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Use of Supplementary Cementitious Materials in Concrete: Bangladesh Perspective

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Abstract

The emission of greenhouse gases from the production of raw materials of concrete is an important issue in construction sector. Cement is the prime constituents of structural concrete and it produces approximately 7% of global man made CO_2. The supplementary cementitious materials such as GGBFS or fly ash can be a supplement for portland cement to reduce CO_2 emissions. This paper presents an experimental investigation carried out to study the effects of supplementary cementitious materials such as GGBFS and fly ash as partial replacement of cement on strength development of concrete. Cement was partially replaced with six percentages (0%, 10%, 20%, 30%, 40% and 50%) of GGBFS and fly ash by weight. Compressive as well as tensile strength of concrete specimens were determined at an age of 7, 28, 60 and 90 days. Among all the concretes studied, the optimum amount of cement replacement in mortar with GGBFS and fly ash is reported to be around 30 to 40%. The study reveals that GGBFS and fly ash concrete achieve higher strength as compared to OPC concrete.

Keywords: *Compressive strength, Concrete, Fly ash, Ground granulated blast furnace slag, Tensile strength.*

1 Introduction

Concrete is the most widely used construction material all over the world since last century. Due to rapid development of infrastructures of developing countries, it is expected that in year of 2050, annual consumption of concrete would reach 18 billion tons per year (Parniani, 2011). Typically concrete contains about 15% of cement by mass. Thus to produce such amount of concrete, 2.3 billion tons of cement will be necessary. Manufacturing of Portland cement consumes high levels of energy and results in significant emissions of CO_2, due to the burning of large quantities of fuel and the decomposition of limestone. Cement manufacturing consumes large amount of energy amounting about $7.36*10^6$ kJ per ton of cement (Tarun, 1996). Also, approximately 1 ton of CO_2 is released into the atmosphere during the production of 1 ton of cement (Min-Hong, 2001). Therefore, with the increasing concern over the environmental issues related to global warming, it is urgent to identify a new replacement for portland cement binder. Thus partial replacement of Portland cements by supplementary cementitious materials such as slag, fly ash, silica fume, etc, can significantly reduce CO_2 emission as well as maintain sustainable environment (Ozkan, 2009). Such type of environmentally friendly cement is known as blended cement which contain, in addition to Portland cement clinker and calcium sulfate, a latently hydraulic component such as ground granulated blast furnace slag or Class C fly ash, or a pozzolanic component such as natural pozzolan, Class F fly ash, condensed silica fume, calcined clay or a filler component such as limestone (Homnuttiwong, 2012). Blended cement reduces CO_2 emissions, fuel consumption and production cost of cement (Dung, 2014). In order to reduce the emission of harmful green house gasses and fuel consumption, use of cement must be replaced with other environmentally friendly and efficient cementitious material (Mark, 2006).

Ground granulated blast furnace slag and fly ash are used as pozzolanic mineral admixture in concrete as well as have the hydraulic properties. These materials are used in concrete to achieve energy conservation, economic, ecological and technical benefits (Juenger, 2015). Various types of chemical admixtures are used to improve the construction properties of concrete such as workability, pumpability, setting properties, the mechanical performance, the durability such as freeze thaw resistance and the shrinkage properties (Plank, 2015). However, the continuous increasing demand and limited global availability of these artificial pozzolans has led to a search for alternative supplementary cementitious materials such as natural pozzolans, ground limestone, and basalt powder (Ahmet, 2016). Blast furnace slag is a by-product obtained during the manufacture of pig iron in the blast furnace and is formed by combination of earthy constituents of iron ore with limestone flux. When the molten slag is swiftly quenched with water in a pond or cooled with powerful water jets, it is formed into a fine, granular, almost fully non crystalline, glassy form known as granulated slag having latent hydraulic properties (Hwang, 1986). Such granulated slag when finely ground and combined with Portland cement, has been found to exhibit excellent cementitious properties (Zandi, 2012). Fly ash is comprised of the non-combustible mineral portion of coal. When coal is consumed in the power plant, it is first ground to the fineness of powder, blown into the power plants boiler, the carbon is consumed, leaving molten particles rich in silica alumina and calcium. These particles solidify as microscopic, glassy spheres that are collected from the power plants exhaust before they can fly away- hence the product is named as fly ash (Papadakis, 2002).

