MECHANICAL PROPERTIES AND DURABILITY OF HIGH PERFORMANCE PROTECRETE CONCRETE

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ABSTRACT

Deterioration of construction materials is of utmost concern in the civil infrastructure. New materials are being developed at a rapid pace to provide high performance, however, information on durability and useful life expectancy of these materials is scarce. Of particular interest is high performance concrete (HPC) which is widely used as a construction and repair material. Protecrete is a form of HPC that includes liquid additives: Mix Water Conditioner (MWC), and/or Concrete Densifier Sealer (CDS). These additives enhance the behavior of concrete in terms of mechanical properties and durability.

An intensive experimental study is underway at the University of Illinois at Chicago to evaluate the mechanical properties and long-term corrosion-resisting characteristics of HPC. A total of 518 (150 x 300 mm) cylinders, 216 (150 x 150 x 525 mm) beams, 12 (600 x 600 x 200 mm) reinforced slabs, and 8 (112.5 x 225 x 2400 mm) reinforced beams were cast. Three mixes were used incorporating MWC and fly ash. A fourth set of concrete specimens was prepared using MWC concrete sprayed under high pressure with CDS. The specimens were cured in the moisture room, in severe environment (15% by weight of NaCl solution) and in laboratory temperature. Tests incorporated the determination of compressive, splitting tensile and flexural strengths, modulus of elasticity, creep and shrinkage, chloride penetration and petrographic analysis at 7, 14, 28 days, 3, 6 months, and 1 year. MWC increases the workability of concrete, compressive strength and modulus of elasticity, while chloride penetration in severe environment was lowest.

KEYWORDS

High performance concrete; Protecrete; durability; mix-water conditioner; concrete densifier sealer; mechanical properties; petrographic analysis; chloride penetration; beams; cylinders.

INTRODUCTION

As structures become larger and more complex, materials of construction are required to meet more demanding standards of performance. To meet these standards, today=s products have to be improved with respect to strength, durability, and overall reliability. The good performance of concrete in service, including durability, is a major factor in its success as a construction material. The durability of reinforced concrete is influenced by the composition of concrete, the chemical composition and type of cement and reinforcement type. Deterioration of concrete in service occurs as a result of a variety of physical and chemical processes, such as attack by acids, sulfate, alkali-aggregate reactions, freeze-thaw cycles, etc.

Currently high performance concrete (HPC) is widely used as a construction and repair material in the civil infrastructure. The increasing use of HPC requires investigations of its various characteristics and properties. Although significant research was accomplished in this field, the behavior of high performance concrete is not yet as fully understood as normal concrete. Many aspects of HPC require further investigations and studies in order to reach an adequate understanding under various types of environmental and loading conditions.

In reinforced concrete, the most serious deterioration mechanisms are those leading to corrosion of the reinforcement and concrete deterioration. Reinforcement corrosion occurs only after carbonation of the surrounding concrete, penetration of chloride ions, or a combination of both. The reinforcement corrosion products occupy more volume than the initial reinforcement resulting in tensile cracking. The end result is spalling, delamination, and loss of structural use. HPC can have an excellent frost and salt scaling resistance, and its use seems particularly useful for protection against corrosion of reinforcing bars. By using low water-cement ratios, superplasticizers, mix water conditioner (MWC), concrete densifier sealer (CDS) and appropriate aggregates, cements, and mineral admixtures, it is possible to produce not only concretes with high compressive strengths, but also concretes with a very low porosity and extremely low permeability.

MWC has been reported to yield higher quality concrete at a fraction of the usual cost, quicker and easier placement which reduces finishing time, less shrinkage and cracking, stronger bond of concrete-to-steel, increased compressive strength. CDS has been reported to yield one-time permanent application that significantly densifies concrete, makes concrete virtually impermeable, improves thermal resistance, increases strength and lowers creep deformation potential.

The use of fly ash in concrete in the United States and Europe is necessitated from the environmental and economical aspects. However, its use in the Arabian Gulf and Asian countries is prompted by its technical advantages. Since fly ash has to be imported it is normally more expensive than Portland cement. Furthermore, the use of fly ash usually results in a reduction of compressive strength. The application of MWC and CDS enhance the durability of concrete at a fraction cost of other pozzolanic materials. This study encompasses the determination of the mechanical properties, petrographic analysis, detection of concrete deterioration and steel corrosion due to chloride penetration, creep and shrinkage of HPC.

