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Durability of Concretes Containing Supplementary Cementing Materials Under Hot and Aggressive Environment

by A. A. Ramezanianpour and A. R. Pourkhorshidi

Synopsis:

It is well known that supplementary cementing materials can enhance the durability of concrete structures particularly in the hot and severe environment. In this study, concrete specimens containing different supplementary cementing materials, namely; silica fume, slag, a natural pozzolan (trass), and mixtures of cement and two pozzolans have been investigated. The tests conducted include, compressive strength, permeability, chloride diffusion, corrosion of reinforcing bars, and carbonation depth, all at different ages. The variables were cement types, supplementary cementing materials, water-cement ratio, and cover thicknesses. After standard curing, concrete specimens were transferred to the Gulf region and maintained in submerged, wetting and drying and coastal environments. For exposure to alternate cycles of wetting and drying, known as the most severe condition, the superior performance of silica fume was followed by the concrete mixture containing trass. However, all concrete mixtures containing natural or artificial pozzolans showed better performance compared with the portland cement control concrete mixtures.

Keywords: corrosion; durability; natural pozzolan; silica fume; slag

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INTRODUCTION

Many concrete structures in the coasts of Persian Gulf countries are suffering from early deterioration and heavy damages. The main causes of the early deterioration are the very corrosive environment, lack of sufficient knowledge, defects in construction practices, and the use of unsuitable and low-quality materials. Because of ever-increasing and multilateral development for the sake of the marine transit and the operation and extraction of oil and gas resources, there is a substantial need for the construction of different concrete structures in this region. Survey of newly built and old concrete structures in the region show that many of these structures are not able to satisfy their minimum service life (1). However, the use of special cements and pozzolans in corrosive regions, has shown desirable performance of reinforced concrete and enhanced the durability of concrete (2~6). The scope of this study was to evaluate the performance of concrete mixtures containing various pozzolanic materials in hot and severe environments.

EXPERIMENTAL PROGRAM

Materials

Cement- ASTM Type II portland cement and ASTM Type V portland cement was used in this investigation.
Slag- slag-modified portland cement (I (SM) per ASTM C 595) was incorporated in the mixtures.
Pozzolan- Trass as a natural pozzolan was used in this program.
Silica fume- A locally produced silica fume (in accordance with ASTM C 1240) was used. The chemical composition of the cements and pozzolans are given in Table 1.

Aggregates- Crushed gravels and sand were used as coarse and fine aggregates, respectively. The properties of aggregates are shown in Table 2.
Superplasticizer- The superplasticizer was a conventional melamine-based admixture with a solids content of 40% and a pH of 8.
Steel Reinforcing Bars- The steel reinforcing bars met the requirements of Grade 60 of ASTM A 615/A 615 M.

Concrete Mixtures

Mixture proportions of concrete are summarized in Table 3. Water-cementitious materials ratios(w/cm) were 0.35 and 0.4. The slump of the fresh concretes was kept between 5 to 8 cm and air content between 3 to 5%. 10x10x10 cm cubes were used for compressive strength and permeability tests. For carbonation test, 15x15x60 cm plain concrete specimens were used. In order to measure the corrosion potential, electrical resistance, and current density, steel bars or wire meshes were embeded at cover depths of 3.5, 5, and 7 cm.

After casting, all the specimens were covered with water-saturated burlap and plastic sheets. The specimens were moist cured for 7 days, followed by 14 days of air drying. Following this, the specimens were transported to the Gulf region and exposed in different conditions, namely in the air in coastal area, tidal region of the sea (cycling wetting and drying), and submerged in the sea. Control unreinforced specimens of each mixture were kept in standard laboratory curing conditions.

