gel [57-59]. With GGBS in concrete,there is a substantial reduction in pore size and volume, according to numerous reports. [60-66].

Luo et al. [68] performeda chloride penetration test on GGBS concrete. They demonstrated that GGBS decreases the chloride diffusivity in concrete. The addition of GGBS to concrete causes a slower rate of concrete strength development [68]. Oner and Akyuz [69] researched to determine the optimal GGBS substitution percentage in concrete. According to their findings, “the sample containing 60% GGBS of total cement content had the highest compressive strength”. The bleed capacity was also reduced by 32% for the mix incorporating GGBS as compared to the mixes containing a hundred percent OPC [70-73].

Rao and Condren [74] reported that the GGBS concrete under the exposure of silage effluent was found out more durable than the OPC concrete. Dash [75] also reported the improved durability of concrete with the incorporation of GGBS under the action of acids and salts. Both mechanical property and durability characteristics of high-performance concrete were enhanced with the inclusion of GGBS in concrete, according to Higgins [76] and Pazhani et al. [77].Shariq et al. [78] used GGBS as supplementary cementitious material and studied the concrete strength. They reported that 40% is the optimum replacement of cement with GGBS. Stanley et al. [79] concluded that the GGBS can be utilized as a partial replacement for both types of cement as well as fine aggregates in concrete. Binici et al. [80] utilized GGBS and corncob ash in concrete to assess the compressive strength after immersion in sulphate solution for two years. They reported a 15% lower compressive strength of GGBS and corncob ash than the reference concrete.Puerta et al. [81] carried out a carbonation test on NaOH-activated slag concrete. They reported that the mortars containing slag have more carbonation depth than the reference mortar. According to Barnett et al. [82],the early strength gain of GGBS mortarsis considerably affected by the temperature. Ling et al. [83] demonstrated various applications of GGBS concrete in precast manufacturing in China. Cheng et al. [84] found out the corrosion resistance of RCC beams incorporating GGBS. Olorunsogo et al. [85] examine the effect of GGBS particle size on the mix's fresh and hardened properties. They observed that the bleeding potential of GGBS samples with uniformly graded distribution is enhanced.

Wan et al. [86] performed experiments with mortar with50% replacement of GGBS. The study showed that there was no considerable effect on strength by the inclusion of a grinding assistant agent.

2. CHEMICAL COMPOSITION OF GGBS

The raw materials used during iron production plays a critical role inthe chemical structure of GGBS. Lower viscosity of slag is mainly due to the presence of aluminate and silicate present in iron ore. Limestone and forsterite are flux's primary constituents used for the extraction of pig iron from ore. Table 1 relate the chemical properties of GGBS used by different authors.

Table 1 Chemical composition of GGBS

Authors	SiO_2	CaO	Fe_2O_3	Al_2O_3	MgO	K_2O	Na_2O	SO_3
Mary et al. [88]	33.45	41.74	0.31	13.46	5.99	0.29	0.16	2.74
Rao et al. [74]	34.4	33.1	2.65	15.6	8.9	0.6	0.62	2.46
Otaibi et al. [87]	35.84	39.53	0.55	13	8.28	0.5	0.35	0.1
Vignesh et al. [95]	35	40	2.42	10	8	0.34	0.51	2.4
Huang et al. [96]	34.4	44.8	2.58	9	4.43	0.5	0.62	2.26

3. PHYSICAL PROPERTIES OF GGBS

The glass content of slag ranges from 90% to 100% depends on the process used to cool the slag as well as the temperature at which the slag is cooled. Silica and alumina act as network-forming agents while calcium and magnesium act as network modifiers. The glass structure is mainly affected by these network formers and network modifiers. More amount of them results in higher reactivity and polymerization. GGBS is cementations and hydrates like OPC. Table 2 lists the physical characteristics of GGBS.

