Properties of High Content Ground Granulated Blast Furnace Slag Concrete

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Abstract. "Ground Granulated Blast-Furnace Slag" (GGBFS) is produced by the process for grinding "Granulated Blast Furnace Slag" (GBFS) that is a kind of by-product produced via blast furnace operated in steel works. Ground granulated blast furnace slag (GGBFS) has been used in the construction industry for years as a replacement for Ordinary Portland Cement (OPC). Ground granulated blast furnace slag also has a lower heat of hydration and, hence, generates less heat during concrete production and curing. GGBFS cement can be added to concrete in the concrete manufacturer's batching plant, along with Portland cement, aggregates and water. The normal ratios of aggregates and water to cementitious material in the mix remain unchanged. GGBS is used as a direct replacement for Portland cement, on a one-to-one basis by weight. Replacement levels for GGBS vary from 30% to up to 85%. Typically, 40 to 50% is used in most instances. This study is the result of using 70% GGBFS instead of cement even if it is allowed to use maximum 25% of GGBFS instead of it. The use of GGBFS, which has an amorph structure and shows pozzolan characteristics when finely granulated, as a replacement material within the systems of cement or concrete positively effects the properties of fresh and hardening concrete.

Keywords: Concrete · By-product · Ground granulated blast-furnace slag Strength · Durability

1 Introduction

Ground granulated blast furnace slag (GGBFS) has been used in the construction industry for years as a replacement for Ordinary Portland Cement (OPC). Ground granulated blast furnace slag also has a lower heat of hydration and, hence, generates less heat during concrete production and curing. GGBFS is a desirable material to utilize in mass concrete placements where control of temperatures is an issue. GGBFS can be used instead of cement with the ratios from 10 to 90%. However, because of its low heat generating characteristics, GGBFS was approved for use at a 70% replacement even if it is allowed to use maximum 25% instead of cement [1].

The general GGBFS literature indicates that the replacement of OPC by GGBFS typically results in lower early strengths (7–28 days), greater long term strengths, lower chloride ion permeability, less creep, greater sulfate attack resistance, greater alkali

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silica reactivity (ASR) durability, enhanced workability, less bleeding, lower heat of hydration, and increased steel corrosion resistance. Results for drying shrinkage and freeze-thaw durability are somewhat mixed, although in general, the use of slag appears to be no detrimental. Besides lower early strength, the downsides to the use of GGBFS include extended curing times, increased salt scaling, increased plastic shrinkage cracking, and increased air entrainment dosage required. When Grade 120 (highest activity) slag is used, at least a 70% replacement may be needed to meet specification requirements. Most ready-mix concrete producers use 50% replacement with highly reactive slag during warm weather [1].

2 Significance of Using High Volume GGBFS

Most of the cement plants consume great amounts of energy and have a negative role in the environmental pollution with the destructive greenhouse gasses they emit to atmosphere during the production process of the cement. Therefore, cement producers benefit from various mineral additives so as to reduce the CO_2 emission and increase the production rate by decreasing the energy consumption.

One of those mineral additives is granulated blast furnace slag which occurs during the production of pig iron in the iron and steel factories and major part of which is ready to be used as an alternative binding material. The use of industrial by-products containing high percentage of silica and alumina as an additive in cement or concrete, an area convenient for the utilization of large volumes of waste materials, will remedy the environmental problems to some extent. By preventing the rapid consumption of limited natural resources, the production of more qualified and more economic materials instead of the traditional ones will also be possible.

The use of GGBFS, which has an amorph structure and shows pozzolan characteristics when finely granulated, as a replacement material within the systems of cement or concrete positively effects the properties of fresh and hardening concrete. The slag use provides advantage especially in avoiding the thermal cracks in mass concrete and solving the durability problems such as corrosion resistance, sulphate attack and ASR (Alkali Silica Reactivity). On the other hand, when the slag is used in the concrete structures which will be exposed to hard conditions, there are some points, especially for cold climates, to be taken into consideration such as, preference of low rate of water/binder in the mixture and due to the fact that the slag has a low speed of hydration, the need of longer cure process compared to concrete with OPC.

