DETERMINING THE CHLORIDE RESISTANCE OF ECC SHOTCRETE

Yi-Wei Lin (1), Allan Scott (2), Derek Lawley (3), Liam Wotherspoon (1) and Jason M. Ingham (1)

(1) Dept. Civil and Environmental Engineering, University of Auckland, NZ

(2) Dept. Civil and Natural Resources Engineering, University of Canterbury, NZ

(3) Reid Construction Systems, NZ

Abstract

Engineered cementitious composite (ECC) shotcrete is a sprayable cement composite reinforced with synthetic fibres that exhibits a strain-hardening characteristic when subjected to load. The ductile behaviour of ECC makes it an ideal repair material for concrete structures as the strains from expansion of the original concrete structure can be accommodated.

Three tests were conducted to assess ECC's performance in resisting chloride ions and thereby determining its suitability as a repair material for concrete structures exposed to marine environments. The three tests conducted determined the total accessible voids, capillary suction rate and chloride diffusion coefficient of the material. Six variations of ECC mix designs (including a standard ECC mix with specified compression strength of 40 MPa) were tested as well as a 40 MPa concrete. The results showed that a standard ECC shotcrete had a significant improvement in chloride resistance when compared to the 40 MPa concrete. The chloride resistance further improved when a metallic soap additive was added to the ECC mix. It was concluded that ECC is a suitable repair material for concrete structures exposed to marine environments.

1 INTRODUCTION

Reinforced concrete bridge construction in New Zealand became common after the 1950s. Due to the nature of design and construction practice during this period, many of the bridges now have insufficient cover concrete when compared to the current New Zealand concrete code [1]. As a result of both insufficient specified cover thickness and loss of cover over time, many bridges now exhibit signs of reinforcement corrosion. To extend the service life of these deteriorated bridges, immediate remediation is necessary and can be categorised into two procedures. Firstly, removal of existing chloride ions and replacement of damaged steel reinforcement, and secondly, the application of new cover concrete to delay future chloride ingress. This study focused on the second step and investigated the effectiveness of sprayed Engineered Cementitious Composite as a cover concrete for repair work.

Engineered Cementitious Composite (ECC) is a cement composite reinforced with synthetic fibres. ECC exhibits a strain-hardening characteristic when subjected to tension through the process of matrix micro-cracking and the transfer of forces through any fibres that bridge the crack. The strain-hardening characteristic means that when applied to existing concrete substrate, the differential volume change between existing structure and ECC can be accommodated by ECC without spalling off the substrate. As a result of the straining capability, the effectiveness of ECC as a repair material has been thoroughly investigated in previous studies [2-4]

ECC is classified into two categories; self compacting cast ECC and sprayed ECC. In this study the focus was on sprayed ECC as it is a more economical application method because it does not require setup of formwork. A typical mix design of sprayed ECC is shown in Table 1, revealing that ECC does not have any large (>300 µm) aggregates in its constituent material. Because of the use of fine materials, ECC is able to achieve a denser structure than conventional concrete, making it more resistant to chloride ion ingress.

Table 1: Sprayed ECC mix design

Materials	kg/m^3
300 µm Sand	640
Portland Cement	760
CA cement	40
Type F Fly ash	240
Water	374
PVA Fibre	26
Additives (Superplasticiser and stabiliser)	0.3

2. EXPERIMENTAL INVESTIGATION

2.1 Materials

Six different ECC mix designs and a 40 MPa concrete were produced and subjected to durability testing, with detailed descriptions of each mix design provided in the following subsections. The 40 MPa concrete was selected as a datum comparison to the durability performance of ECC as the standard ECC shotcrete also has a specified compression strength of 40 MPa. To simulate the spraying process that would take place for repair work on existing concrete structures, all ECC mixes were sprayed into a 1 m high × 1 m long × 100 mm deep box that was placed vertically against a wall (see Figure 1a). After spraying the ECC mix into the box, it was left standing vertically for 24 hours before the ECC panel was extracted from the mould and then covered with a plastic sheet with the temperature maintained between 23±2°C. The concrete panel was cast directly into the box mould laid on the ground. All samples were cured and tested at 56 days. Prior to testing the panels were removed from curing and each panel was cut to obtain samples required for different tests (see Figure 1b).