Table 2 Physical characteristics of GGBS

Authors	Colour	Specific Gravity	Fineness (m^2/Kg)
Mary et al. [88]	Off-white	2.9	350
Otaibi et al. [87]	White	2.91	458
Huang et al. [96]	White	2.90	542
Oner et al. [91]	White	2.87	500
Rao etal. [74]	Off-white	2.82	422.2

4. HARDENED PROPERTIES

Hardened concrete's properties are explained based on strength and performance under various types of loads and conditions. The main properties which come under hardened properties are as below:

4.1 Compressive strength

It is the resistance of concrete to cracking or deflection in compression. Thestrength of concrete in compressionincorporating GGBS & fly-ash was investigated by Vignesh et al. [95]. They concluded that the mix containing 40% and 60% GGBS and fly ash respectively had the ultimate strength in compressive. Findings suggest that 10–40% GGBS can replace OPC by weight in concrete (Fig. 1).

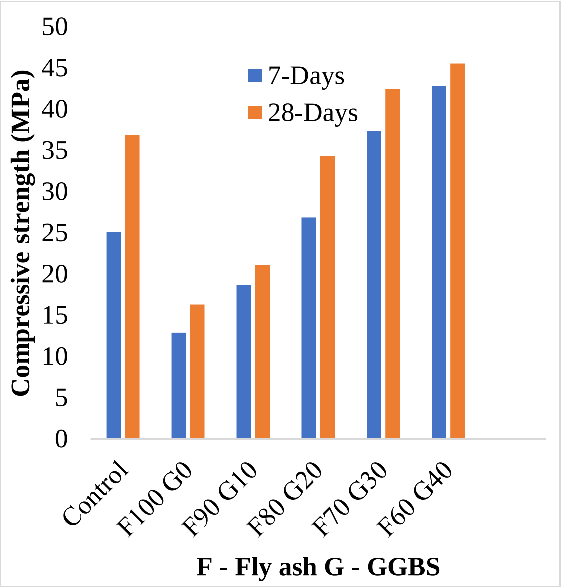

Fig. 1 Compressive strength results [95]

The properties of concrete incorporating GGBSwereexamined by Mary et al. [87]. The compressive strength was 49, 52, 50.8, 49, 47, and 45 MPa for concrete at 28 days with 0, 10, 20, 30, 40, and 50 percentage GGBS as a substitute of cementrespectively. They noticed that a combination comprising 10% GGBS and 50% M-Sand had the highest compressive strength.

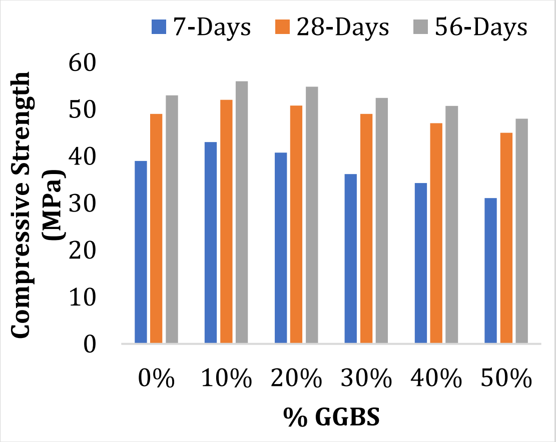

Fig. 2 Compressive strength results [87]

Huang et al. [96] conducted research to assess the compressive strength of concrete incorporating GGBS.The strength of concrete after 91 days aimed at specimens of 0%, 40% and 60% replacement was 42.4 MPa, 45.2 MPa and 48.6MPa respectively. The compressive strength of concrete is affected by the GGBS substitution level of concrete and the maturity of the concrete. Concrete containing GGBS has higher compressive strength than control concrete, as stated by several researchers [97,98]. They reported that GGBS can replace cement in concrete up to 50-75% by weight.

Nagaraju et al. [99] did an experimental study to determine the characteristics of concrete incorporating GGBS. They concluded that the concrete'scompressive strength containing 50% GGBS is almost comparable to the control mix. Further increase in replacement percentage of GGBS resulted in compressive strength reduction. Strength gain in GGBS concrete is slower than the strength gain in concrete with OPC.