RESEARCH SIGNIFICANCE

A wide variety of construction materials are being developed at a rapid pace. The performance and life expectancy of these materials are of utmost concern. The presence of a pozzolan in a hydrating cement paste can lead to substantial improvement in strength and durability. The application of MWC and CDS enhance the durability of concrete at a fraction cost of other pozzolanic materials without any reduction in compressive strength. The data obtained from this on going research will be helpful for selecting ideal concrete materials that are appropriate for aggressive environments.

BACKGROUND

The long term durability of concrete is a significant concern in the civil infrastructure. In practical applications of concrete, the emphasis has in many cases gradually shifted from the compressive strength to other properties of the material, such as high modulus of elasticity, high density, low permeability, and resistance to some forms of attack. If the steel corrodes actively, the corrosion rate value established will depend on concrete humidity content, oxygen availability, temperature and presence of aggressive substances such as chlorides, sulfates, etc.

The durability of concrete depends largely on its ability to resist the penetration of water and aggressive solutions. There are four major types of environmental distresses in reinforced concretes: corrosion of the reinforcement, alkali-aggregate reactivity, freezing and thawing deterioration, and attack by sulfates. Corrosion of the reinforcing steel is the most extensive. In each case, water or solutions penetrating into the concrete initiate or accelerate the distress, making costly repairs necessary.

In the United States and Canada, concrete is subjected not only to freezing and thawing cycles, but also to the application of deicing salts. These salts are responsible for the scaling of concrete surfaces, and for corrosion of reinforcement. The problems generated by deicing salts are of major importance, particularly because of the high repair costs associated with their use. Issa et al. (1994) based on their investigation of popout and scaling in concrete driveways reported that the high levels of chloride ions were caused by the ease of intrusion of deicing materials through the weak and porous concrete surface. Due to inadequate finishing, the concrete surface was not condensed enough and had a high permeability coefficient through which the deicing material intruded. This lead to weakness, porosity and a loss of durability, consequently resulting in concrete scaling or flaking of the finished surface. Fitzpatrick (1996) reported that the coastal salt laden air in the Arabian Gulf carries highly alkaline chloride ions as far as two miles inland. These chloride ions saturate concrete structures, destroying the ferric oxide coating that protects the reinforcement. The result is an expansion of the reinforcement, generally causing the surrounding concrete to crack. When a concrete spall or fracture is cut out and a patch made with new concrete installed, an electro-chemical reaction occurs as in an alkaline battery. Hence, corrosion is accelerated adjacent to the patched area. Funahashi (1990) reported that the rate of chloride ion migration into concrete is principally a function of concrete porosity, temperature, type of cation associated with chloride ions, and concentration of the surrounding salt.

Mehta and Monteiro (1993) found that the presence of a pozzolan in a hydrating cement paste can lead to the process of pore-size and grain-size refinement, which reduces both size and volume of voids, micro-cracks, and calcium hydroxide crystals, thus causing a substantial improvement in strength and impermeability. Page et al. (1986) reported that ordinary Portland cement with pulverized fly ash or blast furnace slag showed a lower chloride migration rate than ordinary Portland cement. Maslehuddin et al. (1990) found that addition of pozzolans or slag increases the corrosion-resisting characteristics of concrete. The corrosion rate of steel in concrete made with blast furnace slag cement was lower than in other concretes.

Al-Amoudi et al. (1994) investigated the effect of chloride attack on concrete. They placed the concrete specimens in a 15.7% chloride plus 2.1% of sulfate solution, which is commonly found in the coastal and continental sabkha brines in the Arabian Gulf countries. They found that chloride ions penetrate significantly faster than sulfates into the steel-concrete interface, hence influencing the corrosion mechanism related to corrosion initiation independently of sulfates. Al-Amoudi et al. (1996) also conducted an investigation to evaluate the performance of fly ash cement concrete in 5% sodium chloride solution. They found that the time-to-initiation of reinforcement corrosion in the 20% fly ash cement concrete specimens was 2.33 times that in the plain cement concrete specimens.

