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Strength behavior of mortar made by using supplementary cementitious material as partial replacement of cement

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Abstract

Sustainability is an important issue in construction sector regarding the use of virgin materials as well as the emission of greenhouse gases from the production of raw materials. Cement is the prime constituents of structural concrete and it produces approximately 7% of global man made CO_2. To create sustainable environment, interest in blended cements is growing up because of its advantages in reducing CO_2 emissions and fuel consumption. Supplementary cementitious materials such as Ground granulated blast furnace slag (GGBFS) as well as fly ash are being used as an effective partial cement replacement material to make blended cement. This paper presents an experimental investigation carried out to study the effects of GGBFS and fly ash on strength development of mortar. Cement was partially replaced with six percentages (10%, 20%, 30%, 40%, 50% and 60%) of GGBFS and fly ash by weight. Ordinary Portland cement (OPC) mortar was also prepared as reference mortar. A total of 600 cube and briquette mortar specimens were cast and compressive as well as tensile strength of the mortar specimens were determined at curing age of 3, 7, 14, 28, 60, 90 and 180 days. Test results show that strength increases with the increase of supplementary cementitious materials up to an optimum value, beyond which, strength values start decreasing with further addition. Among all the mortars used, the optimum amount of cement replacement in mortar is found around 40% of GGBFS that provides 22% higher compressive and 23% higher tensile strength as compared to OPC mortar. On the other side, 40% cement replaced fly ash mortar shows 13% higher compressive and 9% higher tensile strength as compared to OPC mortar.

Keywords: Cement, compressive strength, fly ash, hydration. ground granulated blast furnace slag, mortar, tensile strength.

1. Introduction

Sustainable development is the development which meets the needs of people living today without compromising the ability of future generations to meet their own needs. It requires a long-term vision of industrial progress, preserving the foundations upon which human quality of life depends: respect for basic human needs and local as well as global ecosystems. Concrete is and will remain a major construction material of choice in Civil Engineering construction and cement is the most important constituent of it. Unfortunately, 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). Thus partial replacement of Portland cement in mortar / concrete 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). It also increases plant capacity, control of alkali-silica reactivity, reduces production of cement kiln dust and improves durability of concrete (Bostanci 2015).

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	--	--

According to ASTM C125, pozzolan is a siliceous or siliceous and aluminous material which itself possesses little or no cementitious value but in finely divided form and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. 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). Pozzolans, such as fly ash (FA), slag, and silica fume, are the most common materials used to produce blended cement. 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).

Table 2
Grading of fine aggregate.

Sieve size	Cumulative % Passing (for Compressive Strength)	Cumulative % Passing (for Tensile Strength)
1.18 mm (No. 16)	100	100
850 µm (No. 20)	--	90
600 µm (No. 30)	97	0
425 µm (No. 40)	73	--
300 µm (No. 50)	28	--
150 µm (No. 100)	3	--

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). The reactivity of ground granulated blast furnace slag (GGBFS) is considered to be an important parameter to assess its effectiveness in concrete composites (Smolczyk 1978). According to ASTM C125, blast furnace slag is defined as the non-metallic product consisting essentially of silicates and aluminosilicates of calcium and other bases that is developed in a molted condition simultaneously with iron in a blast furnace.

Table 3
Mix proportions of various ingredients of mortar.

Sl. No	Specimen Type/ Materials	For Compressive strength test	For Tensile strength test	Remarks
1.	Specimen	50 mm Cube*	25 mm Briquette**	Materials required for 6 specimens.
2.	Cementitious materials (Cement + Slag/Fly Ash)	500 gm	300 gm	
3.	Sand	1375 gm	900 gm	
4.	w/cm ratio	0.485	0.44***	
4.	Water	242 ml	132 ml	

*ASTM C109-87; **ASTM C190-85; ***For Normal Consistency = 27%*

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 products name fly ash (Papadakis 2002). There are two basic types of fly ash: Class F and Class C. According to ASTM C618, fly ash belongs to Class F if (SiO_2+Al_2O_3+Fe_2O_3) >= 70% and belongs to Class C if 70% > (SiO_2+Al_2O_3+Fe_2O_3) > 50% (Oner 2005). Fly ash is usually found to improve workability and contribute to strength development and hence considered to be an effective cementitius component of concrete (Elkhadiri 2002). It also has high fineness, which decreases the porosity and pore size and increases the compressive strength (Sanchez 2008). Both these fly ashes undergo pozzolanic reaction with lime (Calcium hydroxide) created by hydration of cement and water to form calcium silicate hydrate like cement (Xie 2015). In addition, some Class C fly ashes may possess enough lime to be self cementing in addition to the pozzolanic reaction with lime from cement hydration.

