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Investigating the Usage of Environmental By-Product Materials in Concrete for Sustainable Development

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Abstract: This research presents laboratory studies on the properties of concrete that contains ternary blends of Portland cement, fly ash, and silica fume. Nine concrete mixtures were prepared with water to cement material ratio of 0.5. The concrete mixtures were designed to have the same degree of workability and percentage of air content. Tests were executed and measurements (i.e. compressive strength, tensile strength, dynamic elastic modulus and static young's modulus) were undertaken. The results indicated that concrete made of such materials (i.e. environmental friends) showed hardened properties since the combination of fly ash and silica fume is somehow synergistic. The research concluded that the replacement of 35% of cement quantity with 25% fly ash and 10% silica fume increased the compressive strength by 20% at 180 days. In addition, the results indicated that the use of ternary natural cement like materials systems in concrete showed a significant resistance to sulphate attack. Moreover; using such materials reduce environmental impacts by reducing the production of cement thus causing the reduction of greenhouse gases emissions, reduction of used energy in cement industry and disposing the natural cement like by-product.

Key words: Environmental; By-Product; Concrete; Portland cement; Fly Ash; Silica Fume

INTRODUCTION

The Egyptian cement industry increased in size and capacity during the last 30 years. In 1975 the Egyptian Cement Industry comprised four factories, which produced 4 million tons/year. Now there are 16 factories, producing 46 million tons/year of clinker from dry kilns from 7 wet kilns in 3 factories. Egypt's production is estimated to be 1.5% of the world production in year 2008 (Askar *et al*., 2010).

The Second National Communication for Egypt (EEAA, 2010) reported that the greenhouse gases (GHG) emissions from the industrial sector are 27.77 Mt/year. Moreover, cement industry is responsible for 17 million ton of CO_2 emissions per year, amounting to about 62% of the total GHG emissions of the industrial sector. This means that any reduction in cement consumption by using natural cement like material can lead to reduce the GHG emission.

Mehta, 1999 outlined that since unused industrial by-products cause land, air, and water pollution, the environmental-friendliness of concrete can be greatly enhanced by incorporating pozzolanic and natural cement like by-products in most of the concrete being produced today. The economic and engineering benefits, such as durability enhancement of using natural mineral admixtures in concrete are already well established. Therefore, when the environmental benefits of using concrete containing fly ash, slag, silica fume, rice straw ash and rubber are also considered, the product acquires a highly attractive position among all building materials. It is for the construction industry to make a better use of this knowledge and to increase the rates of utilization of pozzolanic and natural cement like by-products in concrete than is the case today. Moreover; he further added that there is already a growing consciousness in society that builders of projects must be held accountable for social and ecological consequences of their actions, including the selection of environmental friendly materials for construction.

Mehta, 2004 reported that fly ash is the combustion residue (coal mineral impurities) in coal burning electric power plants, which flies out with flue gas stream and is collected by mechanical separators, electrostatic filters. He stated that upon ignition in the furnace, most of the volatile matter and carbon in the coal are burned off. During combustion, the coal's mineral impurities (such as clay, feldspar, quartz, and shale) fuse in suspension and are carried away from the combustion chamber by the exhaust gases

Kumar, 2006 stated that in the process, the fused material cools and solidifies into spherical glassy particles called fly ash. The fly ash is then collected from the exhaust gases by electrostatic precipitators or bag filters. Fly ash is a finely divided powder resembling Portland cement. Moreover, King, 2012 indicated that silica fume is a by-product material that is used as a pozzolan. This by-product is a result of the reduction of high-purity quartz with coal in an electric arc furnace in the manufacture of silicon or ferrosilicon alloy. Silica fume rises as an oxidized vapor from the 2000°C (3630°F) furnaces. When it cools, it condenses and is collected in huge cloth bags. The condensed silica fume is then processed to remove impurities to control particle size. Condensed

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silica fume is essentially silicon dioxide (usually more than 85%) in non-crystalline (amorphous) form. Since it is an airborne material like fly ash, it has a spherical shape. It is extremely fine with particles less than 1 μm in diameter with an average diameter of about 0.1 μm (i.e. about 100 times smaller than average cement particles.

The main objective of this research was set, which is radically to present a solution to reduce GHG emissions from concrete industry by reducing the cement content in the concrete and reducing the pollutant from the by-product materials disposal. The research also aims to assess the effect of the replacement percentage of cement by fly ash and silica fume on the properties of concrete.