Ozyildirim (1998) reported that for bridge decks, low permeability is achieved by the use of a low water to cementitious material ratio (0.45 or less) and the use of pozzolans (fly ash or silica fume) or slag. With the use of a pozzolan or slag, the alkali content of cement can be as high as 1%.

The overall objectives of the study are to conduct the following tasks with respect to HPC with MWC, CDS, and fly ash, compared with normal concrete to:

X Evaluate the compressive, flexural and tensile strength and modulus of elasticity.
X Conduct chloride penetration test.
X Perform petrographic analysis to determine scale resistance.
X Study the creep and shrinkage characteristics.

EXPERIMENTAL PROGRAM

A description of specimen design, mix proportions, testing equipment, and testing procedures are presented in this section. The objective of this research was to study the mechanical properties and durability of high performance concrete. Test specimens were cast from three different mix designs selected as a result of a preliminary investigation. Prior to testing, the specimens were cured in three curing environments; normal environment (moisture room with 100% saturation and constant temperature of 23°C), severe environment (tank with 15% by weight sodium chloride solution) and outside in room temperature and moisture.

To fulfill the purpose of this study, more than 40 different mix designs were made prior to the selection of the three mix designs used in casting the test specimens. Water cement ratios (w/c) ranging from 0.43 to 0.64 and various ratios of gravel to sand were considered in the preliminary mix design. The optimum w/c ratio was 0.54 after considering a workable mix in addition to an acceptable slump. The water-cementitious material ratio (w/cm) was modified in order to obtain a workable mix for the concrete prepared with MWC and fly ash (15% by weight of cementitious materials). The slump obtained for this mix the same w/cm ratio (0.54) was excessive. Thus, the w/cm was reduced to 0.50 to obtain a workable mix. Different concrete mixes were prepared using Type I Portland cement, regular river sand with a maximum size of 4.75 mm, and coarse aggregates of 19 mm maximum size. The recommended amount of MWC added to the concrete mixes was 650 ml per 100 kg of cementitious materials. ASTM C 618 class C fly ash was used in one of the mixes. The fourth set of specimens (with MWC) was sprayed under high pressure with CDS immediately after demolding. The mix proportions of concrete are presented in Table 1.

Table 1. Mix proportions

Mix design description	Mix proportions (kg per m^3)					MWC (L/m^3)	Slump (mm)
	Cement	Fly ash	Water	Sand	Coarse aggregate		
Control mix	354	-----	191	866	990	-----	87.5
MWC	354	-----	191	866	990	2.31	137.5
MWC with fly ash	302	53	178	871	996	2.31	100

Specimen Preparation and Configuration

A total of 518 (150 x 300 mm) cylinders, 216 (150 x 150 x 525 mm) beams, 12 (600 x 600 x 200 mm) reinforced slabs, and 8 (112.5 x 225 x 2400 mm) reinforced concrete beams were cast. The specimens were demolded 24 hours from casting. The number of specimens cast for the normal environment (moisture room) is presented in Table 2. A similar number of specimens were cast for severe environments. Four additional slabs were cast for the severe environment to be used for coring purposes. Fifty-six cylinders and 24 beams were made with MWC, sprayed under high pressure with CDS and kept outside subject to room temperature and moisture. In addition, 14 cylinders were cast for creep and shrinkage measurements.

Curing and Environmental Conditions

In order to evaluate the environmental impact on the mechanical properties and durability of HPC with MWC and CDS, the specimens were cured in the following three curing environments prior to testing:

1. Normal environment (moisture room with 100% saturation and a constant temperature of 23° C) 24 hours from casting time until testing.

2. Specimens cured in normal environment (moisture room with 100% saturation and a constant temperature of 23° C) 24 hours from casting for 7 days. Then, they were cured in severe environment (tank with 15% by weight sodium chloride solution) until testing.

3. Specimens cured under laboratory or room temperature and moisture until testing.

Table 2. Specimens under normal (room moisture) or severe environment

Type of concrete	Reinforced slabs 600 x 600 x 200 mm (RCT*)	150 x 300 mm Cylinders				Flexural beams 150 x 150 x 525 mm	Reinforced beams 112.5 x 225 x 2400 mm
		Compressive	Splitting tensile	Modulus of elasticity	Petrographic analysis		
Control	1	24	24	4	4	24	1
MWC	1	24	24	4	4	24	1
MWC with CDS	1	24	24	4	4	24	1
MWC with fly ash	1	24	24	4	4	24	1

* Rapid chloride test (resistance of concrete to chloride ion penetration)

Figures 1 and 2 show the specimens cured in normal and severe environments, respectively.