3 Hardened Concrete Properties with High Volume GGBFS

Unit weight, compressive strength and strength development, tensile strength, splitting-tensile strength, modulus of elasticity, creep, shrinkage, permeability and chemical stability and capillary water absorption are examined in high volume GGBFS.

3.1 Unit Weight

The unit weight of hardened concrete with GGBFS is less than of control concrete. Regarding the concrete age, the unit weight of the concrete with GGBFS is increasing more than normal concrete. While the unit weight in normal concrete does not importantly change by years, generally, it noticeably increases in concrete with GGBFS. The most significant reason of this is that the slag in the concrete with GGBFS produces new C–S–H, by combining with CH in the first times of hydration.

As it is known, even if the concrete gets older, the hydration slowly continues. As a result of this the new C–S–H production goes on until the silicates finish deriving from slag and the unit weight value slightly increases. For further ages, however, due to the fact that the density of the slag is less than of the cement, the unit weight of the concrete with high volume GGBFS is smaller than the control concrete. For instance, the dry unit weight of the 28-days old concrete with 10, 20, 30% GGBFS are 5, 10 and 14% less than the control concrete. The unit weight of the same concretes after 90 days are 2, 5 and 6% less than the control concrete as well [2].

3.2 Compressive Strength and Strength Development

When the equal amount of cement and w/b rate is concerned, the slag concrete has less compressive strength at early ages, more compressive strength at late ages than the concrete with OPC has. Because of the fact that the GGBFS hydrates slower than OPC, the rate of strength development is lower at early ages for slag concrete.

High volume slag replacement instead results in a lower rate of strength development. However, when a suitable humidity condition is provided, the long-term strength of the slag concrete will probably be higher. This higher strength in late terms stems from the partial long-term strength of the slag and the micro structure which is intensively hydrated due to the slower hydration reaction. When the temperature is increased, the rate of strength development of the slag concrete is also more than of the concrete with OPC [3].

It is informed that on 28th day the performance of the concrete with GGBFS is similar to of control concrete; however, on 56th day the concrete with GGBFS has a superior performance comparatively to the concrete with OPC. According to the researchers, all of the concretes with up to 55% slag showed a lower compressive strength than the control concrete within 7 days. The results of the tests demonstrated that the hidden binding property of GGBFS, together with the increasing rate of slag replacement slow down the strength development at early ages. But at ages such as 28, 56 and 91 days, the strength development of the concrete with GGBFS is similar or more compared to of the slag-free control concrete with OPC [4].

It is studied on the features of slag concrete which they produced mixing blast furnace slag of four different fineness such as 300, 400, 500 and 600 m^2/kg into 300 m^2/kg cement with a replacement rate from 50 to 80%, informed that the finer the slag, the higher the compressive strength according to the results of the experiments [5].

In a research performed, for the compounds at 100 MPa pressure level, with slag of 70% when compared to the compounds with OPC, the strength percentage for 7th, 28th, 56th and 91st days were respectively found as 46, 71, 85 and 96%. The strength percentage on 91st day, for the compounds with 50% slag at 40 MPa is found 97% [6].

Another study includes 0, 50, 60, 70 and 80% replacement rates of GGBFS at concretes and shows that the changes of compressive strengths in accordance with the concretes age and curing conditions. The compressive strength values of the control concretes are between 50.6 and 63.1 MPa and compressive strength values of the GGBFS concretes are between 27.9 and 66.2 MPa as shown in Fig. 1 [7].