When blended cement is mixed with water, initial hydration is much slower than OPC mixed with water. Hydration of blended cement depends upon the breakdown and dissolution of the supplementary cementitious materials by hydroxyl ions released during the hydration of cement (Scrivener, 2015). In the hydration process, supplementary cementitious materials react with $Ca(OH)_2$, hydration product of cement and produces calcium silicate hydrate (CSH) gel. When Portland cement reacts with water, it forms calcium silicate hydrate (CSH) and calcium hydroxide ($Ca(OH)_2$). CSH is the glue that provides strength and holds concrete together while $Ca(OH)_2$ is a by-product of portland cement hydration that does not contribute to strength (Dubey, 2012). When supplementary cementitious material is used as part of cementitious material in a concrete mix, it reacts with water and $Ca(OH)_2$ to form more CSH. The additional CSH increase the density of concrete matrix thereby enhancing strength (Hwang, 2004). The reactivity of supplementary cementitious material, to a great extent, depends on its composition. In general, the more basic the supplementary cementitious material, the greater its hydraulic reactivity in the presence of alkaline activators; the higher the glassy phase, the lime, alumina and magnesia contents, the higher the hydraulic reactivity.

2 Experimental Programs

The experimental program was planned to study the effect of replacement of cement with supplementary cementitious materials ground granulated blast furnace (GGBF) slag and fly ash in making concrete on the compressive and tensile strength of concrete at various ages of curing.

2.1 Materials Used

(a) Cement: ASTM Type-I Portland Cement conforming to ASTM C-150 (1988) was used as binding material. Physical properties and chemical compositions of OPC are given in **Table 1.**

(b) Supplementary cementitious materials: Ground granulated blast furnace slag and low calcium ASTM Class F fly ash was used in this investigation. Physical properties and chemical compositions of SCM's are given in **Table 1.**

(c) Aggregate: 12.5 mm downgraded crushed stone, with fineness modulus 6.58 and specific gravity 2.7, was used as coarse aggregate. Locally available natural sand passing through 4.75 mm and retained on 0.075 mm sieve with fineness modulus 2.58 and specific gravity 2.61 was used as fine aggregate.

2.2 Variables Studied

(a) Concrete type: Concrete having mix ratio of cement, fine aggregate and coarse aggregate 1: 1.5: 3 (by volume) with water cement ratio 0.41 was used in this experimental investigation. Five different mix proportions of cement and supplementary cementitious material (90:10, 80:20, 70:30, 60:40, 50:50) were used as cementitious material. Ordinary Portland cement concrete (100% OPC) specimens were also cast as reference concrete for comparing the properties of slag and fly ash concretes. The concrete that was made by using cement and GGBFS as cementitious material is known as GGBF slag concrete. In fly ash concrete, cement and fly ash was used as cementitious material.

(b) Size, Curing and testing of concrete specimens: 100 mm cubical concrete specimens were made for various tests. A total of 600 concrete specimens were cast in the laboratory. After casting, the specimens were kept at 27°C temperature and 90% relative humidity for 24 hours. After demoulding, all the specimens were cured in water in a curing tank at room temperature. Specimens were tested periodically after the specific curing periods of 7, 28, 60, 90 and 180 days. Specimens were tested in accordance with test procedure BS EN 12390-3:2009 for compressive strength and BS EN 12390-6:2000 for tensile strength.

Table 1. Physical properties and chemical compositions of OPC, GGBFS and Fly Ash

Physical properties	**ASTM Type-I Cement**	**GGBF Slag**	**ASTM Class F Fly ash**
Fineness			
Passing #200 Sieve, %	95%	99%	99%
Blains, m^2/kg	3400	4100	4000
Vicat Setting Time, min			
Initial	145	--	--
Final	190	--	--
Compressive Strength, MPa		--	
3 days	15.4		--
7 days	19.9		--
28 days	30.2		--
Specific gravity	3.15	2.99	--
Chemical compositions, %			
Calcium oxide, CaO	65.18	41.3	8.6
Silicon dioxide, SiO_2	20.80	32.7	59.3
Aluminum oxide, Al_2O_3	5.22	18.4	23.4
Ferric oxide, Fe_2O_3	3.15	1.3	4.8
Magnesium oxide, MgO	1.16	4.2	0.6
Sulfur trioxide, SO_3	2.19	--	0.1
Sodium Oxide, Na_2O	--	1.8	3.2
Loss on ignition	1.70	--	--
Insoluble residue	0.6	--	--

3 Results and Discussion

GGBF slag and fly ash concrete specimens were tested after specific exposure periods. The test results are graphically presented and discussed in the following sections:

3.1 Compressive Strength:

The compressive strengths of OPC and GGBF slag concretes have been graphically presented in **Fig.1.** Also the same for OPC and fly ash concretes are presented in **Fig.2.** For the ease of comparison, the relative compressive strengths for both GGBF slag and fly ash concretes are plotted in **Fig.3** and **Fig.4.** At early ages of curing, OPC concretes achieve relatively higher compressive strength as compared to GGBF slag as well as fly ash concrete.