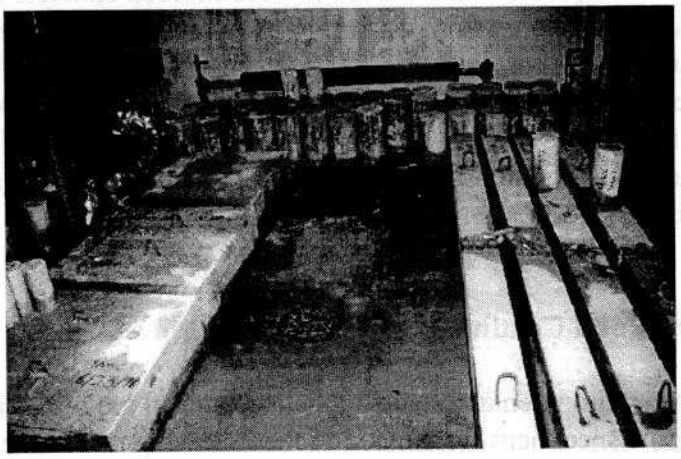

Fig. 1. Specimens in normal curing environment

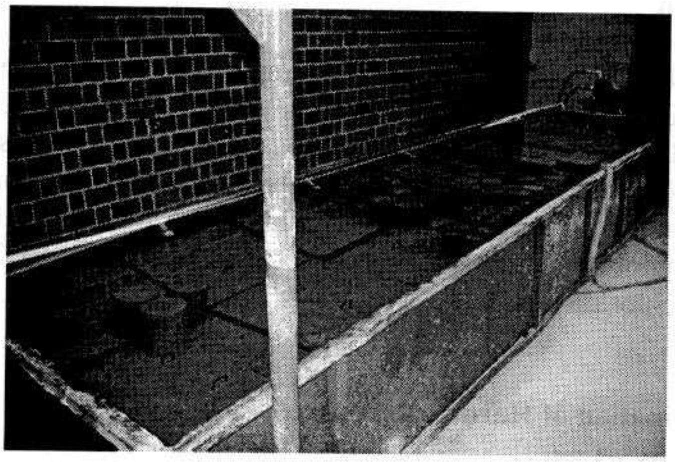

Fig. 2. Specimens in severe curing environment

TESTING PROCEDURE

In order to determine the compressive (ASTM C39) and splitting tensile strength (ASTM C496), 4 (150 x 300 mm) cylinders from each concrete type from the 3 different environments were tested for each type of ASTM method. The flexural tensile strength was measured using third-point loading, 4 (150 x 150 x 525 mm) prismatic concrete beams from each concrete type from the 3 different environments were loaded according to ASTM C78. The static modulus of elasticity for a material under tension or compression is given by the slope of the stress-strain curve for concrete under uniaxial loading. Three (150 x 300 mm) cylinders from each concrete type from the 3 different environments were instrumented with strain gages on the longitudinal axis and tested at 28 days. Figure 3 is a typical stress-strain diagram of concrete made with MWC.