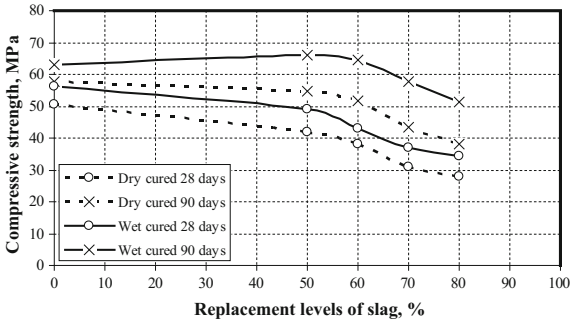


Fig. 1. Effects of slag replacement and curing conditions on 28 and 90-day compressive strength of concretes [7]

3.3 Flexural Strength

The slag concrete, under a determined compressive strength, has a higher tensile strength than the concrete with OPC [8]. It is obtained nearly 8 MPa of strength in 14-day [9].

3.4 Splitting-Tensile Strength

The results of splitting experiment are similar to of compressive. By increasing slag amount, the splitting strength decreases. It is mentioned that it is not valid for the samples having 50 and 60% slag and cured in water for 90 days [7]. Furthermore, as shown on Fig. 2, the decrease in splitting strength is less than the decrease in compressive strength. The results of splitting and compressive strength for the samples with 80% are lower.

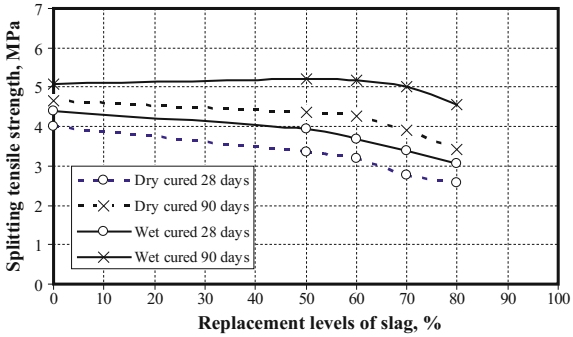


Fig. 2. Effects of slag replacement and curing conditions on 28 and 90-day splitting tensile strength of concretes [7]

3.5 The Capillary Water Absorption

The capillary water absorption values of the concrete formed by partial replacement of OPC with GGBFS decreases to an important extent, this is especially crucial for concretes which are exposed to getting wet and dry.

Capillary water absorption value decreases by increasing compressive strength, also reports that the capillary water absorption value is so vulnerable against the cure conditions [10], and the lowest coefficient of capillary water absorption is obtained from the samples which are kept under 20 °C in lime-saturated water cures during 28-day [3].

Figure 3 shows the variation in water absorption rates with concrete age and curing condition for the control and slag concretes. It is clear that rate of water absorption decreases systematically with an increase in curing period (from 28 to 90-day), and the gradients of the water absorption tends to decrease with increase in the replacement level of slag.

Generally, slag concrete performed better than the control concrete and marked improvements in terms of lower rate of water penetration through capillary suction were apparent, particularly under wet curing condition.

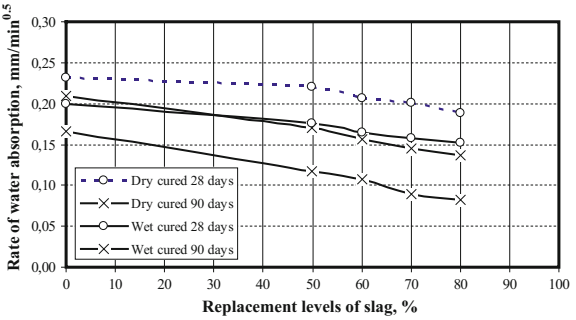


Fig. 3. Effects of slag replacement and curing conditions on 28 and 90-day water absorption rate of concretes [7]

Furthermore, the reduction in the water absorption with increasing test age was about 12 and 15% for air and wet cured conventional concretes, respectively, while it was about 18–22% and 30–35% for air and wet cured slag concretes, respectively. This reduction in the water absorption with age indicates better performance of slag blended cement concretes over conventional concrete. The improvement in the performance of the air cured samples might be explained due to the surface carbonation of the air-cured concrete resulted in enhanced reduction in sorptivity.

