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Transport and Mechanical Characteristics of Corrosion-Inhibited High- Strength Self-Compacting Concrete

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Abstract: *This paper is on the study of traditional silica fume (SG) self-compacting concrete (SCC) samples that was made as control and then incorporated with carboxylic inhibitor (SM) to study the transport, rheological and mechanical responses of the inhibited samples. Comparison with the respective SG control, showed that the carboxylic inhibitor resulted in the reduction of the homogeneity of the SM samples and there was the development of flaws that could have contributed to the reduction in strength of the SM samples. When the concentration of the inhibitor was increased from the basic content to 100% higher, there was a noticeable increase in the chloride migration resistance of the SM samples. The study also showed that the transit time of the ultrasonic pulse that was transmitted was slower in the carboxylic inhibited-samples.*

Keywords : *Chloride Migration; Mechanic Properties; Rheology; Self-compacting Concrete.*

I. INTRODUCTION

Chloride-induced corrosion is one of the major deteriorating agents leading to the degradation of reinforced concrete structures. The chloride from marine environments, de-icing agents, admixtures and even concrete constituents, can attack the steel in reinforced concrete and contributes not only to early deterioration but also to increased maintenance activities. At this point it should be pointed out that the protection strategy of many corrosion-inhibiting compounds seems satisfactory as far as staving off the initiation of corrosion in the first fifty years of reinforced concrete members. However, there is a plethora of important buildings that are established as monumental edifices (such as the Burj Al Arab, Dubai) and others that may form part of essential services (such as the Øresund Bridge, Sweden and the Sydney Harbour Bridge, Australia) that will require longevity. For over 50 years corrosion inhibitor has been used in traditional reinforced concrete to protect the steel from corrosion. Moreover, with the present international emphasis on sustainability and low carbon emission, more consideration is given to reinforced concrete design that will not just span decades but centuries. However, there are other issues that are pertinent to the use of corrosion-inhibited SCC. With rising sea levels and the greater incidence of storm surges leading to inundation of the built environment, the issue of the reduction/depletion of the inhibiting capacity of the concrete and the matter of self-healing of corroded reinforced concrete will be of greater concern.

In more recent years SCC was developed and it is reported as having the potential to produce a durable material [1] mainly by nature of the refinement [2] and relatively low level of porosity in the interfacial zone in its microstructure [3]. Currently, researches are advancing the design of SCC admixed with corrosion inhibitor with a view to combine the attributes of the individual materials in one product.

This paper will focus on the study of traditional silica fume (SG) self-compacting concrete (SCC) samples that was made as control and then incorporated with carboxylic inhibitor to study the transport, rheological and mechanical responses of the inhibited samples.

II. EXPERIMENTAL PROGRAMME

2.1 Materials

Self-compacting concrete samples were made with ordinary Portland cement CEM1 52.5R and with silica fume admixture. The gradings of the cement and silica fume powders are depicted in Fig. 1. The cement was donated by Castle Cement Ltd, UK. The silica fume was provided by Elkem, Norway. A carboxylic type corrosion inhibitor was used in the experiment. The carboxylic inhibitor is an organic migrating compound that is formulated with a high range water-reducing admixture and viscosity modifying agent. A polycarboxylic high range water-reducing admixture was used in SCC mixtures that were not admixed with the multi-phase corrosion inhibitor.

The concrete mixtures were proportioned with and without corrosion inhibitors as shown in Table 1. The silica fume SCC without inhibitor (SG) was made as the control for the carboxylic silica fume SCC (SM). The combined grading of the used aggregates is shown in Fig. 1. The basic corrosion-inhibited SCCs used the concentration of inhibitor that is exhibited in Table 1 but some samples were also made with 2x the basic concentration. After the mixing of the concrete, the fresh material was used for the slump flow tests and for the casting of cubes, prisms, cylinders. The samples were cast without vibration. After de-moulding, all concrete samples were cured until 28 days.