Test result shows that 7 days compressive strength for OPC concrete is around 14, 16, 24 and 42% higher than GGBF slag concrete of cement replacement level of 20, 30, 40 and 50%; wheras the same value for OPC concrete is 15, 20, 31 and 44% higher than fly ash concrete of similar replacement level. At initial age of curing upto 28 days, compressive strength is seen to decrease with the increase of GGBF slag and fly ash content in concrete when compared with no fly ash concrete. 60 days compressive strength test result of both the specimens up to 40% replacement level are very similar to OPC concrete. After that compressive strength of GGBF slag and fly ash concrete starts to increase compared to OPC concrete. 90 days compressive strength for GGBF slag concrete of 10, 20, 30, 40% cement replacement level is higher by 8, 6, 14 and 10% respectively as compared to OPC concrete; whereas the same values for similar fly ash concrete are 5, 3, 9 and 7% higher as compared to OPC concrete. Rate of strength gaining for different types of concrete is observed to vary with the type of concrete. Among all the concrete studied, 90 days compressive strength for GGBF slag concretes of cement replacement level 10, 20, 30, 40 and 50% are 126, 124, 133, 129 and 110% of 28 days compressive strength of OPC concrete; whereas the same value for fly ash concrete of similar replacement levels are 122, 120, 127, 125 and 104% as compared to 28 days compressive strength of OPC concrete. Similar values for 180 days of curing period is 134, 128, 142, 139, 115% for GGBF slag concrete and 129, 125, 137, 134, 111% respectively for fly ash concrete as compared to OPC concrete for 10, 20, 30, 40, 50% replacement level. For relatively longer period of curing, compressive strength of the GGBF slag and fly ash concrete specimens up to 40% replacement level are higher than that of OPC concrete. Cement normally gains its maximum strength within 28 days. During that period, lime produced from cement hydration remains within the hydration product. Generally, this lime reacts with fly ash and imparts more strength. For this reason, concrete made with fly ash will have slightly lower strength than cement concrete at early ages of curing and higher strength at the later ages of curing. Also fly ash retards the hydration of C_3S in the early stages but accelerates it at later stages. Conversely in cement concrete, this lime would remain intact and with time it would be susceptible to the effects of weathering, loss of strength and durability. 180 days compressive strength data shows almost similar trend.