The correlation between water absorption with the curing conditions and the age of the concrete is given in Fig. 4 [7]. Similar to the rate of water absorption test results, water absorption characteristics of the concrete specimens decreased with increasing slag content, irrespective of curing condition and testing age. However, the differences

at water absorptions are more characteristic after 28 days of curing, water absorption of the GGBFS concretes are less than control concretes.

At the age of 90-day, water absorption decreases with the ratio of between 12 and 15% at wet and dry cured control concretes. Decreasing ratio of water absorption at dry cured GGBFS concretes are between 18 and 22% and at wet cured GGBFS concretes are between 30 and 35%.

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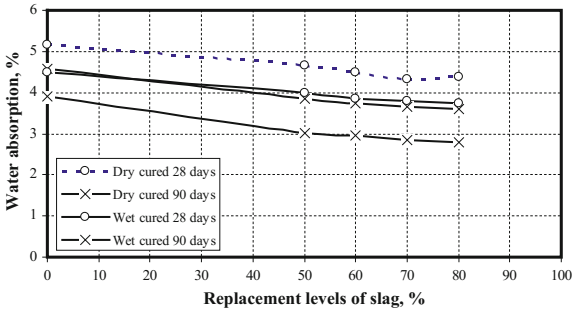


Fig. 4. Effects of slag replacement and curing conditions on 28 and 90-day water absorption of concretes [7]

4 Durability of Concretes with High Volume GGBFS

4.1 Sulfate Resistance

In a study in which Hooton and Emery (1990) used solutions of $MgSO_4$, $CaSO_4$ and Na_2SO_4, 130 different cement were used and proportionally to the amount of GGBFS, even though the concrete obtained by respectively 45 and 72% GGBFS replacement by sulphate OPC, did not show a deterioration inside 3000 mg/lt SO_4 solution for 10.5 years, the concrete with C_3A of a ratio from 3.5 to 12.3% with OPC was badly affected [11].

The sulphate resistance of the concrete is affected from GGBFS content rather than water/cement content [12]. The reason of it is related to the decrease in permeability caused by GGBFS. Furthermore, it is known that the increase in sulphate resistance, caused by GGBFS is due to the decrease in C_3A content. Additionally, slag decreases $Ca(OH)_2$, increases the gels of C–S–H and improves the strength, weakens the permeability of the concrete [1].

4.2 Resistance to Chloride-Ion Penetration and Reinforcement Corrosion

Resistance to the effects of chloride: the effects of different cure conditions such as autoclave (175 °C, 0.5 MPa), steam cure (80 °C) and normal cure (20 °C, 100% RH) on the properties of concrete produced by four different slag replacement (0, 25, 50 and 75%) reported that the cure at room conditions is the best to improve durability, to prefer steam cure instead of autoclave cure when early strength development is desired [2], and finally a reduction in chloride permeability occurs by increasing slag replacement rate, depending on also application, the use of different slag rates is possible to increase the strength and to decrease the chloride permeability [3].

Chloride permeability: The slag cement or slag concrete is more resistant to penetration of chloride ions into the concrete than OPC. This positive effect stems from the chemical combination of chloride ions and slag hydration products which have reducing feature of chloride stream and at the same time the decreasing permeability of slag cement. Moreover, this increased strength has a potential to decrease the corrosion risk of steel in concrete structures.

The important point in chloride permeability is the chloride binding capacity of the cement. Through studies, it is known that C_3A binds chloride. Even though OPC is supposed to bind more chloride ions and to decrease chloride penetration due to having C_3A more than slag cement, the studies proved the contrary. In the analysis done by cement with GGBFS, it is observed that the penetration of chloride ions in OPC is less. This is because the gels of C–S–H bind more chloride. Owing to the fact that the C–S–H occurred after the hydration of slag cement is more than OPC, due to binding chloride ions, the chloride permeability of slag concrete mainly decreases.