2.2 Tests

Compressive strength tests were carried out on 100 x 100 x 100 mm samples and three concrete cubes were used for the determination of compressive strength for each SCC sample. A Zwick universal testing machine was used to determine the flexural tensile strength of the concrete specimens. Four 100 x 100 x 500 mm prisms were used for the four point flexural tensile test. A PUNDIT (portable ultrasonic non-destructive digital tester) was used to determine the dynamic modulus of elasticity and other parameters of each of the SCC samples.. The non-steady state chloride migration test was done on 100 mm diameter x 50 mm thick specimens in accordance to NT Build 492 [4] test method. The reference [5] and real test set-up used in this study is shown in Fig. 2. The fractures surfaces of the samples were also characterized using the digital image analysis technique.

III. RESULTS AND DISCUSSION

3.1 Rheology and Mechanical Properties

Table 3 shows the slump flow and flow rate values of the inhibited SCC and the silica fume control as measured from the Abrams cone. All the slump flow measurements were greater than 550 mm – the minimum slump flow requirement for SCC (EFNARC, [6]).

The 28-day compressive strengths of the SCC samples are shown in Table 4. The compressive strength of the respective carboxylic SM samples were 37% less than the corresponding SG control samples. However, further comparison with the respective SG controls showed that the carboxylic inhibitor increased the 28-day tensile strength of the SM sample. The tensile strength of SM samples were approximately 42% higher than the respective SG samples. Therefore it is evident that there are other mechanistic-related variables that are affecting the strength of the inhibited SCC samples.

The other result that is shown in Table 4 is that of the PUNDIT test. When comparison is made with the respective control, the transit time of the ultrasonic pulse that was transmitted was slower in the carboxylic inhibited-samples (SM) and this contributed to close to 100 m/µs reduction in the velocity of the SM samples. The PUNDIT dynamic moduli of the samples are also provided in Table 4.

3.2 Transport Property

The coefficients of non-steady state migration of chloride D_{nssm} of 28-day SCC samples are shown in Table 5. The average measurement from three specimens was used for the D_{nssm} reading of each sample. The SM SCC had a D_{nssm} coefficient that was approximately 12% higher than that of the SG control. It was further shown that the D_{nssm} values of the SM samples increased by 84% above that of the respective SG samples as the concentration of inhibitor increased by 100%.

In the SM SCC samples, the D_{nssm} coefficients showed that the addition of the carboxylic inhibitor increased the transport of chloride ions in the concrete. The PUNDIT velocities also showed that the homogeneity of the SM samples was reduced and this facilitated a higher chloride migration. However, the difference in the D_{nssm} coefficients of the SM and the SG samples is very low.

3.1 Failure Pattern

Cracking of the SM sample showed a more meandering pattern than the pattern in the control SG sample, and there were a couple of cracks branching from the main cracks. The manner of cracking in the SM sample is attributed to the more heterogeneous structure (Table 3) that resulted from the use of the carboxylic inhibitor in the silica fume SCC. As cracks preferentially travel through the path of least resistance, the ITZ properties become of major importance for the behaviour of this concrete under compressive loading. The stronger ITZ in the SM SCC concrete would efficiently participate in transferring stress through the composite, resulting in a greater compression force.

When the fracture extended to the surfaces of the SG samples, the cracks appeared less gradually and the cracks were larger, which showed a fracture that is typical of brittle materials. There were also manifestations of transverse cracking in the silica fume samples. The typical fractured surfaces and calculated fractal dimensions of the samples are shown in Fig.3 and Fig.4, respectively. A higher fractal dimension for the SM SCC sample indicates that more energy was dissipated under compression loading compared to the SG SCC sample.