MATERIALS AND METHODS

Usually, by-products of manufacturing cement cause different types of pollutions. The reduction in cement reduces the pollution related to manufacturing processes. In this paper, silica fume (SF) and fly ash (FA) were used as natural cement like materials are used with the ordinary portland cement (OPC) to find out the behavior of these binary and ternary natural cement like materials.

Preparing The Samples:

Nine concrete mixtures were prepared with water natural like cement and sand/aggregate ratios of 0.5 and 0.4, respectively. The measurements of fresh concrete include slump, air content (the concrete mixtures were designed to achieve slump of 10 ± 2 cm and air content of 4 ± 1%) and unit weight.

Chemical admixtures were used (i.e. high performance super-plasticizer, which is a high range water reducing admixture possessing air entraining effect; air entraining agent).

Executing The Experiments:

The materials were put into the mixer as follows: first; coarse aggregate followed by sand, then natural cement like materials (OPC, FA, and SF are mixed well before putting into the mixer) added to the mixer. The total mixing time is three minutes divided into two stages, starting with 60 seconds dry mixing and then the required water (mixed with chemical admixture) is added within 30 seconds, then mixer continues for the next 90 seconds of mixing. After casting, the concrete specimens were compacted by a vibrator. The test specimens were stripped from their molds the day after casting. The specimens were cured in water until the testing time.

The experimental work was conducted in Japan. The properties of Portland cement comply with Japanese Industrial Standard. The properties of Portland cement, silica fume and fly ash used are listed in Table (1).

Table 1: Properties of Portland cement, silica fume and fly ash

Constituents	Ordinary Portland Cement (OPC)	Fly Ash (FA)	Silica Fume (SF)
Specific gravity	3.16	2.32	2.24
Surface area (cm^2/g)	3310	3910	153000
Loss on ignition, L.O.I	2.05	1.95	1.30
Silicon dioxide, SiO_2	22.0	45.0	94.90
Magnesium oxide, MgO	1.12	N/A	0.61
Sulfur trioxide, SO_3	2.13	N/A	0.33
Chloride Ion, Cl^-	0.011	N/A	0.048

Executing Measurements:

After preparing the samples, measurements were undertaken. The measurements of hardened concrete included compressive strength, tensile strength, static elastic modulus, and dynamic elastic modulus.

Table (2) shows the binary and ternary systems of combination of Portland cement, silica fume and fly ash while the mix proportions of concrete mixtures are summarized in Table 3.

Where:

W: Water

OPC: Ordinary Portland Cement

FA: Fly Ash

SF: Silica Fume

Ad: Chemical admixture (High performance superplasticizer, high range water reducer agent includes air entraining effect, Rheobuild (SP8SB)

AE: Air Entraining Agent, Micro-air 775S.

Table 2: Binary and ternary systems of Portland cement, silica fume and fly ash

Mix No.	S/A ratio	W/C ratio	OPC (%)	Fly ash (%)	Silica fume (%)
1	0.4	0.5	100	0	0
2			85	15	0
3			75	25	0
4			95	0	5
5			90	0	10
6			80	15	5
7			70	25	5
8			75	15	10
9			65	25	10

Table 3: Mix proportions of concrete

Mix No.	Kg/m^3										
	W	OPC	FA	SF	Sand	Gravel		Ad		AE	
						20mm	15mm	C %	Kg/m^3	C %	Kg/m^3
1	165	330	0	0	704	530	528	1.0	3.300	0.0020	0.660
2		280.5	49.5	0	699	526	524	0.85	2.805	0.0060	1.980
3		247.5	82.5	0	695	523	521	0.75	2.475	0.0090	2.970
4		313.5	0	16.5	702	529	527	1.0	3.300	0.0000	0.000
5		297	0	33	700	527	525	1.05	3.465	0.0000	0.000
6		264	49.5	16.5	696	524	522	0.90	2.970	0.0040	1.320
7		231	82.5	16.5	693	522	519	0.80	2.640	0.0055	1.815
8		247.5	49.5	33	694	523	521	1.00	3.300	0.0040	1.320
9		214.5	82.5	33	690	520	518	0.95	3.135	0.0045	1.485

The properties of hardened concrete were measured by means of destructive and non-destructive tests. Compressive strength and tensile strength are performed via the destructive tests, while the static young's modulus and dynamic elastic modulus were carried out via the non-destructive ones. The compressive strength and dynamic elastic modulus were measured at 3, 7, 28, 90 and 180 days after concrete casting while the tensile strength (cylinder of 15 cm diameter and height 30 cm) and static young's modulus were measured only after 28 days. Concrete specimens (prism of 10 x 10 x 40 cm) were used to measure the dynamic elastic modulus.