The hydration of cement is an exothermic reaction. High amount of heat is generally developed during this reaction. The generated heat causes the rise in temperature and accelerates the setting time and strength gain of mortar. In many structures, the rapid heat gain of cement increases the chances of thermal cracking leading to reduce concrete strength and durability. The hydration mechanism of blended cement is different from that of ordinary Portland cement (Singh 2015). When OPC comes in contact with water, the dissolution of some phases takes place quite rapidly. But 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). The hydration of these materials consumes calcium hydroxide and uses it for additional CSH formation. As a result the rate of heat liberation is correspondingly slow (Erdogan 2014).

When blended cement is mixed with water, initial hydration rate is much slower as compared to OPC. In the hydration process, Supplemenatry 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. In many specifications basicity is quantitatively defined as a mass ratio between the sum of (CaO+Al_2O_3+MgO) and SiO_2, which is known as the basicity factor.

2. Research significance

Concrete is 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. Accordingly, a huge amount of CO_2 will be added to green house gasses from such a huge amount of cement production (Taylor 2006). 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 Reiner 2006). The local climate of Bangladesh is hot and humid with an average temperature of approximately 30°C. This high ambient temperature is favorable for the early hydration of supplementary cementitious material such as slag and fly ash. It also ensures the proper utilization of slag and fly ash in an effective way which otherwise been dumped making environmental hazard. In the present study, GGBF slag and fly ash mortar specimens were made with different cement replacement levels and cured up to 180 days. Compressive as well as tensile strength tests were carried out at different period to observe the performance of GGBF slag and fly ash mortar as compared to OPC mortar.

3. Experimental program

The experimental program was planned to study the effect of replacement of cement with supplementary cementitious materials GGBFS and fly ash in making mortar on the compressive and tensile strength at various ages of curing.

3.1 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) Slag: Ground granulated blast furnace slag (GGBFS) was used for this investigation. The physical properties and chemical compositions of slag are given in Table 1. The slag activity indexes at 7 and 28 days are 78.3 and 103.9%, respectively. The slag meets the classification requirement of ASTM C989 for Grade 100.

(c) Fly ash: A low calcium ASTM Class F fly ash was used in this investigation. Physical properties and chemical compositions of the used fly ash are given in Table 1.

(d) Sand: Locally available natural sand with fineness modulus 2.6 and specific gravity 2.65 was used as fine aggregate. Gradation of this sand is given in Table 2.

3.2 Variables studied

(a) Mortar type: Six different mix proportions of cement and supplementary cementitious material (90:10, 80:20, 70:30, 60:40, 50:50, and 40:60) were used as cementitious material. Ordinary Portland cement mortar (100% OPC) specimens were also cast as reference mortar for comparing the properties of slag and fly ash mortars. The mortar that is made by using cement and GGBFS as cementitious material is known as slag mortar. In fly ash mortar, cement and fly ash is used as cementitious material.

(b) Exposure period: Specimens were tested periodically after the specific curing periods of 3, 7, 14, 28, 60, 90 and 180 days.

(c) Size of specimens: 50 mm cubical specimens were made for compressive strength and 25 mm briquette specimens were made for tensile strength test as per ASTM standard.

(d) Mortar mix ratios: The mix ratio of cementitious material and sand was 1:2.75 for compressive strength and 1:3 for tensile strength test specimens. Details of mix proportion of materials are shown in Table 3.

(e) Curing environment and testing: A total of 600 mortar 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. After specific exposure period, specimens were tested for compressive and tensile strength in accordance with test procedure ASTM C109-87 (1988) and ASTM C190-85 (1988).

4. Results and discussion

4.1 Compressive strength

The compressive strengths of OPC and slag mortars have been graphically presented in Figure 1 and the same for fly ash mortar in Figure 2. Also for the ease of comparison, the relative compressive strengths are plotted in Figure 3 and Figure 4. At the initial age of curing, OPC mortar shows higher strength as compared to slag as well as fly ash mortar. Test results showed that the 7 days compressive strength for OPC mortar is 6%, 10%, 13%, 15%, 29% and 44% higher than slag mortar of replacement level 10%, 20%, 30%, 40%, 50% and 60%; whereas the same value for OPC mortar is 20%, 16%, 23%, 28%, 37% and 53% higher than fly ash mortar of similar replacement level respectively. Up to curing period of 14 days, compressive strength is seen to decrease with the increase in slag or fly ash content when compared with no slag or fly ash mortar.