IV. FIGURES AND TABLES

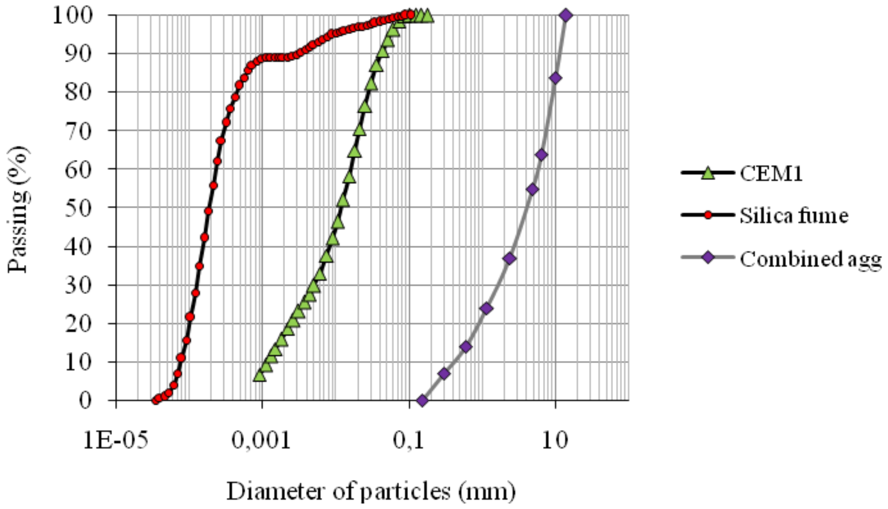
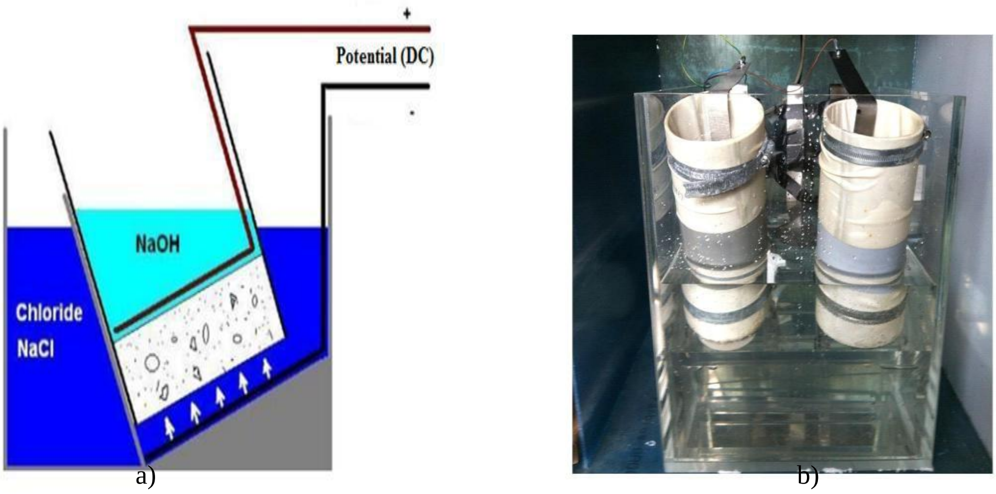
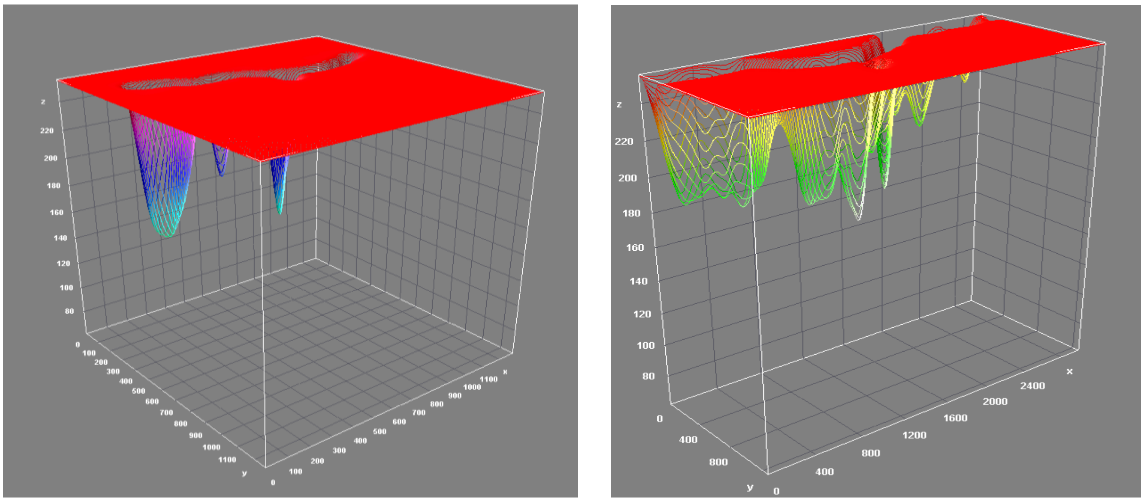