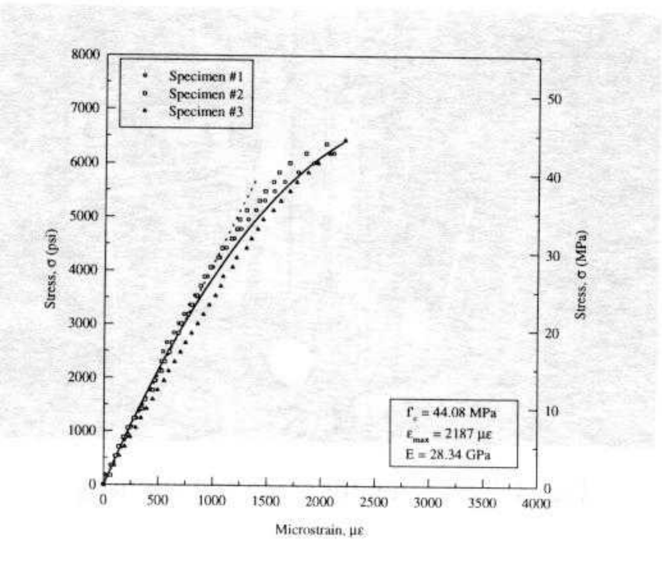

Fig. 3. Typical stress-strain diagram for concrete made with MWC

Chloride Penetration

The standard AASHTO T 259, Resistance of Concrete to Chloride Ion Penetration was used to determine chloride diffusion. The Rapid Chloride Test (RCT) provides a reliable and fast method of measuring the acid soluble chlorides. The test has a similar precision as a standard laboratory titration test (ASTM C114). In this test, slabs from both environments (normal and severe) were tested for chloride ion penetration at different depths across the slab thickness. Samples were taken at three different locations and dust was collected at depths of 5, 10, 20, 30, 40, 50, 70, and 90 mm to obtain the chloride profile.

Petrographic Examination of Hardened Concrete

A quantitative determination of concrete constituents was carried out using an automated concrete analysis system (CAS 2000). Samples were cut from each set of specimens from the 3 different environments at 28 days according to ASTM C856 standards. All scratches and unwanted debris were polished off. The linear-traverse method with a magnification of 50x was used.

Creep and Shrinkage

Many concrete structures are subjected to sustained loads, therefore, they exhibit time-dependent deformation in addition to the initial elastic strain and strain due to shrinkage. Long-term deflections, cracking and prestress losses are major consequences of creep and shrinkage in concrete structures. Fourteen cylinders (MWC and control specimens) are being tested in the same environmental and loading conditions to investigate the effect of creep and shrinkage in HPC. Each specimen was instrumented with two surface strain gages in addition to two mechanical strain gages for strain measurements. The creep specimens are loaded in series using special creep racks (three specimens in each rack (Fig. 4)). The total creep is calculated by subtracting the initial elastic strain and shrinkage strain from the total strain.

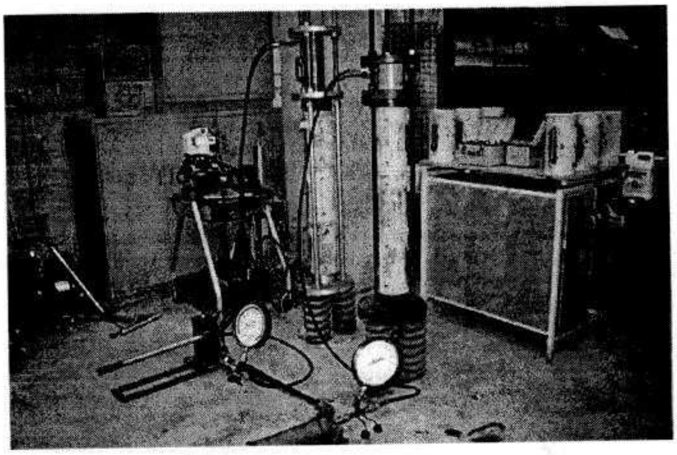

Fig. 4. Test setup for creep and shrinkage

TEST RESULTS AND DISCUSSION

Concrete specimens that were prepared with three different mixes were tested for compressive, splitting tensile, and flexural strength. An additional set of specimens that included MWC and sprayed with CDS was also tested. These specimens were cured in three different environments. The period of testing covered was 7, 14, and 28 days. Additional testing will be conducted at 3, 6 months, and 1 year. The results for the creep and shrinkage study are at the preliminary stage.

Workability

Inspection of Table 1 reveals that addition of MWC increases the slump from 87.5 to 137.5 mm. This increase in slump greatly enhanced the workability of the concrete mix through increased lubricity as well as resulting in a better surface finish and improving aesthetic appearance. Neither bleeding nor segregation was observed in any of the mixes with MWC. MWC also reduced plastic separation and improved surface abrasion resistance.