TEST METHODS

Half-cell potential (Ag/AgCl), polarization resistance, and cover concrete resistance were measured by a portable corrosion monitor. Polarization resistance and concrete resistance were measured by a DC impedence technique (Galvanostatic Pulse Technique). The applied currents were normally in the range of 10 to 100 μA and the typical pulse durations were between 5 to 30 seconds.
Micro-cell corrosion current was estimated based on the measured polarization resistance using the following expression:

$$I_{corr} = \frac{B}{R_P}$$

Where, I_{corr}= the micro-cell corrosion current density in μA/cm^2. B = an emprical constant assumed to be 25 mV for actively corroding steel and 50 mV for passive steel. R_P = the polarization resistance.

Carbonation depth of the specimens was measured by spraying a 1% phenolphthalein solution on freshly cut surfaces.

Acid soluble choloride-ion concentrations were determined at depths 0~10, 10~20, 20~30, 30~40, and 40~50 mm as per ASTM C1152/C 1152M-97.

The compressive strength and permeability of concrete mixtures under water pressure(per DIN 1048) were measured for control concrete specimens.

RESULTS AND DISCUSSIONS

Corrosion Potential, Electrical Resistance, and Micro-cell Corrosion

The corrosion potential, concrete electrical resistance, and micro-cell current density were measured at 90, 180, and 360 days. Test results are illustrated in Tables 4 to 8 and Figs. 1 to 14.

For the tidal region, concretes made with ASTM Type V cement, and slag cement with 5% silica fume showed more negative potentials. For concretes with ASTM Type II cement, Type II with 7% silica fume, and trass cement, less negative potentials were observed. Higher current density and lower electrical resistance were observed for the specimens made with ASTM Type V cement and cover thicknesses of 3.5 and 5 cm and for specimens made with slag cement with 5% silica fume having 3.5 cm cover, when compared with other specimens. For these concrete mixtures, current density increased and electrical resistance decreased with time. Concretes containing trass cement and ASTM Type II cement with 7% silica fume and (w/cm)=0.35 showed lower current density and higher electrical resistance. For greater cover depth, a tendency of lower negative potential, lower current density, and higher electrical resistance was observed.

All concrete mixtures showed no corrosion activity and very low current densities after 12 months of exposure in air. These concretes showed very significant electrical resistances. For this exposure condition, there were no significant differences in the concrete electrical resistance, corrosion current density and corrosion potential for concrete mixtures made with different cements, for the different cover depths, and various water-cementitious materials ratios.

For all of the concrete mixtures in a submerged condition and after 3 months, a very high negative potential was observed. However, the current densities were low. The results show that although chloride-ions have penetrated into the concrete and have reached the surface of reinforcement, due to the lack of oxygen, there is little micro-cell corrosion. For this condition, no significant difference in performance of concretes with different cements and w/cm was observed.

Carbonation Depth and Chloride-ion Concentration

In the tidal region and dry condition, carbonation depths in the specimens were negligible irrespective of the types of cement.

In the tidal region condition, for all concrete mixtures, concentration of more chloride-ion was observed at the surface, however it is reduced to a negligible value at deeper depth (see Fig. 15). Due to this high concentration of chlorides, especially for concrete with slag cement, steel bars with 3.5 cm of cover concrete, showed a high possibility of corrosion generally. Relatively more chloride-ions penetrated to a greater depth in concrete with ASTM Type V cement compared with Type II, trass, Type II with silica fume, and slag cement.

Compressive Strength and Permeability

Compressive strength test results for concrete mixtures under standard curing conditions are shown in Figs. 16 and 17. It can be seen that the compressive strength of all concrete mixtures is over 60 MPa at 360 days, regardless of w/cm ratio. Higher compressive strengths are expected at later ages for concretes containing pozzolans. Relatively higher strength was observed in the case of ASTM Type V, Type II and Type II + silica fume concrete mixtures when compared with trass and slag cement mixtures. However, concrete mixtures containing ASTM Type V cement showed undesirable performance in terms of corrosion.