Figure 1. Particle size distribution of cement, silica fume and aggregate



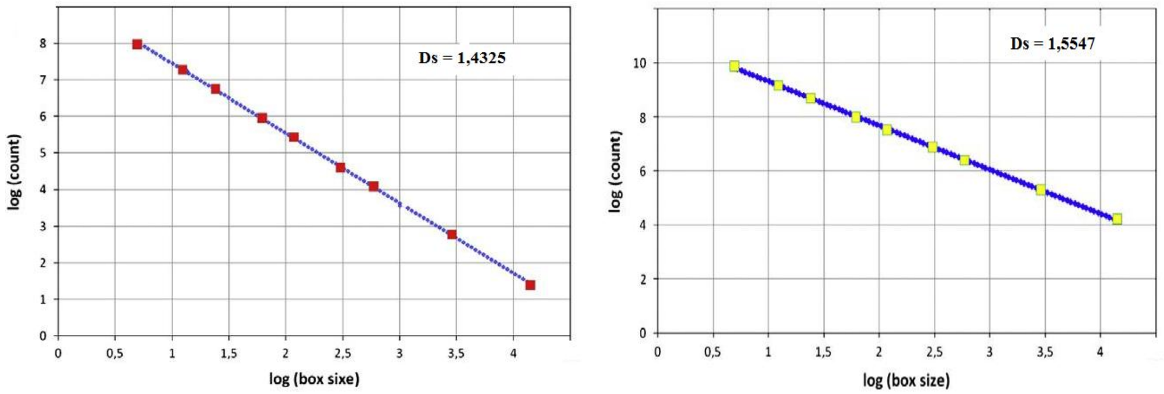
a) b)

Figure 2. The reference (a) and real (b) test set-up used in this study for chloride migration measurement



a-) b)

Figure 3. Typical fractured surfaces of the samples a-) SG sample and b-) SM sample



a-) **b-)**

Figure 4. Calculated fractal dimensions of the samples a-) SG ample and b-) SM sample

Table 1 Basic proportions of SCC mixtures

Materials	SG	SM
Cement - kg/m^3	542	542
Silica fume - kg/m^3	28	28
Coarse aggregate - kg/m^3	868	868
Sand - kg/m^3	778	778
Water - kg/m^3	180	180
W/P ratio (wt.)	0.32	0.32
Corrosion inhibitor* - %		0.300 approx. (carboxylic)
HRWRA# - %	1 (carboxylate)	

* Minimum recommended percentages based on based on mass of dry ingredients
# Minimum recommended based on total mass of ingredients

Table 2 Properties of Fresh Concrete

	SM	SG
Slump flow (mm)	780	610
Flow rate (s)	6	7

Table 3 Mechanical Properties of SCC

	SM	SG
Relative density	2.28	2.41
Compressive strength (MPa)	68	93
Flexural tensile strength (MPa)	12.2	8.6
Pundit velocity (m/µs)	4668	4766
Dynamic moduli of elasticity (GPa)	45.11	49.1

Table 4 Non-steady state chloride migration coefficients

SCC samples	SM	SG	SM(2x)
D_{nssm} x 10^{-12} (m^2/s)	1.9 ±0.4	1.7 ±0.5	3.5

V. CONCLUSION

The study of the inhibited SCC samples revealed that the homogeneity of the SM samples was reduced and this facilitated a higher chloride migration. This will, in turn, probably increase the propensity of the SM samples to corrosion. However, the difference in the D_{nssm} coefficients of the SM and the SG samples is very low and hence the protection strategy of the carboxylic compound was able to reduce the corrosion. The 28-day compressive strengths of the SM samples became less that the strength of the respective SG controls at the same age.

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