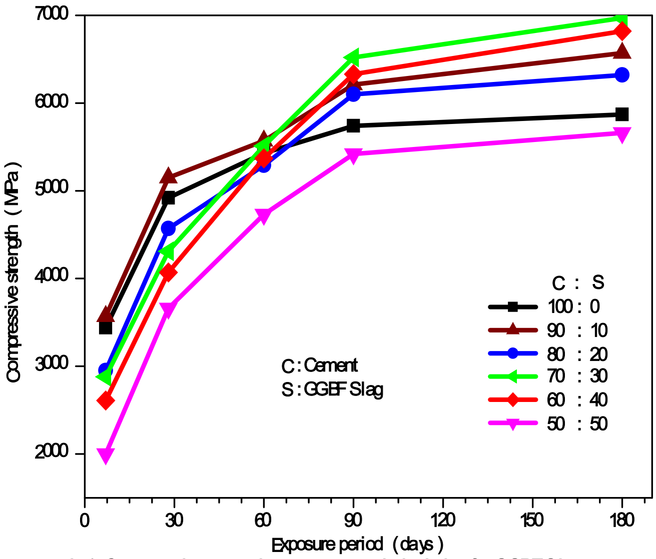

Fig.1: Compressive strength - exposure period relation for GGBF Slag concrete

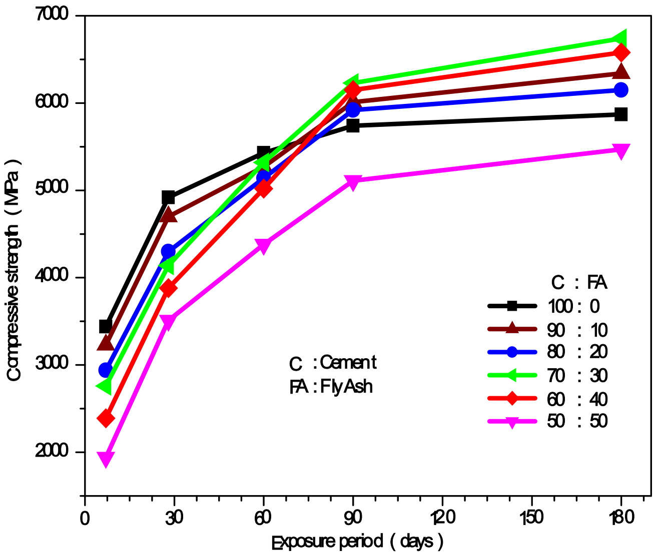

Fig.2: Compressive strength - exposure period relation for Flyash concrete

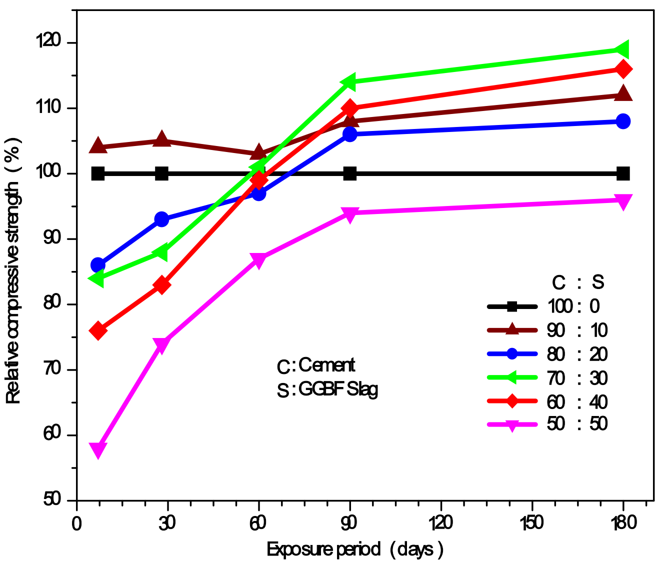

Fig.3: Relative compressive strength - exposure period relation for GGBFS Concrete

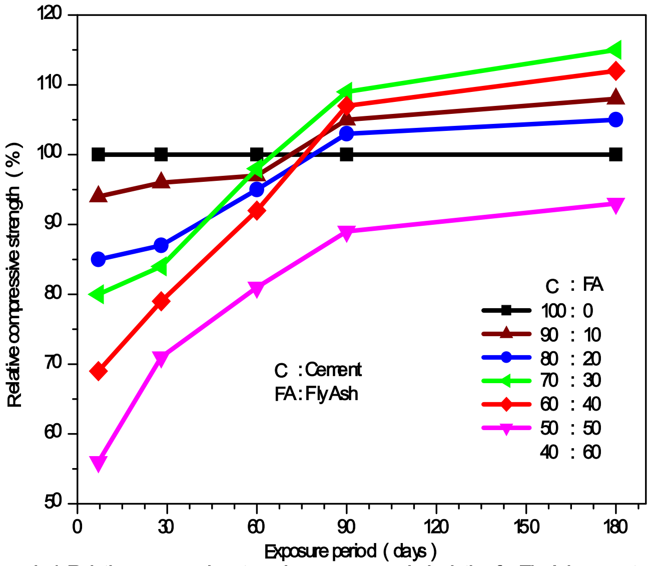

Fig.4: Relative compressive strength - exposure period relation for Fly Ash concrete

At the end of 180 days of curing, compressive strengths obtained for 10, 20, 30, 40% cement replaced GGBF slag concrete were respectively 12, 8, 19, 16% higher as compared to OPC concrete. Also the compressive strength for fly ash concrete were 8, 5, 15, 12% higher respectively as compared to OPC concrete for cement replacement level of 10, 20, 30, 40%. As per chemical composition of slag and fly ash, it is clear that both the materials are pozzolanic in nature and slag has hydraulic properties too. So the strength value for GGBF slag concrete is relatively higher as compared to fly ash concrete for similar age of curing and replacement level of cement.