Permeability under water pressure for all concrete mixtures was low irrespective of the type of cement and water-cement ratios used in this investigation (see Figs. 18 and 19)

CONCLUSIONS

1- For specimens exposed to the tidal region, specimens made with ASTM Type V cement (with 3.5 and 5 cm cover) and specimens made with slag and silica fume (with 3.5 cm cover) showed undesirable performance. The best performances was obtained for concrete mixtures containing trass cement and ASTM Type II cement + silica fume.
2- In totally submerged specimens, although corrosion potential is high and concrete electrical resistance is low, current density is negligible after 360 days.

3- All concrete mixtures showed no activity and very low current densities after 12 months of exposure in air. These concretes had high electrical resistance. For this exposure condition, there was no significant difference in the performance of concrete mixtures made with different cements and for various cover thicknesses.
4- In general, exposure in the tidal region was the worst condition for concrete mixtures when compared with the submerged and dry conditions.

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Table 1- Chemical Composition(%) of Cements and Cement Replacement Materials

	Type II	*Type V*	*Slag*	*Trass*	*Silica fume*
SiO_2	20.96	21.47	23.08	24.24	95.1
Al_2O_3	4.2	3.95	5.5	4.25	0.6
Fe_2O_3	4.6	4.4	3.4	3.8	1.1
MgO	3.4	2.3	3.4	3.8	0.6
CaO	61.88	63.84	60.2	58.8	1.02
SO_3	1.79	2.17	2.64	3.82	1.2
Na_2O+0.658 K_2O	1.47	1.01	1.08	1.26	-
C_3S	52.74	57.72	-	-	-
C_2S	20.31	18.01	-	-	-
C_3A	3.35	3.02	-	-	-

Table 2- Aggregate Properties

	Relative Density	Absorption (%)	Fineness Modulus
Sand	2.53	2.6	2.7
Gravel	2.56	1.46	6.5

Table 3- Mixture Proportions (per cubic meter)

Mixture	Cement type	CRM type	w/cm	Water (kg)	Cement (kg)	CRM (kg)	Sand (kg)	Gravel (kg)
A1	Type II	-	0.40	160	400	-	760	1050
A2	Type II	-	0.35	140	400	-	760	1050
B1	TypeV	-	0.40	160	400	-	760	1050
B2	Type V	-	0.35	140	400	-	760	1050
C1	Type II	Silica fume	0.40	160	372	28	760	1050
C2	Type II	Silica fume	0.35	140	372	28	760	1050
D1	Trass	-	0.40	160	400	-	760	1050
D2	Trass	-	0.35	140	400	-	760	1050
E1	Slag	Silica fume	0.40	160	380	20	760	1050
E2	Slag	Silica fume	0.35	140	380	20	760	1050

Table 4- Current Density and Concrete Resistance at 90 days; in the Dry Condition

Mixture	w/cm	Current ($\mu A/cm^2$)			Resistance (kohm)		
		3.5 cm	5 cm	7 cm	3.5 cm	5 cm	7 cm
A1	0.40	1.12	0.77	0.80	2.2	2.7	3.9
A2	0.35	0.53	0.41	0.22	3.9	4.5	4.3
B1	0.40	1.20	0.80	0.60	2.7	3.1	2.8
B2	0.35	0.60	0.54	0.41	4.5	5.5	5.0
C1	0.40	1.10	0.70	0.42	3.5	3.5	4.5
C2	0.35	1.50	0.80	0.36	3.5	4.0	4.0
D1	0.40	1.30	0.55	0.55	3.5	4.1	5.5
D2	0.35	0.72	0.53	0.45	4.0	5.5	5.8
E1	0.40	1.02	0.60	0.45	3.0	5.0	4.6
E2	0.35	0.70	0.70	0.45	5.0	5.0	5.2

Table 5- Current Density and Concrete Resistance at 360 days; in the Dry Condition