Characteristics of compressive strength of concrete containing GGBS and ROBO sand were studied by Malagavelli et al. [100]. Thecompressive strength was found to be maximum in the concrete sample containing 25% and 50% of ROBO sand andGGBS was used respectively.

The properties of geopolymer concrete incorporating various substitution percentages of GGBS were studied by Kumar et al. [101].

The test results revealed that geopolymer concrete samples containing 80% GGBS had the maximum compressive strength, which was 35.3% greater than the control mix. As the GGBS replacement rate was increased, there was a subsequent increase in compressive strength of geopolymer concrete. (Fig.3)

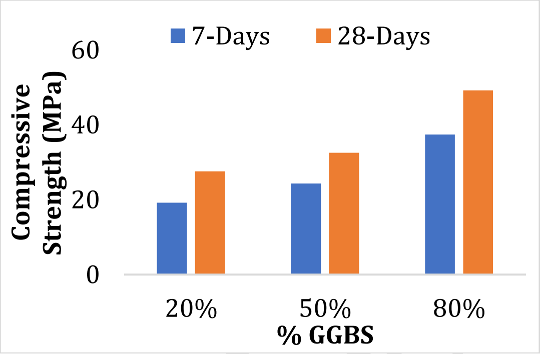

Fig. 3 Compressive strength results [101]

In the study conducted by Venkat et al. [103] compressive strength of concrete admixed with GGBS, micro-silica, and metakaolin was analyzed. The concrete sample containing 10% GGBS had the maximum compressive strength.Fig.4representthe results of their study.

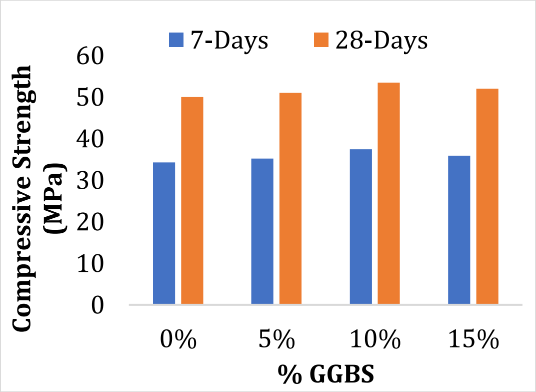

Fig. 4 Compressive strength results [103]

Oner et al. [104] partially substitute GGBS with cement. They revealed that the samples containing GGBS has lower early strength as compared to control mix. But after a prolonged period of time GGBS specimen show better compressive strength then control mix.

Karri et al. [106] performed a test to use GGBS as partial replacement of cement. They observed that at 40% replacement of cement with GGBS, Compressive strength of concrete was maximum.

Table 3 Compressive strength test results [106]

S.No.	% GGBS	Compressive strength (M20)		Compressive strength (M40)	
		28-Days	90-Days	28-Days	90-Days
1	0	33.3	46.2	49.99	54.22
2	30	35	50.11	51.12	55.02
3	40	36.42	52.49	53.6	57.46
4	50	32.2	48.12	50.12	54.27

4.2 Split tensile strength

The ability of concrete to withstand tensile stresses caused by the application of a load at which the specimen fails is known as tensile strength.

Arivalaganet al. [89] studied the tensile strength of GGBS concrete of grade M35. They replaced the cement with GGBS with cement in the proportion of 20%, 30%, and 40%. The maximum split tensile strength was observed at 20% of cement replacement withGGBS. Results of their findings are represented in Fig.5.