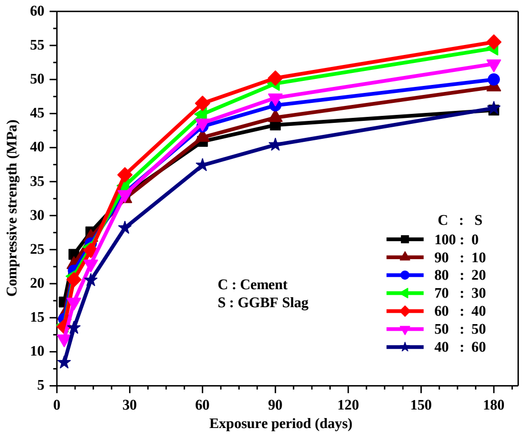

Fig.1: Compressive strength - exposure period relation for GGBF Slag mortar

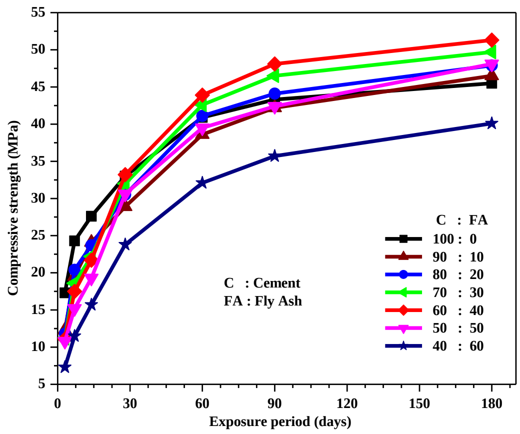

Fig.2: Compressive strength - exposure period relation for Fly Ash mortar

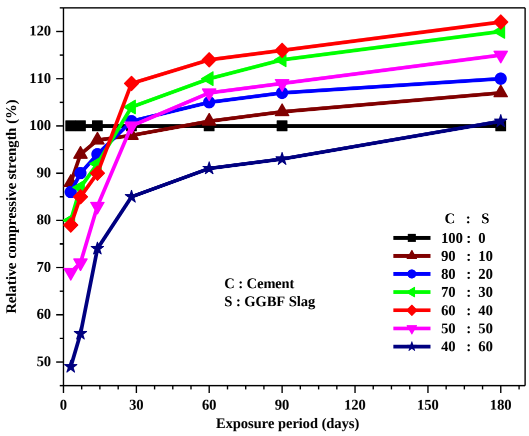

Fig.3: Relative compressive strength - exposure period relation for GGBF Slag mortar

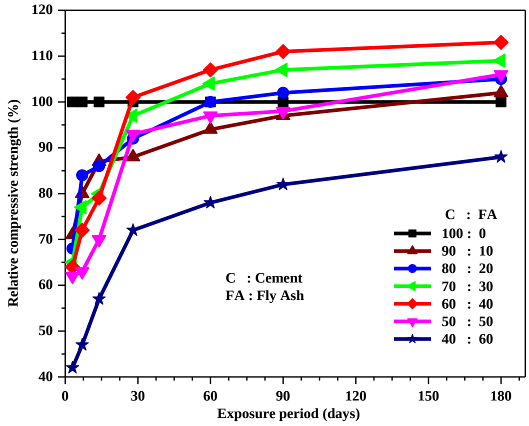

Fig.4: Relative compressive strength - exposure period relation for Fly Ash mortar

28 days compressive strength test result of the specimens up to 50% replacement level by slag or fly ash were very similar with OPC mortar strength. 28 days strength for the 60% cement replaced slag and fly ash mortar was lower by 15% and 28% when compared with no slag and fly ash mortar respectively. 60 days compressive strength data obtained for 20%, 30%, 40%

cement replaced slag and fly ash mortar were respectively 5%, 10%, 14% higher than no slag mortar and 1%, 4%, 7% higher compared to no fly ash mortar. After 90 days of curing, compressive strength data obtained for 20%, 30%, 40% cement replaced slag mortar were respectively 7%, 14%, 16% higher than OPC mortar and the same value for similar cement replaced fly ash mortar are 2%, 7%, 11% higher compared to OPC mortar respectively. At the end of 180 days of curing, compressive strengths obtained for 30%, 40%, 50% cement replaced slag mortar were respectively 20%, 22%, 15% higher as compared to OPC mortar. Also the similar values for fly ash mortar were 9%, 13%, 6% higher respectively compared to OPC mortar. 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 slag mortar is relatively higher as compared to fly ash mortar for similar age of curing and replacement level of cement.