Mixture	w/cm	Current ($\mu A/cm^2$)			Resistance (kohm)		
		3.5 cm	5 cm	7 cm	3.5 cm	5 cm	7 cm
A1	0.40	0.22	0.17	0.20	4.0	4.5	5.0
A2	0.35	0.16	0.09	0.12	5.0	5.1	6.1
B1	0.40	0.29	0.25	0.17	2.1	2.9	3.5
B2	0.35	0.28	0.15	0.14	3.2	3.7	3.8
C1	0.40	0.28	0.19	0.14	5.4	5.7	6.0
C2	0.35	0.22	0.18	0.11	6.4	6.8	6.7
D1	0.40	0.20	0.18	0.19	5.6	5.8	6.0
D2	0.35	0.26	0.19	0.14	5.9	5.9	5.9
E1	0.40	0.23	0.23	0.19	4.1	5.0	5.5
E2	0.35	0.19	0.13	0.14	6.0	6.0	6.1

Table 6- Current Density and Concrete Resistance at 90 days; in the Tidal Zone

Mixture	w/cm	Current ($\mu A/cm^2$)			Resistance (kohm)		
		3.5 cm	5 cm	7 cm	3.5 cm	5 cm	7 cm
A1	0.40	0.96	0.88	0.59	1.8	1.7	1.6
A2	0.35	0.92	0.77	0.53	2.1	2.6	2.2
B1	0.40	2.84	1.72	0.70	1.0	1.9	1.9
B2	0.35	1.32	1.28	0.38	0.5	2.5	2.6
C1	0.40	0.95	0.80	0.43	1.8	2.0	2.1
C2	0.35	0.92	0.71	0.37	1.6	1.8	1.8
D1	0.40	1.60	1.05	0.97	0.8	1.9	2.1
D2	0.35	0.72	0.88	0.62	1.8	2.3	2.2
E1	0.40	1.80	1.56	1.36	1.4	1.3	1.7
E2	0.35	0.90	0.60	0.56	1.2	2.0	2.0

Table 7- Current Density and Concrete Resistance at 360 days; in the Tidal Zone

Mixture	w/cm	Current ($\mu A/cm^2$)			Resistance (kohm)		
		3.5 cm	5 cm	7 cm	3.5 cm	5 cm	7 cm
A1	0.40	1.84	1.38	1.79	0.8	1.2	1.2
A2	0.35	1.60	0.95	0.80	0.8	1.5	1.7
B1	0.40	3.08	2.51	1.86	0.4	0.5	0.7
B2	0.35	2.85	1.96	1.53	0.5	1.3	1.4
C1	0.40	1.18	1.66	1.10	1.2	1.3	1.3
C2	0.35	1.14	1.39	1.15	1.8	2.1	2.8
D1	0.40	1.40	2.35	1.23	1.1	1.3	1.5
D2	0.35	1.23	1.41	1.11	1.3	1.4	1.8
E1	0.40	2.58	1.79	1.28	0.9	1.4	1.8
E2	0.35	2.27	1.66	0.97	1.0	1.7	2.4

Table 8- Current Density and Concrete Resistance; in the Submerged Condition

Mixture	w/cm	90 days		360 days	
		Current ($\mu A/cm^2$)	Resistance (kohm)	Current ($\mu A/cm^2$)	Resistance (kohm)
		7 cm		7 cm	
A1	0.40	1.52	1.2	1.17	2.4
A2	0.35	1.15	2.0	0.50	1.8
B1	0.40	1.87	1.1	1.09	0.9
B2	0.35	1.95	1.2	0.70	1.0
C1	0.40	0.75	1.5	0.62	1.4
C2	0.35	0.40	2.2	0.38	1.9
D1	0.40	0.90	1.3	1.20	1.1
D2	0.35	1.00	1.6	0.90	1.5
E1	0.40	1.25	1.9	0.78	1.8
E2	0.35	1.10	2.2	0.51	2.0

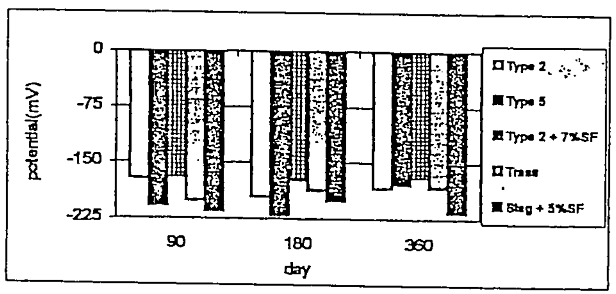

Fig. 1-Half-cell Potential versus Age; (w/cm)=0.35,cover=7 cm,submerged condition