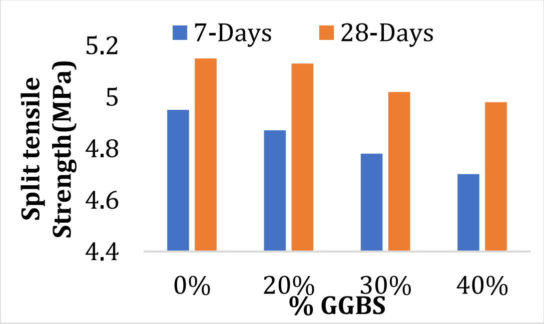

Fig. 5 Split tensile test results [89]

Vignesh et al. [95] used a combination of both GGBS as well as fly-ash by partially replacing cement. The combination containing 30% GGBS and 70% fly-ash had the highest split tensile strength, according to the findings (fig. 6).

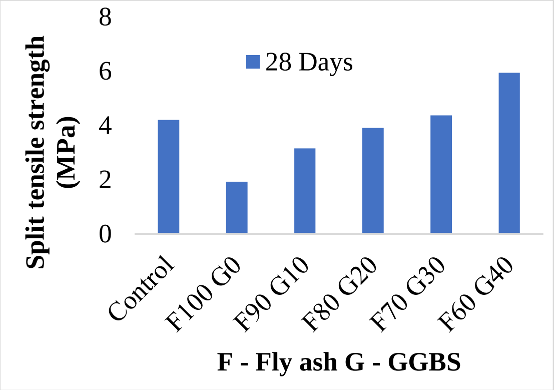

Fig. 6 Splittensile test results [95]

Mary et al. [88] examined the test resultswith different percentages (10%,20%,30%, 40% and 50%) of GGBS and 50% MSand.Concrete incorporating 10 percent GGBS and 50 percent M-Sand showed the highest split tensile strength which is 0.85 percent more than that of the control mix.

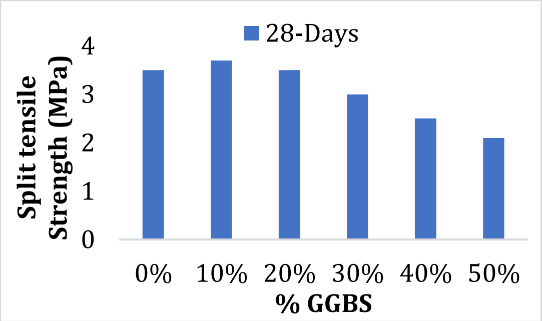

Fig. 7 Split tensile test results [88]

Kumar et al. [101] studied the behavior of geopolymer concrete incorporating GGBS.They discovered that with an increase in the percentage of GGBS substituted with cementthe split tensile strength also increased. The concrete containing 80 percent GGBS has the highest split tensile strength, which may be related to the formation of a compact interfacial transition region.

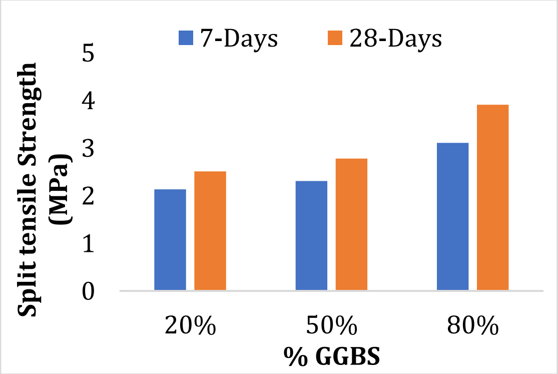

Fig. 8 Split tensiletest results [101]

Venkat et al. [103] studied the split tensile strength of concrete containsa mixture of

GGBS and micro silica. Fig.9 describes the effect of the results of their findings. Concrete specimens with ten percent GGBS had the maximum split tensile strength.

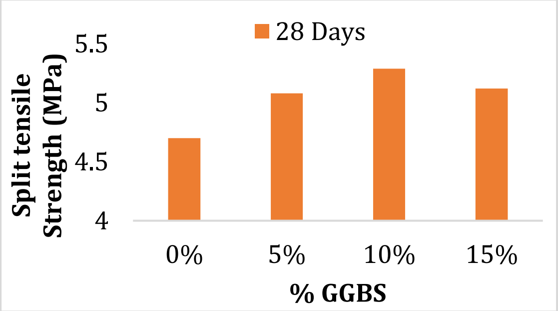

Fig. 9 Split tensile test results [103]

Karri et al. [106] also determined the split tensile strength of concrete containing GGBS as a partialreplacement of cement. Both M20 grade and M40 gradeconcreteSand samples with 40 percent GGBS had the highest split tensile strength.