After curing in water for 28 day, some of the concrete specimens were immersed in a 5% sodium sulphate solution for 180 days. The compressive strengths of the concrete specimens were measured at 28, 90 and 180 days.

RESULTS AND DISCUSSION

After executing the measurements, their results were analyzed and presented, here, as follows.

Properties Of Fresh Concrete:

As mentioned above, the measurements of fresh concrete include slump, air content (the concrete mixtures designed to achieve slump of 10 ± 2 cm and air content of 4 ± 1 %) and unit weight. Dose of the chemical admixtures (high performance super-plasticizer and air entraining agent) were changed to achieve the required values of slump and air content.

The measured values of slump, air content and unit weight are summarized in Table 4. In the concrete mixtures, it is noticed that fly ash mixtures need high dose of the air entraining agent to achieve the designed air content while silica fume mixtures need low dose of the air entraining agent.

Concerning the super-plasticizer, silica fume mixtures need higher dose than those of fly ash ones. The mixtures that include ternary systems of fly ash and silica fume showed that both silica fume and fly ash compensate each other regarding the dose of air entraining agent and super-plasticizer.

The measured values of slump and air content fall within the designed rang (i.e. all measured slump are 10 ± 2 cm and air content of 4 ± 1 %). The results of unit weight of concrete change according to the type of used natural cement like materials.

This is attributed to the difference in the specific gravity of the natural cement like materials and air content. Therefore, the type of natural cement like materials affects the properties of fresh concrete.

Table 4: Properties of fresh concrete mixtures

Mix No.	Slump (cm)	Air content (%)	Unit weight (t/m^3)
1	9.7	4.0	2.385
2	11.1	4.7	2.347
3	11.6	3.7	2.368
4	10.6	4.4	2.377
5	10.6	3.5	2.368
6	11.2	4.7	2.347
7	11.0	3.7	2.359
8	11.6	4.5	2.364
9	10.6	4.3	2.368

Properties Of Hardened Concrete:

As mentioned earlier, the measured properties of hardened concrete up to age of 180 days involved compressive strength and dynamic elastic modulus, while the measured properties of hardened concrete at age of 28 days included tensile strength and static Young's modulus.

The test results of the properties of different concrete mixtures are shown in Figure (1) to Figure (4) for compressive strength, tensile strength, dynamic elastic modulus, and static Young's modulus, respectively.

A comparison between the results was held. The comparison of the compressive strength results, Figure (1), provides an indication of fly ash and silica fume contributions in the ternary blends. The compressive strengths of silica fume concrete (mixes 4 and 5) are higher than those of all studied mixes until age 90 day. The control mix (OPC) shows higher strengths than those of mix 2 (15% FA) at all ages. Mix 3 of fly ash (25% FA) shows lower compressive strengths than those of the control concrete at all ages due to the effect of high replacement percent (25%) of fly ash. The mixes of ternary systems show lower compressive strength than those of OPC mix (control mix) at ages 3, 7 and 28 days and they indicate an almost equivalent or greater compressive strength to the control mix at ages 90 and 180 days. Mix 8 (15% FA + 10 SF) and Mix 9 (25% FA + 10 SF) achieved higher compressive strength between all mixes at age 180 days. Compressive strength trends at 3 days to 90 days were the same trends obtained by Anwar (2006), but they have values less by 30%, as a mean value, where he used water/natural cement like material equal to 0.4.