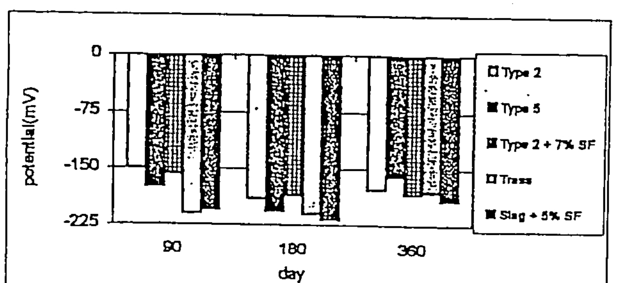

Fig. 2-Half-cell Potential versus Age; (w/cm)=0.4,cover=7 cm,submerged condition

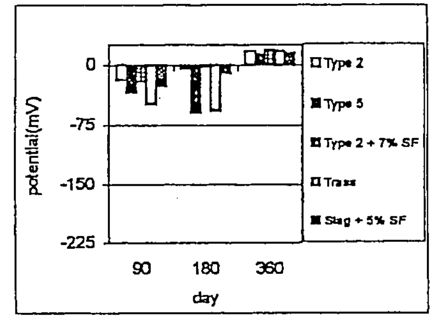

Fig. 3-Half-cell Potential versus Age; (w/cm)=0.4,cover=3.5 cm,dry condition

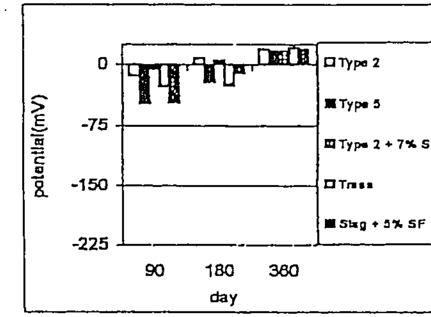

Fig. 4-Half-cell Potential versus Age; (w/cm)=0.35,cover=3.5 cm,dry condition

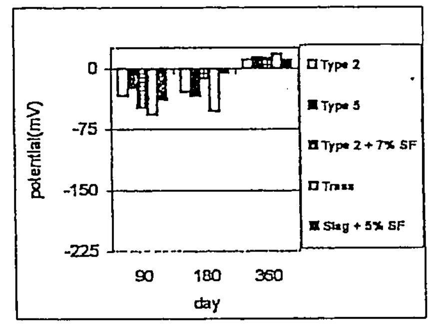

Fig. 5-Half-cell Potential versus Age; (w/cm)=0.4,cover=5 cm,dry condition

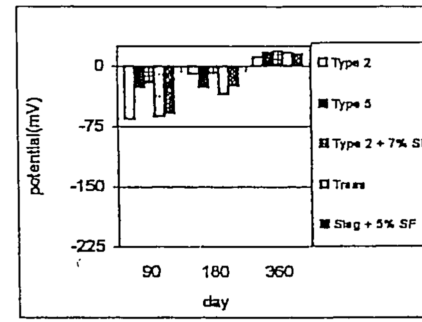

Fig. 6-Half-cell Potential versus Age; (w/cm)=0.35,cover=5 cm,dry condition

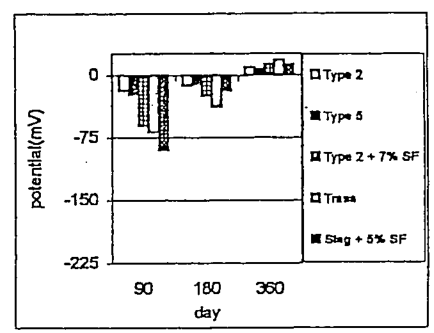