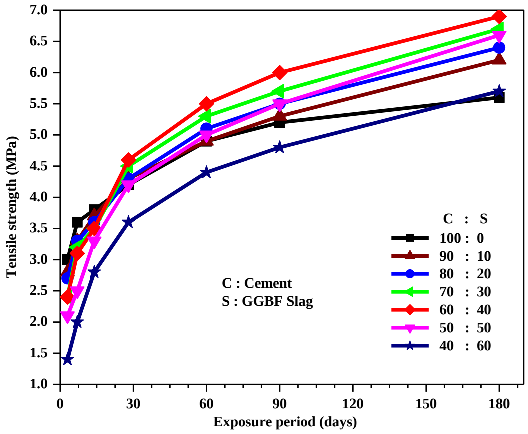

Fig.5: Tensile strength - exposure period relation for GGBF Slag mortar

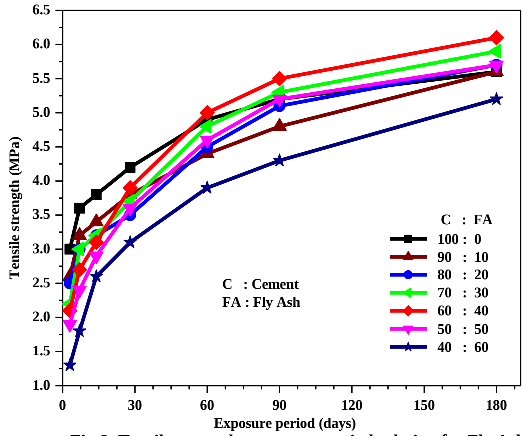

Fig.6: Tensile strength - exposure period relation for Fly Ash mortar

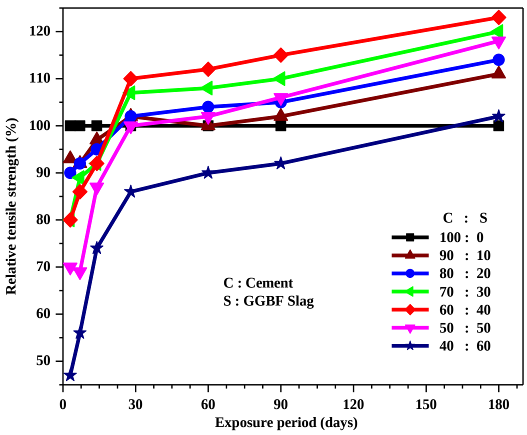

Fig.7: Relative tensile strength - exposure period relation for GGBF Slag mortar

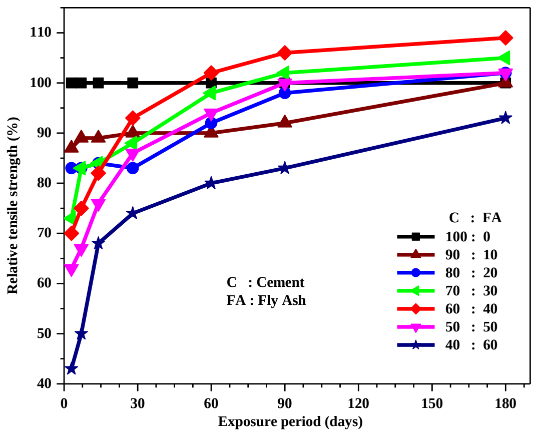

Fig.8: Relative tensile strength - exposure period relation for Fly Ash mortar

In the presence of slag, C_3S hydration is slightly delayed, while hydration at later ages is accelerated (Ogawa 1980). Slag also acts as a retarder to the hydration of C_3A (Uchikawa and Uchida 1980). The setting time of slag-blended cement is delayed as compared to ordinary Portland cement by 10 to 20 minutes per 10% addition of slag (Hogan and Meisel 1981). It has also been reported that the chemical composition of the calcium silicate hydrate formed in hardened blended cement paste is different from that of Portland cement hydration products. For this reason, mortar made with slag will have lower strength than cement mortar at early ages and substantially higher strength at longer ages of curing. Cement normally gains its maximum strength within 28 days. During that period, lime produced form cement hydration remains within the hydration product. Generally, this lime reacts with fly ash and imparts more strength. For this reason, mortar made with fly ash will have slightly lower strength than cement mortar up to 28 days and substantially higher strength within 90 days. Fly ash retards the hydration of C_3S in the early stages but accelerates it at later stages (Jawed 1981). Conversely in cement mortar, this lime would remain intact and with time it would be susceptible to the effects of weathering and loss of strength and durability. (Yamato and Sugita 1983) found that the later age strength of fly ash concrete was higher than that of the control and that the modulus of elasticity was comparable to that of concrete made with moderate heat Portland cement.