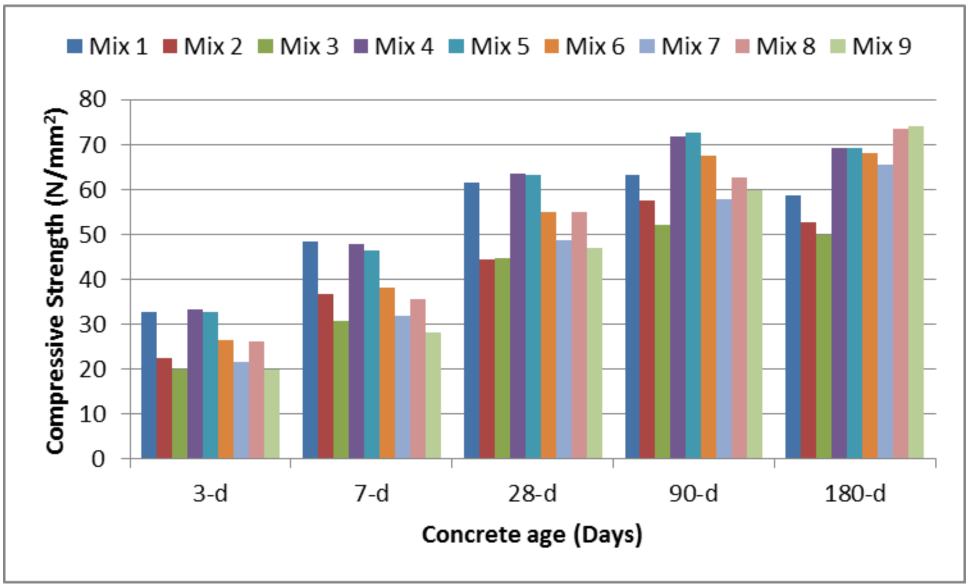

Fig. 1: Compressive strength of the studied concretes.

Generally, replacement specific ratios of cement in the concrete by fly ash and silica fume leads to enhancement of compressive strength of the concrete.

The rates of the compressive strength development up to the age of 180 days of concrete mixes with various combinations of Portland cement, fly ash, and silica fume are presented in Figure (2).

The obtained results complied with Thomas *et al.*, 1990 who reported that the combination of Portland cement, silica fume and fly ash in a ternary cement system should result in a number of synergistic effects, some of which are obvious or intuitive, as follows; (a) Silica fume compensates for low early strength of concrete with low CaO fly ash, (b) Fly ash increases long-term strength development of silica fume concrete, and (c) The relatively low cost of fly ash offsets the increased cost of silica fume.

Also, the results comply with the finding of Lane and Ozyildirim, 1999, who indicated that the use of ternary blends incorporating small amounts of silica fume with smaller amounts of fly ash or slag becomes a viable approach to counteract the negative effect of higher replacement of fly ash and slag on early strength. The obtained results of the rate of strength by day show that binary natural cement like blends of Portland cement and silica fume were slightly higher than plain Portland cement at the first 3 days, vice versa with blends of Portland cement and fly ash.

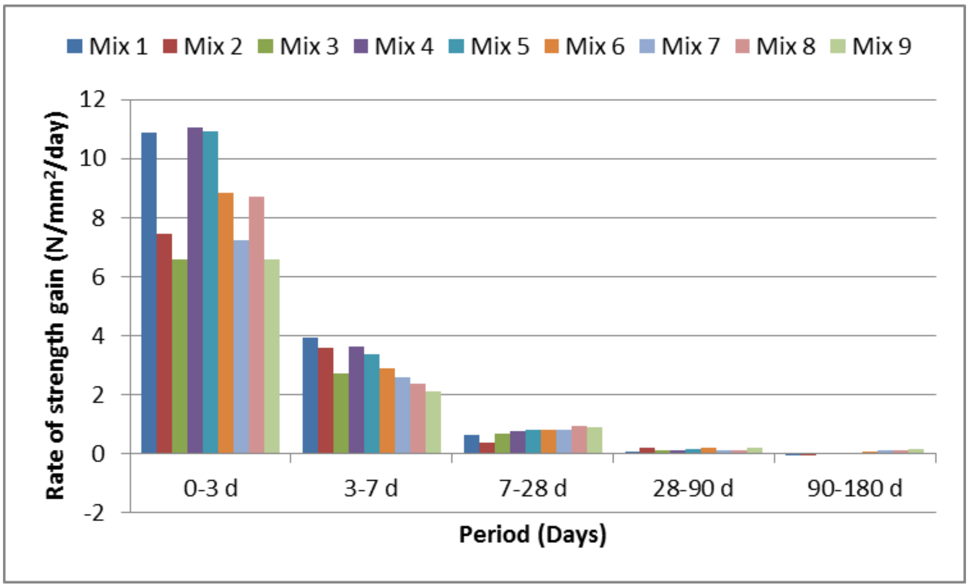

Fig. 2: Rate of compressive strength development.