Fernandez and Malhotra [13] examined the effects of different cure conditions, (natural environment cure and wet cure) on chloride permeability of concrete with 70% GGBFS. At the end of their study, they observed that the use of GGBFS at a rate of 70% decreases the chloride ion permeability [13]. The chloride permeability decreases considerable at the concretes include more than 50% of GGBFS shown in Fig. 5. For example, permeability value of 70 and 80% of GGBFS concretes at the age of 90-day is 1000 Coulombs and this value is qualified as wonderful in accordance with the ASTM 1202 [7].

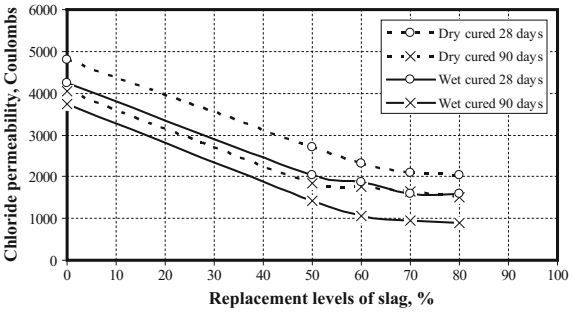


Fig. 5. Effects of slag replacement and curing conditions on 28 and 90-day chloride permeability of concretes [7]

Corrosion resistance: Free chloride permeability of the concrete with GGBFS and they saw that the higher the amount of GGBFS, the lower the values of free chloride permeability. Additionally, they found out that the free chloride permeability of the concrete with 70% GGBFS is 43.8% less than of the control concrete [14].

Corrosion resistance of the concrete with GGBFS and they discovered that the steel corrosion potential of the concrete with GGBFS is smaller than 250 mV. This corrosion value is a very small value. In addition to that, they studied the surface of the steel exposed to corrosion according to the percentage of GGBFS and they found out that the surface under corrosion decreases while the amount of GGBFS increases [4].

4.3 Durability to Sea Water

In his experimental study in which he worked with mortar samples completely sunk in sea water, it is examined the effect of the slag amount against sea water attack and pointed that by increasing GGBFS amount in cement the expansion decreases [15]. It is made a research on the performance of the concrete with slag and OPC of different C_3A content and sea water, reported that the strength development of the concrete with 70% slag and completely sunk in sea water better improves and it is exposed to less chemical attacks with a mediocre chloride permeability [16].

4.4 Resistance to Carbonation

Carbonation occurs when CO_2 penetrates into the concrete. Both the porosity and the permeability of the concrete have an important role in the mechanism of carbonation. The carbonation of the concrete depends on the cure conditions, water/binding rate, the temperature at which the concrete exposed to carbonation and relative humidity, and the properties of the mineral additives used. The decreased permeability delays the CO_2 penetration deeply through the concrete [3]. The examination of the carbonation depth of the concrete with 0, 30, 50 and 70% of GGBFS showed that the more the slag rate, the less the carbonation depth [17].

It is found that for low Blaine fineness slag (4500 cm^2/g), although the slag concretes were denser, the carbonation rate increased with increasing amounts of slag. This was thought to be attributable to less CH being available due to the pozzolanic reaction, so the carbonation must progress deeper to get at the available CH. There is less material available prone to carbonation per unit area to react with CO_2. Initially the pozzolanic reaction is slow, thus porosity is higher and CO_2 diffusion is rapid [18].

However, they found that for higher fineness slags (6000–8000 cm^2/g), carbonation rates were lower than that for OPC, thus pore modification was more dominant than the change in CH content. So, slag mixes tend to have greater depths of carbonation and are more permeable (although not necessarily more porous) and therefore would tend to scale more, especially under severe environmental conditions [1].

4.5 Freeze-Thaw Durability (Resistance)

In the study, it is obtained perfect results in the study with the samples of 60% GGBFS and OPC. However, for all experiments, better results are gained for the mixtures with

GGBFS rather than for with OPC. The highest resistance factor was obtained in the sample with 50% GGBFS [19]. The mixtures with OPC and 66% slag compared. For both group of samples, length changes, massive loss and changes in dynamic modulus of elasticity and compressive strength, air-gap systems, air-gap conditions are similarly obtained [20].