Mechanical Properties

Compressive, splitting tensile and flexural strengths and modulus of elasticity of specimens tested at 7, 14 and 28 days are shown in Table 3. A well established trend was observed for compressive strength of all specimens tested as shown in Fig. 5. Inspection of Table 3 shows a considerable increase in compressive strength for specimens prepared with MWC followed by specimens prepared with MWC and fly ash, and specimens prepared with MWC and sprayed with CDS. Control specimens showed the lowest compressive strength of all four types of concrete. A decrease in compressive strength for the specimens cured at laboratory temperature was noticed. Generally, the compressive strengths for all specimens cured in normal environment were higher than the specimens cured in severe environment. Furthermore, MWC specimens proved to be effective in both environments, which indicates that MWC can provide an adequate strength to the mix. The specimens sprayed with CDS exhibited a decrease in strength at the early stages of curing as shown in Table 3. However, the strengths increased at the later stages. This phenomena is attributed to the fact that CDS seals the moisture within the specimen, i.e., it does not allow the intrusion of moisture in or out of the specimen. For instance, the splitting tensile strength is initially (7 and 14 days) lower for the CDS specimens than the control specimens (6%), while this strength increases (6%) at 28 days.

Inspection of Table 3 also reveals that the modulus of elasticity at 28 days for the MWC specimens was the highest among all four types of concrete, followed by specimens prepared with MWC and fly ash, MWC sprayed with CDS, and control specimens. The modulus of elasticity of the specimens in the severe environment was lower than those in the normal environment with the same trend mentioned above. Inspection of Table 3 also reveals that splitting tensile and flexural strengths for the control specimens under 3 different environments were the lowest among all four different types of concrete. The lower strengths associated with the specimens prepared with MWC and fly ash are attributed to the lower water-cementitious material ratio. The strengths are expected to increase after a period of three months due to the nature of fly ash, which densifies the concrete. These tests are ongoing where more tests will be conducted at 3 months, 6 months, and 1 year.

Table 3. Mechanical properties of concrete specimens cured under normal environment, severe environment and laboratory or room temperature

		Environmental Condition								
		Normal (moisture room)				Severe (15% NaCl by weight)				Room temp.
Mechanical Property	Days	Control	MWC	MWC with CDS	MWC with Fly Ash	Control	MWC	MWC with CDS	MWC with Fly Ash	MWC with CDS
Compressive Strength (MPa)	7	30.0	33.3	31.1	32.4	30.0	33.3	31.1	32.4	26.3
	14	37.8	39.6	36.4	39.1	36.7	38.7	34.9	36.5	30.5
	28	42.6	45.5	44.1	44.2	41.0	43.9	40.7	42.8	35.2
Splitting Tensile Strength (MPa)	7	1.50	1.52	1.39	1.45	1.50	1.52	1.39	1.45	1.49
	14	1.62	1.66	1.53	1.69	1.42	1.64	1.64	1.50	1.63
	28	1.83	1.84	1.94	1.86	1.78	1.88	1.88	1.81	1.78
Flexural Strength (MPa)	7	3.63	3.67	3.42	4.31	3.50	3.67	3.42	4.31	3.88
	14	4.48	4.47	3.85	5.26	4.93	4.86	5.34	5.85	3.96
	28	5.15	5.33	4.16	5.77	5.27	5.34	6.11	6.68	4.25
Modulus of Elasticity (GPa)	28	29.2	32.4	30.8	32.0	23.4	28.3	27.9	28.0	23.1

Chloride Content

The chloride contents at different depths along the slab thickness of concrete from all four different types of concrete and environmental conditions at 28 days are plotted in Fig. 6. The chloride content for the specimens cured in normal environment ranged between 0.014 and 0.032%. For the specimens in severe environment, the chloride content range was between 0.013 and 0.67%. It is clear from Fig. 6 that chloride penetration in saline environment in specimens with MWC is lower than those specimens without MWC. This phenomena is yet to be investigated at the long term range of 3, 6, and 12 months.