3.2 Tensile Strength

The tensile strengths of concrete mixes made with and without GGBF slag and fly ash were determined at the ages of 7, 28, 60, 90 and 180 days. **Fig.5** and **Fig.6** shows the development of tensile strength for GGBF slag and fly ash concrete for different curing age. Also for the ease of comparison, the relative tensile strengths were plotted in **Fig.7** and **Fig.8** for GGBF slag and fly ash concrete respectively. At early ages of curing tensile strength decreases with increase of GGBF slag and fly ash content in concrete. However the rate of decrease diminishes with increasing age of curing. As compared to control specimen tensile strength values are 86, 82, 77, 60% for 20, 30, 40, 50% cement replaced GGBF slag concrete respectively; whereas the similar values are 92, 89, 87, 73% for the curing age of 28 days. On the other hand, for fly ash concrete of cement replacement level 20, 30, 40, 50% at an age of 7 days of curing, tensile strength values are 83, 78, 75, 58%; whereas the similar values for 28 days of curing are 88, 91, 89 and 81% respectively compared to no fly ash concrete.

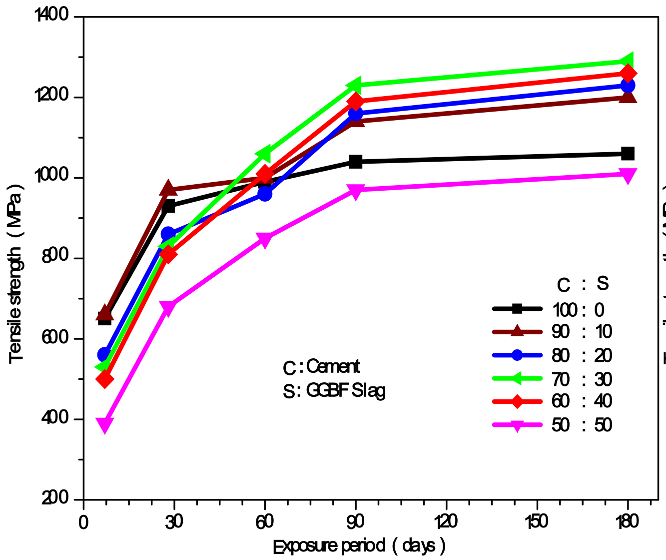

Fig.5: Tensile strength - exposure period relation for GGBF Slag concrete

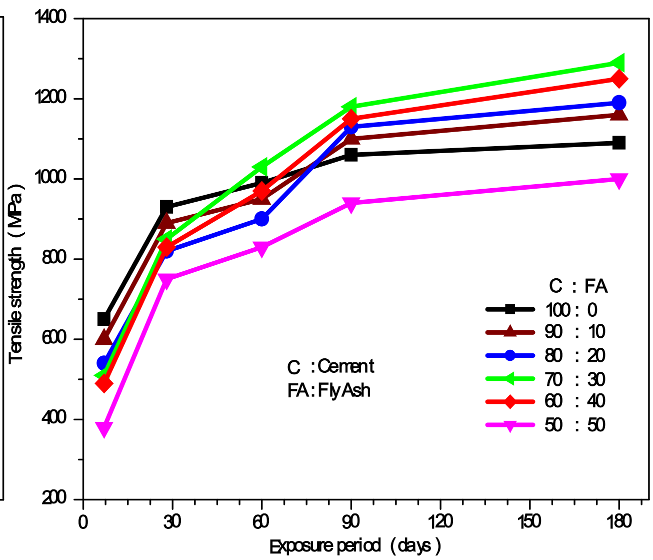

Fig.6: Tensile strength - exposure period relation for Fly ash concrete

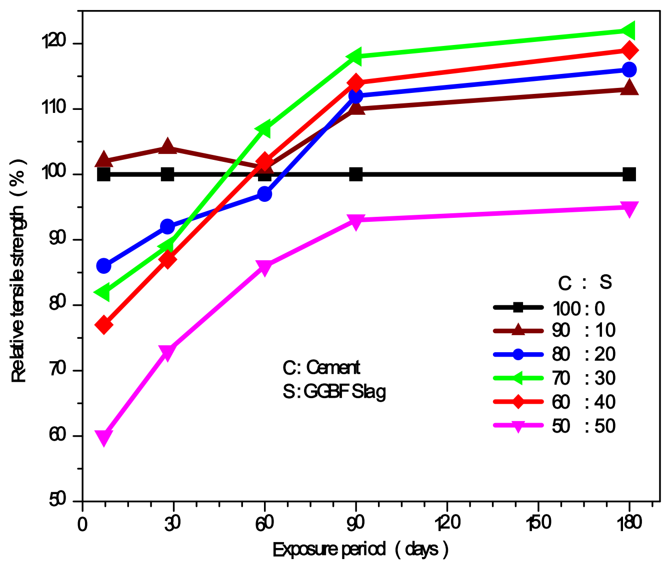

Fig.7: Relative tensile strength - exposure period relation for GGBFS Concrete

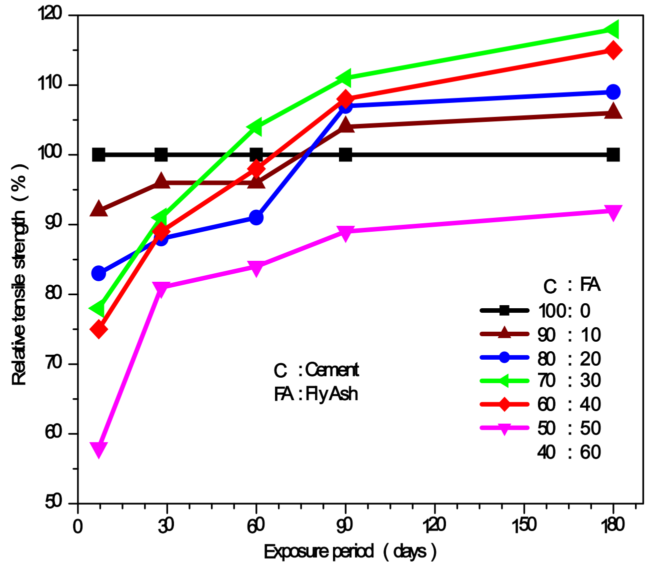

Fig.8: Relative tensile strength - exposure period relation for Fly Ash concrete

Similar to compressive strength, upto 28 days, tensile strengths are seen to decrease with the increase of GGBF slag and fly ash content in concrete when compared with OPC concrete. Also 60 days tensile strength values of both the specimens up to 40% replacement level are very similar to OPC concrete. After that tensile strengths of GGBF slag and fly ash concrete start to increase as compared to OPC concrete. After 90 days of curing, tensile strength values of GGBF slag concrete of cement replacement level 10, 20, 30, 40% are increased by 10, 12, 18, 14% as compared to no GGBF slag concrete; whereas the same values for fly ash concrete of similar cement replacement