The results of the tensile strength of concrete mixtures after 28 days of curing are represented in Figure (3). The tensile strength results show approximately the same trend as the compressive strength at 28 days. However, Mix 3 shows the lowest tensile strength due to the effect of using large replacement percent of fly ash, on the other hand mixes (4 and 5) shows the highest tensile strength. The results of the tensile strength indicate that the binary and ternary natural cement like material of silica fume mixes show an equivalent tensile strength to the control mix. Tensile strength results revealed that the binary and ternary natural cement like material using Portland cement, fly ash and silica fume does not significantly affect the tensile strength of concrete.

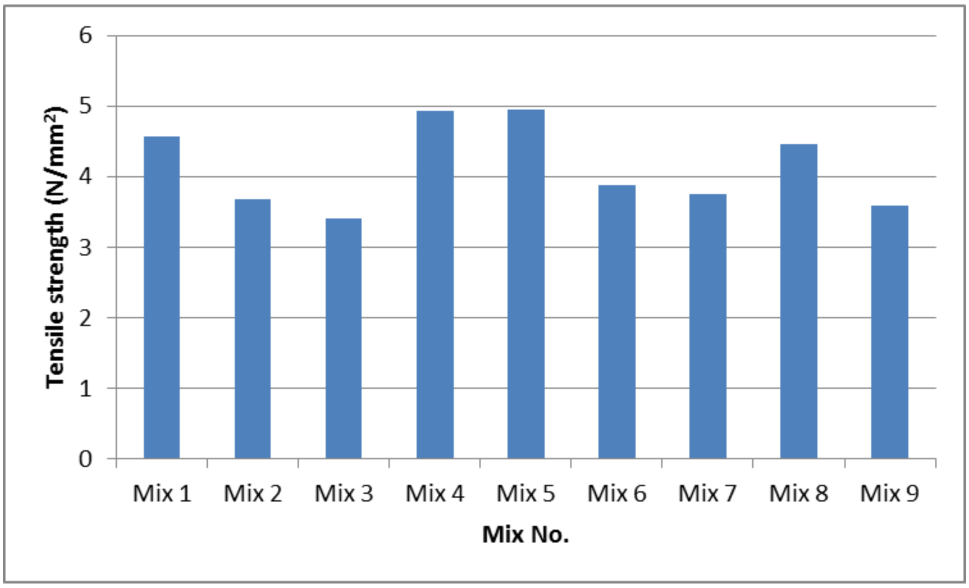

Fig. 3: Tensile strength of the studied concretes.

Approximately similar tensile strength was observed for the control, binary and ternary natural cement like materials concrete mixes, Figure (3).

It is noted that the dynamic elastic modulus is different from the Young's modulus (or static elastic modulus) commonly determined by a static unidirectional compression test of a concrete specimen.

Generally, the ratio of dynamic modulus to the static modulus of elasticity is more than 1 and its value varies with the mix proportion of concrete (Salman and Al-Amawee, 2006). The obtained test results of dynamic elastic modulus for different concrete mixtures up to age of 180 days are presented in Figure (4), while the measured values of static elastic modulus at 28 days are represented in Figure (5).