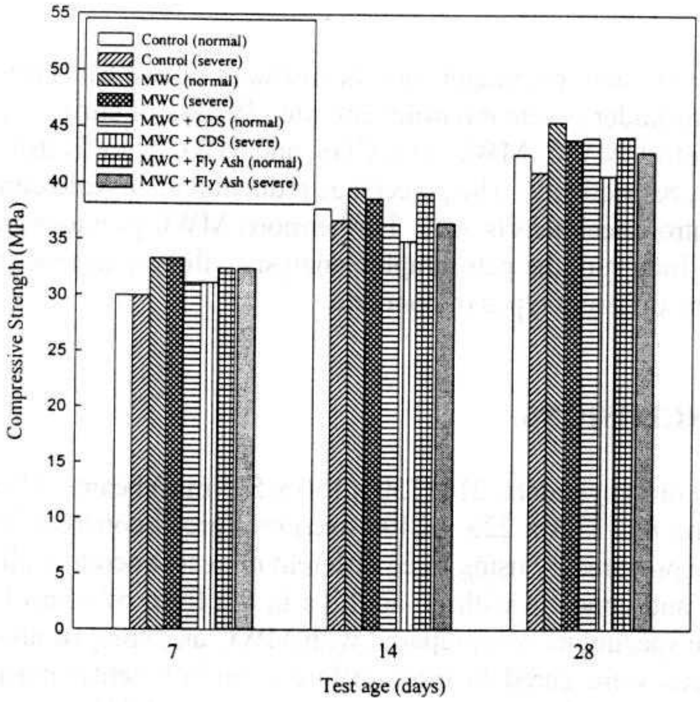

Fig. 5. Comparison of compressive strengths of specimens cured in different environments

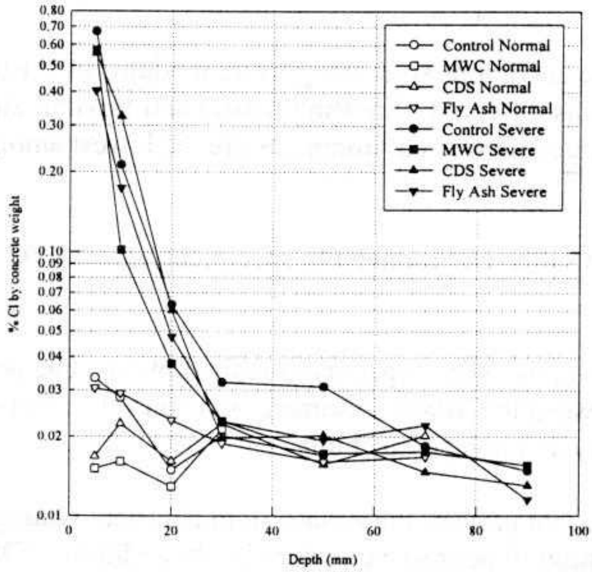

Fig. 6. Comparison of chloride penetration in specimens cured in different environments

Petrographic Analysis

The results for the air-void system parameters are the averages of two trials for all four types of concrete for the specimens under severe environment after 28 days of curing. The average void contents found for the control, MWC, MWC with CDS, and MWC with fly ash specimens, were 2.07, 1.04, 1.88, and 1.81, respectively. The percentage reduction in air-void content between the MWC specimens and control specimens is 50%. Furthermore, MWC provides greater density and less permeability. In the long run, the petrographic analysis will help in assessing the effect of severe environment on the different types of concrete.

SUMMARY AND CONCLUSIONS

A total of 518 (150 x 300 mm) cylinders, 216 (150 x 150 x 525 mm) beams, 12 (600 x 600 x 200 mm) reinforced slabs, and 8 (112.5 x 225 x 2400 mm) reinforced concrete beams were cast. Concrete specimens were prepared by using three different mixes: concrete with MWC, concrete with MWC and fly ash, and concrete with no additive in the form of control specimens. An additional set of concrete specimens was prepared with MWC and sprayed under high pressure with CDS. The specimens were cured in three different environments: normal environment (moisture room with 100% saturation under constant temperature of 23° C), severe environment (tank with 15% by weight of sodium chloride solution) and in laboratory or room temperature. Based on the results obtained from the ongoing research, the following conclusions can be drawn:

1. Addition of MWC increased the slump, which greatly enhanced the workability of the mix through increased lubricity as well as yielded a better surface finish and improved aesthetic appearance.

2. A considerable increase in compressive strength and modulus of elasticity for specimens prepared with MWC was observed. Splitting tensile and flexural strengths for control specimens under the three different environments are the lowest among all four different types of concrete.

3. Chloride penetration in saline environment in specimens with MWC is lower than those without MWC.

4. Percentage of air voids in the MWC specimens is the lowest. The percentage reduction in air-void content between the MWC specimens and control specimens is 50%. MWC provides greater density and less permeability.

5. The use of CDS as a sealant protects the surface from abrasion, scaling, deterioration, and preventing the penetration of aggressive materials. In addition, CDS provides a better surface appearance.

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