Table 4 Result of Split tensile strength106]

S.No.	% GGBS	Split tensilestrength (M20)		Split tensile strength (M40)	
		28-Days	90-Days	28-Days	90-Days
1	0	2.69	3.5	3.11	3.67
2	30	2.85	3.6	3.33	3.85
3	40	3.05	3.85	3.74	4.15
4	50	2.75	3.57	3.18	3.71

4.3 Flexural strength test

To find out the tensile strength of the concrete, a flexural strength test is performed. It assesses an unreinforced concrete beam's capacity to sustain loading failure.

Arivalagan et al. [89] experimented to assessGGBS-incorporated concrete’s flexural strength. The mix containing 20% GGBS showed the highest flexural strength.Fig. 10 depicts the study findings.GGBS densifies the concrete’s microstructure which is responsible for the rise in flexural strength.

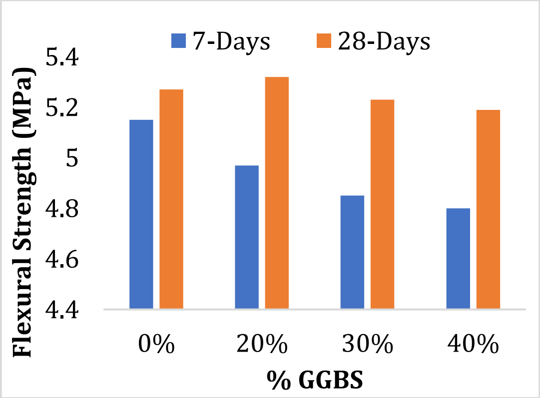

Fig. 10 Flexural strength results [89]

Vignesh et al. [95] examined the concrete’s properties by admixing cementitious material such as GGBS and fly-ash.They discovered that with an increase in GGBS content and a subsequent decrease in fly-ash content the flexural strength increases.

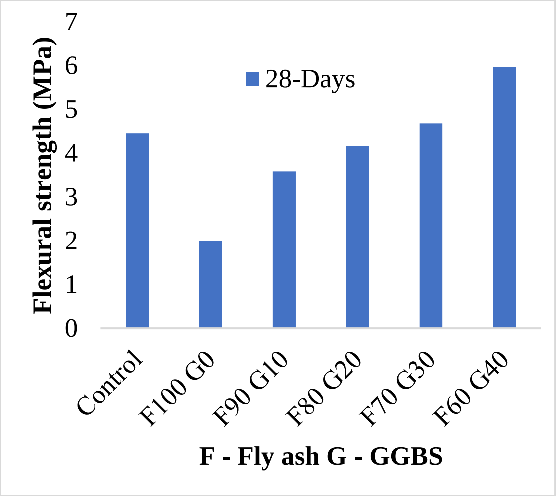

Fig. 11 Flexural strength results [95]

The investigation to find out the flexural strengthof high-performance concrete with 10%,20%,30%,40%, and 50% of GGBS and 50% MSand was done by Mary et al.[88]. Test results are represented in Fig. 12. Concrete samples incorporating 30 percent GGBS and 50 percent M-Sand showed maximum flexural strength. The sample of 30% GGBSdemonstrated a 75.36 percent improvement in flexural strengthconcerningthe control mix.