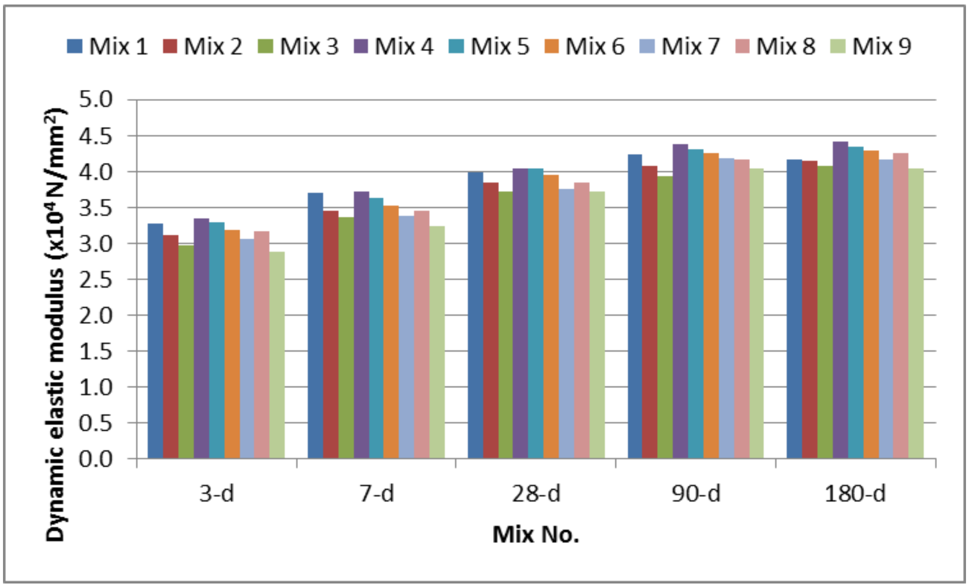

Fig. 4: Dynamic elastic modulus of concretes.

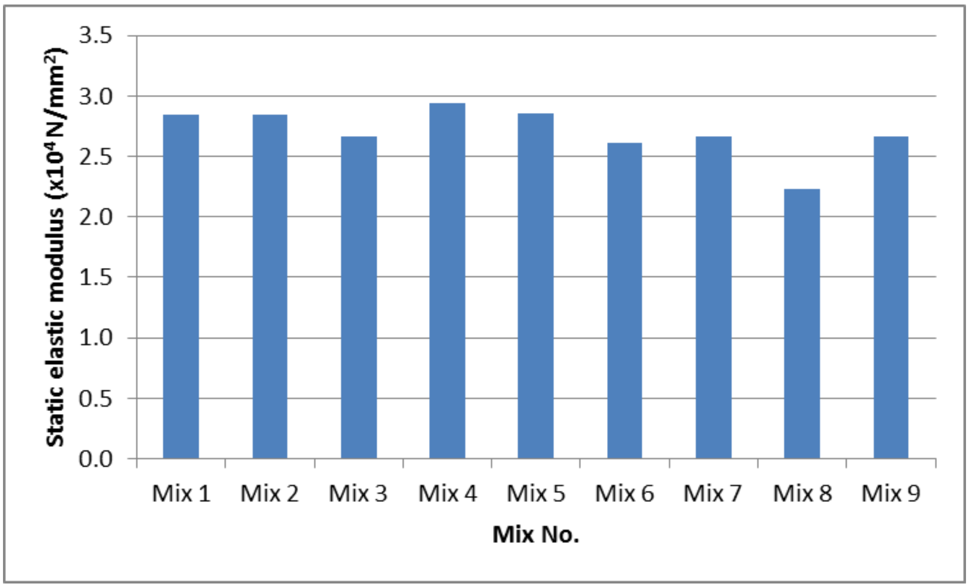

Fig. 5: Static elastic modulus of the studied concretes.

The results of dynamic elastic modulus of tested concrete show approximately the same trend as the compressive strength and it is possible to use this test to compare or check the quality of concrete. The dynamic elastic modulus values of tested concrete indicate slight differences due to the change in the combination of the natural cement like materials at all testing ages. However, Mix 3 (25% FA) shows the lowest values of dynamic elastic modulus at all testing ages. The results of the static elastic modulus at the age of 28 days of all mixtures are affected by the change in the type of supplementary cementing materials as well as the replacement percent.

However, Mix 3 shows lower static elastic modulus than that of control mix while Mix 4 (5% SF) show higher static elastic modulus than that of control mix as indicated in Fig. 5.

Sulphate Resistance:

The obtained compressive strength results of the concrete specimens after immersion in 5% sodium sulphate solution are shown in Figure (6). It can be noted that, mixes 4 and 5 exhibit better performances than the reference concrete of OPC at 28 days after exposure to sulphate, while mixes 4, 5, 6, 7, 8 and 9 exhibit better performances than the reference concrete of OPC at 90 and 180 days after exposure to sulphate. Moreover, mix 8 (15% FA + 10 SF) indicates the highest values of compressive strength at all testing ages. Concrete of ternary natural cement like materials systems showed an excellent sulphate resistance during 180 days of exposure to the 5% sodium sulphate solution and no detectable trace of deterioration caused by the sulphate attack was found within the test period. The compressive strengths of all mixes after immersion in 5 % sodium sulphate for 28 days show higher values than those of concrete immersed in fresh water for the same period. By passing 180 days, the compressive strengths of only mixes 1, 3, 5, 7 and 8 after immersion in 5 % sodium sulphate show higher values than those of concrete immersed in fresh water.