Fig. 7-Half-cell Potential versus Age; (w/cm)=0.4,cover=7 cm,dry condition

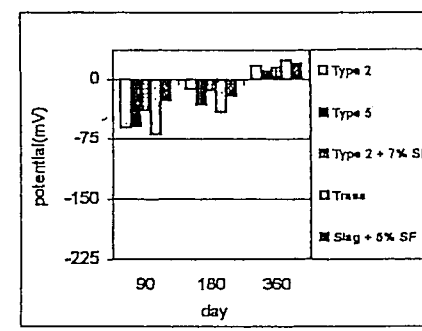

Fig. 8-Half-cell Potential versus Age; (w/cm)=0.35,cover=7 cm,dry condition

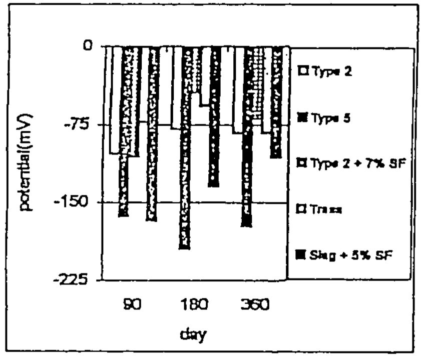

Fig. 9-Half-cell Potential versus Age; (w/cm)=0.4,cover=3.5 cm,tidal zone

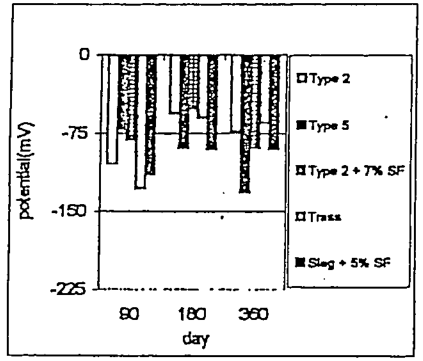

Fig. 10-Half-cell Potential versus Age; (w/cm)=0.35,cover=3.5 cm,tidal zone

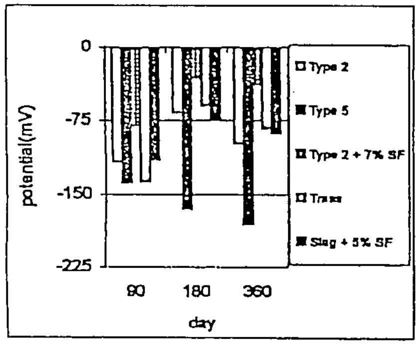

Fig. 11-Half-cell Potential versus Age; (w/cm)=0.4,cover=5 cm,tidal zone

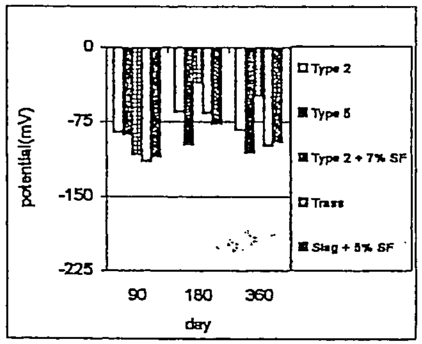