levels are increased by 4, 7, 11, 8% compared to no fly ash concrete. At the end of 180 days of curing, tensile strength values for 10, 20, 30, 40% cement replaced GGBF slag concretes are increased by 13, 16, 22, 19% and for fly ash concrete these values are 6, 9, 18, 15% as compared to OPC concrete. Pozzolan cements are generally somewhat slower to develop strength than OPC. For long-term continuous curing, the ultimate strengths of pozzolan cement concretes will be higher than that of Portland cement concrete. It is due to fact that GGBF slag and fly ash are pozzolanic material and the reactive silica of pozzolan and calcium hydroxide producing from the hydration of cement reacts together and produces calcium silicate hydrate which imparts strength for concrete. As it takes time to produce $Ca(OH)_2$ by hydration of cement, strength gaining rate slows down at initial ages of curing but increases at the later ages.

4 Conclusions

Based on the results of this experimental investigation on different GGBF slag and fly ash concretes made with different cement replacement level for various curing period up to 180 days, the following conclusions can be drawn:
(1) The rate of gain in strength at early age of curing for both GGBF slag and fly ash concrete is observed to be lower as compared to OPC concrete upto 28 days.
(2) GGBF Slag and fly ash concrete mix having cement replacement levels up to 40% shows higher compressive as well as tensile strength as compared to OPC concrete.
(3) The optimum amount of GGBF slag in the concrete is observed to be 30% of cement. After 180 days curing, GGBF slag concretes with 30% cement replacement shows 19% higher compressive strength than OPC concrete. The corresponding increase in tensile strength is reported to be 22%.
(4) The optimum fly ash content is also observed to be 30% of cement. After 180 days of curing, fly ash concretes with 30% cement replacement shows 15% higher compressive strength than OPC concrete. The corresponding increase in tensile strength is reported to be around 18%.
(5) Use of GGBF slag or fly ash as a replacement of cement provides lower impact on environment by reducing CO_2 emission in cement industry and judicious use of resources.

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