4.2 Tensile strength

Figure 5 shows the development of tensile strength with age for different slag mortars, whereas Figure 6 shows the tensile strength of different types of fly ash mortars. Also for the ease of comparison, the relative tensile strength is plotted in Figure 7 for slag mortar and in Figure 8 for fly ash mortar. The tensile strength of the specimens is seen to increase with age. At early ages of curing (3 days and 7 days), the tensile strength decreases with increase in slag content in slag mortar and fly ash content in fly ash mortar.

However, the rate of decrease diminished with the increasing age of curing. The slag mortar as well as fly ash mortar specimen shows that tensile strength results are almost identical with that of reference mortar up to cement replacement of 50% at 28 days. Tensile strength values are 102%, 103%, 107%, 110% and 101% for slag mortar of replacement level of 10%, 20%, 30%, 40% and 50% respectively for the curing age of 28 days. After 60 days, maximum tensile strength of 5.5 MPa for the slag mortar and 5.0 MPa for fly ash mortar was achieved at 40% cement replaced slag and fly ash mortar respectively, with 9% and 2% higher than the OPC mortar. After 90 days, maximum tensile strength of 6.0 and 5.6 MPa was achieved for 40% cement replaced slag and fly ash mortar respectively which is 15% and 6% higher than the reference mortar.

After 180 days of curing, a maximum tensile strength of 6.97 MPa and 6.1 MPa was also achieved for 40% cement replaced slag and fly ash mortar, which is 23% and 10% higher than OPC mortar. Even 30% and 50% cement replaced slag mortar showed 20% and 18% higher strength and fly ash mortar showed 5% and 3% higher strength respectively. According to (Mehta 1986), pozzolan cements are generally somewhat slower to develop strength than slag cements. For long-term continuous curing, the ultimate strengths of slag cement mortar will be higher than that of Portland cement.

According to (Gee 1979), early strength development in slag cement is affected by the chemistry of the clinker, since the manner in which it releases calcium and alkali cations affects the rate of hydration of the slag. As slag cement takes time to produce $Ca(OH)_2$ by hydration of cement, strength gaining rate slows down at initial ages of curing but increases for later age of curing. Also (Korac and Ukraincik 1983) found that the early-age strengths upto 50% fly ash concretes were lower than for the controls; after long curing period the strengths were comparable. The hydration of cement is an exothermic reaction. High amount of heat is generally developed during this reaction. The generated heat causes the rise in temperature and accelerates the setting time and strength gain of mortar. Such rapid heat gain of cement increases the chances of thermal cracking, leading to reduce concrete strength and durability. The applications of replacing cement by high percentage of supplementary cementitious material can reduce the damaging effects of thermal cracking. The cumulative heat of hydration evolved from paste containing slag or fly ash remained less than that form ordinary Portland cement paste.

5. Conclusion

Based on the results of the investigation conducted on different slag and fly ash mortars made with various level of cement replacement for varying curing period up to 180 days, the following conclusions can be drawn:

- The rate of gain in strength of both slag and fly ash mortar specimens is observed to be lower than the corresponding OPC mortar at the early age of curing up to 28 days.
- Both Slag and fly ash mortar mix having cement replacement levels up to 50% exhibited higher compressive as well as tensile strength as compared to OPC mortar.
- The optimum use of slag in the mortar is observed to be 40% of cement. After 180 days curing, slag mortars with 40% cement replacement shows 22% higher compressive strength than OPC mortar. The corresponding increase in tensile strength is reported to be 23%.
- The optimum fly ash content is also observed to be 40% of cement. After 180 days of curing, fly ash mortars with 40% cement replacement shows 13% higher compressive strength than OPC mortar. The corresponding increase in tensile strength is reported to be around 9%.
- Use of high volume slag or fly ash as a replacement of cement in concrete in any construction work, provides lower impact on environment (reduce CO_2 emission) and judicious use of resources (energy conservation, use of by-product).
- Use of slag or fly ash in blended cement reduces the heat of hydration in a mortar/ concrete mix. Thus, the use of blended cement in construction work become environmentally safe and also economical.

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