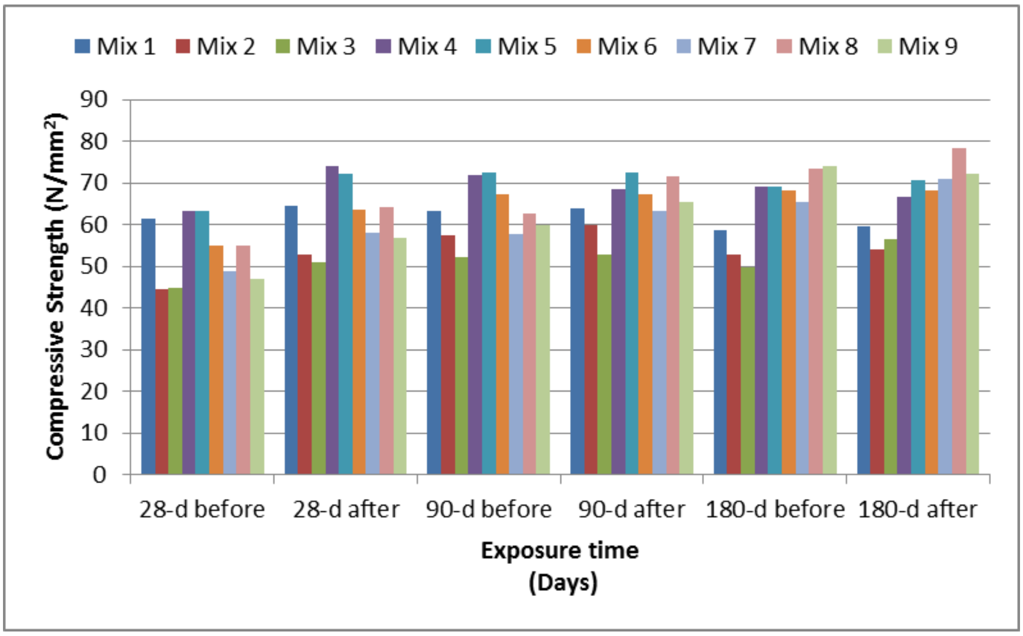

Fig. 6: Compressive strength of tested concrete before and after exposure to sodium sulphate.

Pointing Out The Environmental Benefits:

Different environmental benefits can be pointed out, when binary or ternary natural cement like material containing silica fume and/or fly ash, are used in concrete. From previous results, it can be pointed out to the following:

- Using 25% fly ash and 10% silica fume in the tested mix gave nearly similar properties of control mix.
- Replacement of 35% from cement content in concrete leads to reduce of cement production by 35%.
- As cement industry in Egypt is responsible of air pollution by GHG emission with 17 million ton CO_2e/year, the reduction in cement production cause the reduction of GHG emission by about 6 million ton CO_2e/year. This reduction in GHG represents about 22.2% and 5.7% from total emissions of industrial sector and total emissions of all sectors in Egypt, respectively.
- As producing a ton of portland cement requires about 4 GJ energy (Malhotra, 1999), reduction of cement industry conducive to reduce of used energy by about 64 million GJ.
- Another benefit can be gained as achieving an environmentally disposing of the by-products (silica fume and fly ash) where the bad practices of by-products disposal causing more GHG emissions. Moreover, following the sustainable development concept, using the by-product natural cement like materials and reduction of cement production conserve the natural resources from depletion and meet the future demands for more concrete.

Conclusion:

From the above, the following conclusions were reached:

- Many environmental benefits can be gained from replacing 35% of cement content in the concrete by 10% silica fume and 25% fly ash, like reduction of GHG by 6 million ton CO_2/year in Egypt.
- The combination of silica fume and fly ash is complementary: the silica fume improves the early age performance of concrete with the fly ash continuously refining the properties of the hardened concrete as it matures.
- Combinations of 15 to 25% fly ash with 5 to 10% silica fume show satisfactory performance in both fresh and hardened concrete. Such combinations produce concrete with generally excellent properties.
- Combinations of 15% fly ash with 10% silica fume give the highest compressive strength during sulphate attack at 180 days.

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