Fig. 12-Half-cell Potential versus Age; (w/cm)=0.35,cover=5 cm,tidal zone

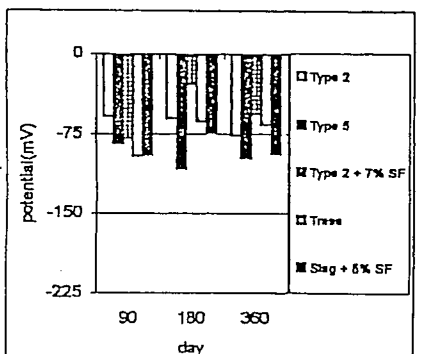

Fig. 13-Half-cell Potential versus Age; (w/cm)=0.4,cover=7 cm,tidal zone

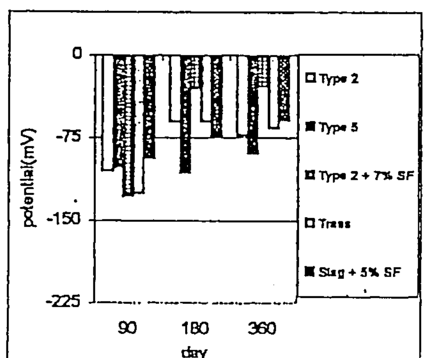

Fig. 14-Half-cell Potential versus Age; (w/cm)=0.35,cover=7 cm,tidal zone

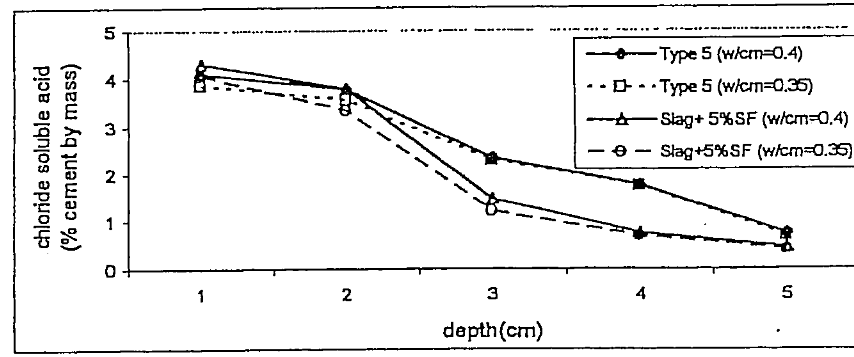

Fig. 15-Profile of Acid Soluble Chloride Ion Concentrations in Mortar; in the Tidal Region

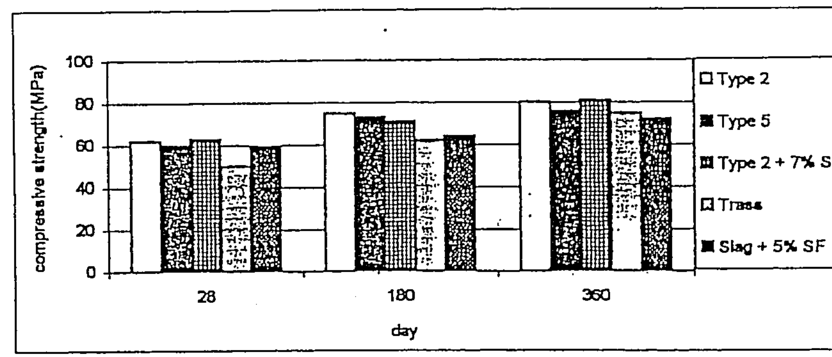

Fig. 16-Compressive Strength of Concrete versus Age; (w/cm=0.35)

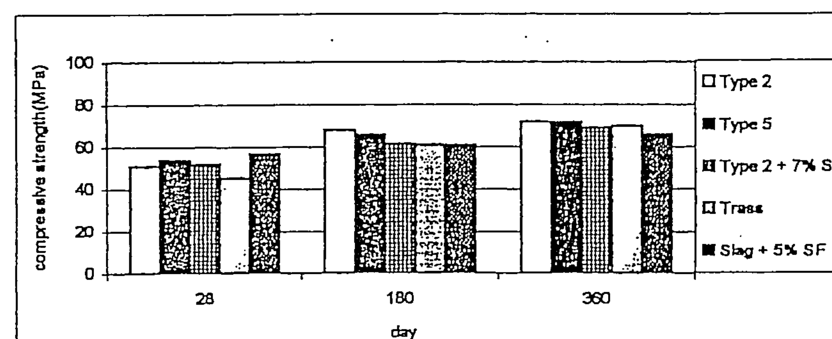

Fig. 17-Compressive Strength of Concrete versus Age; (w/cm=0.4)