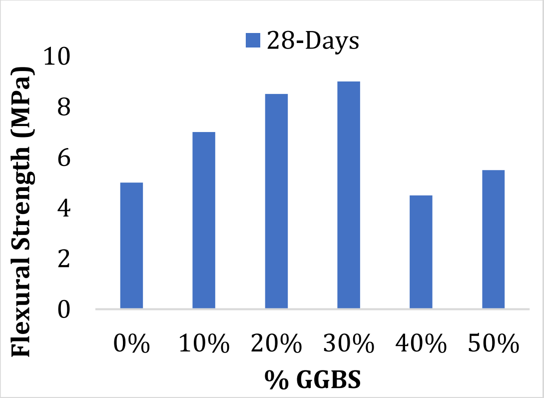

Fig. 12 Flexural strength results [88]

Kumar et al. [101]incorporated GGBS and micro-silica in concrete, they observed that the blend containing 20% GGBS and 20% metakaolin, imparts the highest flexural strength. Up to a point, increasing the substitution percentage of GGBS contributes to an improvement in flexural strength.

Karri et al. [106] replaced cement with GGBS 0%, 30%, 40% and 50% in concrete. He found that the flexure strength of concrete is maximum when 40% of GGBS was replaced by cement.

Table 5 Flexural strength test results [106]

S.No.	% GGBS	Flexural strength (M20)		Flexural strength (M40)	
		28 Days	90 Days	28 Days	90 Days
1	0	5.21	6.51	6.1	7.02
2	30	5.60	7.05	6.42	7.42
3	40	5.82	7.77	7.02	7.9
4	50	5.3	6.8	6.25	7.1

4.4 Durability properties

Otaibi et al. [87]carried out a durability test of concrete with GGBS as a substitute for cement.An increase in porosity is observed in the concrete samples containing 60 percent GGBS. The carbonation depth of concrete with GGBS is also more than the control specimen. The alkali-silica reaction expansions are found lower in GGBS concrete than the control specimen.

The durability properties of concrete admixed with GGBS were investigated by Mary et al. [88].The rapid chloride penetration test result shows that the chloride diffusion is lowest in concrete with 10% GGBS and 50% M-Sand. With an increase in GGBS content in concrete, chloride penetration decreased.

Huang et al. [96]examined the durability of concrete incorporated with GGBS. They observed that adding GGBS in concrete enhances porosity and decreases pore depth. The production of C-S-H gel as a result of the pozzolanic action between water and GGBS results in low permeability in GGBS concrete. The lower porosity of concrete represents high strength and prolong durability. The decrease in pore volume also prevents the reinforcements from corrosion. The concrete beam made up of GGBS concrete showed higher corrosion resistance.

Saranya et al. [107] studied the durability of GGBS concrete They reported that the concrete incorporated GGBS has enhanced durability. The addition of GGBS in concrete results in less heat of hydration, improved ductility, reduced pore volume. The concrete containing 30 percent to 40 percent GGBS showed enhanced durability. Chloride tolerance, sulphate resistance, and susceptibility to alkali-silica reactions all improve when GGBS is added.

5. CONCLUSIONS

By analyzing the researcher's works on utilizing GGBS as a partial substitute of cement in concrete production,the following conclusions can be drawn:

- There is an increase in compressive strength of concrete with an increase in the percentage of GGBS up to 65%; after that, the strength decreases. This increase in compressive strength is due to the transformation of calcium hydroxide $Ca(OH)_2$ present in GGBS into secondary calcium silicate hydrate gel.

- The split tensile strength of concrete increases when cement is replaced with GGBS. The split tensile strength is maximum at 40% of replacement. The increase in split tensile strength is due to the formation of a denser interfacial zone developed between the aggregate and binder phases due to the addition of GGBS.

- The flexural strength of concrete is also increased when the cement is replaced by GGBS. At 40% replacement, the flexural strength is maximum.
- GGBS improves the durability properties of concrete, such as higher resistance to sulphate attack, increased resistance to alkali-silica reaction, reduced chloride ion penetration which enhances corrosion resistance. Denser microstructure and lower porosity due to the addition of GGBS,which in turn enhances the durability of concrete.

From the above study, it can be suggested that GGBS can be utilized effectively in sustainable concrete to decrease the accumulation of GGBS. With the use of GGBS in concrete cement, content can be reduced, which turns into an Eco-friendly solution.

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