4.6 Acid Resistance

In their study where they study the long and short term performance of the concrete with GGBS and FA, prepared concretes are prepared with 40% FA and OPC. After 3 days of wet cure, among the samples left in 2% H_2SO_4 solution, under room temperature by a time of 4, 8, 16 and 50 weeks, it is observed that the concrete with 15% GGBFS and 25% FA are more superior against acid attack than both concrete with OPC and 40% FA are. They informed that the change in weight at the end of 50th week is approximately 8%. According to them, the weak resistance of concrete with OPC against H_2SO_4 attack is due to the presence of large pores and frees $Ca(OH)_2$ in the concrete [21].

The concrete with 40% FA is also poor against H_2SO_4 attack at the early age. The reason is that there are numerous un-hydrated FA particles in the concrete, and the matrix is significantly porous at the early age. Furthermore, the amount of C–S–H gel in the concrete with 40% FA formed by cement hydration, is less than the amount of C–S–H in concretes with OPC or with FA and slag [3].

4.7 Durability of High and Low Temperature Effect

By use of GGBFS in concrete, the resistance of the concrete under high temperatures increases as a result of pozzolanic activity of the slag. High strength concretes including SF, FA and GGBFS were exposed to different temperature conditions maximally to 800 °C. According to experiment results, the concrete with FA and GGBFS, especially under 600 °C showed the best performance compared to control concrete. In previous studies, it stated that the resistance of the concrete with 40% GGBFS and exposed to 200 °C high temperature increased at a rate of 15% in comparison to those tested under room conditions. While the remaining resistance of the concrete with 40% under 400, 600 and 800 °C is 100%, 61 and 29%, the resistance of the controlled concrete is 89, 58 and 24% [22].

An earlier work on the performance of slag cement at elevated temperatures was done [15]. Four cement pastes containing 0, 50, 70, and 90% replacement of slag were tested by weight with OPC. The maximum tested temperature was 500 °C with an interval of 100 °C. All slag-cement paste specimens experienced an increase in strength between 100 and 250 °C. The 70% slag replacement showed the best results with a residual compressive strength of 190% of the original strength at 110 °C.

Moreover, the residual strength of this paste was higher at all temperatures as compared to the original strength. The other two slag-cement paste specimens also showed better residual strengths as compared to the pure cement paste specimen. Cement paste and concrete specimens incorporating 65% slag were prepared by weight of cement and firebrick aggregates. The results were compared with pure OPC cement

paste/concrete and 30% PFA cement paste. The maximum temperature was 700 °C, while the residual properties were measured at every 100 °C interval. They found that the slag-cement paste and concrete gave the best results among all the specimens tested. The residual compressive strengths of slag concrete were 102 and 80% of the initial cold strength at 450 and 600 °C [23].

4.8 Abrasion Durability (Resistance)

The abrasion durability of concrete with GGBFS increases by applying the suitable and sufficient cure. While the insufficient cure conditions decrease the abrasion durability to a large extent, slag concrete is affected from that more than concrete with OPC. In their study on abrasion durability and its mechanical features, it is reported that the strength development of slag concrete indicates the partial usage of GGBFS instead of cement in concrete; however, the abrasion durability of slag concrete is lower than of control concrete without slag [13]. In condition that suitable and sufficient cure is applied, the use of GGBFS in concrete provides some advantage in abrasion durability [8].

5 Future Trends on Concretes High Volume GGBFS

In the concrete production applications of today and future, the expected concrete types with GGBFS and the result of the studies done about this is tried to be listed below.

Self-Compacting Concrete: The self-compacting concrete (SCC), which is developed especially to be used in structures with dense reinforcement at the end of 80s in Japan, has a perfect workability and high resistance to segregation. SCC can easily furnish itself to the dense reinforced areas without using any vibration. The fresh SSC can be defined as a concrete which has ability to fill the molding and hold the reinforcement by means of its own weight, while keeping necessary homogeneity. Regarding the positive effects of GGBFS used instead of cement on cost and hydration will be better for the strength feature of the concrete [24].

Roller Compacted Concrete: Roller compacted concrete (RCC) is a low-viscosity concrete which is laid in plates and before hardening which is able to carry at least 5 tons of roller in order to be compacted. The reason which renders RCC economic is its very little content of cement. This small amount of cement in RCC brings about a decrease in hydration heat. Hence, RCC is used in mass concrete such as barrage constructions.

The effects of interval between mixing and compacting in RCC including high volume GGBFS were examined. For the mixture having 0, 25, 50 and 75% of GGBFS, he observed that the interval between mixing and compacting mainly influences the compressive strength by increasing rate of GGBFS. He pointed out the increased distance between cement granules by increased amount of GGBFS as the reason of this. For RCC, concrete without sedimentation is produced [21].

Non-Slump Concrete: It is noted that GGBFS used instead of fine aggregate up to 30% is useful for the compacting and compressive strength of RCC, the surface area of the GGBFS effects the development of strength. Larger surface area at early ages,

smaller surface area at late ages show higher strength. They also mentioned that the GGBFS with small surface area is more effective in reducing the temperature of concrete [25].

Reactive Powder Concrete: It is mentioned that for reactive powder concretes with 20, 40 and 60% GGBFS even at 40 and 60%, they obtained compressive strength over 200 MPa, among concrete with 20, 40 and 60% GGBFS and applied standard, steam and autoclave cure, obtained compressive strength over 250 MPa in concrete that had autoclave cure with 20% GGBFS addition. In the presence of external pressure, they observed that this value paramount up to 400 MPa with addition of 40 and 60% GGBFS they reached strength of 210 and 254 MPa by standard cure in 90 days, they attained 33.2 MPa of flexural strength, 6161 N/m of fractural energy and 17,210 Nmm of toughness value and they obtained approximately the same results with autoclave cure [26].

Lightweight Concrete: It is observed that compressive strength in aerated concrete with GGBFS addition increases at a rate of 8–63% depending on the cure conditions, adding high volume of GGBFS improves compressive strength in aerated concretes and it contributes to a better microstructure formation [4].

Ungrounded BFS: It is mentioned that, for concretes in which they use 10, 20, 30, 40, 50% of GBFS and BA (Bottom Ash) as aggregate, by increasing replacement rates, the resistance of the concrete decreases.

BA gives rise to reduction in resistance more than GGBFS does and replacement over 40% is more effective. The resistance of concrete prepared by industrial waste such as polypropylene fiber, GBFS and BA as fine aggregate towards 800 °C high temperatures, showed how it is possible to use these wastes with a ratio of 50% of aggregate which covers 30% volume of the concrete [27].

The study on shrinkage done by GBFS as fine aggregate, determined that by increasing GBFS rate, there is a decrease in shrinkage cracks. They also mentioned that the reason of this is the gap form related to GBFS structure and linked with the same reason flexural strength, compressive strength and modulus of elasticity decreases [28].

Alkali Activated Slags: By means of the activation of GGBFS with alkalis such as NaOH, $NaCO_3$ and $NaSiO_3$ super qualified concrete can be produced. It is informed that the alkali activated mortar with GGBFS exceeds the potential danger limit in ASR but does not exceed the danger limit [29].

6 Conclusion and Recommendations

For 28 days and older ages, to add 50–60% GGBFS to concrete results in higher resistance, whereas to add GGBFS over 80% results in lower resistance. It is understood that to obtain the maximum resistance, the optimum GGBFS rate is 40–60%. The more vitreous content, fineness and alkali content of GGBFS and greater fineness and alkali content of OPC was used together with it improve the strength development.

Using GGBFS up to 80% can increase the resistance to 28 MPa. Therefore, it will be useful to prepare specifications for mixture design and regulations concentrated on the factory operating requirements for high volume GGBFS and the real expectations

from the concrete. Hence, more qualified concrete will be obtained regarding workability, resistance and strength, as well as more economic concrete by waste reduction. At the same time air pollution could be reduced.

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