(a) Spraying ECC into box (b) Panel cut up to extract samples

Figure 1: Sample preparation process

ECC-S

ECC-S is the standard ECC shotcrete provided by the supplier, where S stands for standard. The main constituents are identical to that listed in Table 1. The mix proportions are also similar to those used by [5]. ECC-S has been previously used in [6] as a strengthening material for masonry walls where bond to clay brick masonry surface was achieved without the use of any bonding agents or physical anchorages.

ECC-IFA

ECC-IFA has identical constituents to ECC-S with the exception that the fly ash ratio was increased to 40% of the cement content from 30% in ECC-S. The code IFA stands for Increased Fly Ash. The reason for increasing the fly ash content was because fly ash particles are small (ranging between 0.5 µm-100 µm), such that an increase in the amount of fly ash within the mix results in an increase in density, and therefore potentially a more impermeable composite.

ECC-CH

ECC-CH is similar to ECC-S, with the only modification being that half of the fly ash has been replaced with calcium carbonate. Calcium carbonate is an inert filler and therefore provides the same physical function (as a filler) as fly ash in ECC. However, fly ash and calcium carbonate do not share the same chemical function as calcium carbonate is not pozzolanic and therefore does not undergo further hydration as does pozzolanic materials such as fly ash. The primary reason for replacing half of the fly ash with calcium carbonate was to reduce cost, as calcium carbonate is a local material in New Zealand and is significantly cheaper than fly ash used in the mix, which was imported due to particle size consistency requirements, which was not available in fly ash produced in New Zealand.

ECC-Si
ECC-Si has a silane based water repellent added to the ECC-S mix. The silane based water repellent is typically used as a surface coated chloride resistance barrier and the effectiveness has been verified in [7]. However, in the case of ECC-Si the water repellent was spread within the whole composite instead of just coated on the surface. The effectiveness of incorporating silane water repellent in the ECC mix was previously tested on cast mixes of ECC [8], where a 90% reduction in the capillary suction was measured when water repellent was added to the mix.

ECC-Zn
ECC-Zn is the same mix as ECC-S except that a Zinc Stearate metallic soap additive was added to the mix design. The metallic soap has a hydrophobic (water repelling) nature and also provides a lubricating effect, which would reduce the chemical bond between the fibres and the cement matrix and therefore potentially provides increased strain capacity.

ECC-RH
ECC-RH is an alternative ECC mix (as oppose to ECC-S) provided by the supplier. The main objective of this mix is to be able to achieve thicker shotcrete layers in a short amount of time (less than 5 minutes as reported by the supplier). The code designation RH stands for Rapid Hardening. The main difference in the constituent material between ECC-RH and ECC-S is that fly ash has been completely replaced with calcium carbonate, and an increased amount of accelerators was used.

OCM-40
OCM-40 stands for Ordinary Concrete Mix, with a compressive strength of 40 MPa. The concrete mix was provided by a local ready mix concrete supplier with the mix design identical to what would be used for a 40 MPa structural concrete.

2.2 Methodology

Three tests were conducted to assess the performance of ECC as a chloride resisting barrier. The tests conducted were the ASTM C642 void test [9], ASTM C1585 sorptivity test [10] and ASTM C1556 bulk diffusion test [11]. The test sequence listed above also indicates the relative time it takes to conduct each test, from shortest to longest. The first two tests are indicative tests that provide a fast and economical method to determine the chloride resistance of the material. However, results of the indicative tests are only valid when they are consistent with the bulk diffusion test, which measures the chloride penetration depth in the sample directly. For each of the test, five samples were tested for each mix design.

ASTM C642 density, absorption and voids in hardened concrete

The ASTM C642 test measures the amount of air voids within a hardened concrete. The process involves oven drying a sample with a minimum volume of 375000 mm^3 (in this study cubes with volume of 75×75×75 mm each were used) until constant mass was achieved (less than 0.5% of change in mass within a 24 hour period). After the samples had been oven dried and the mass recorded, they were immersed in cold water until constant mass was achieved and the mass recorded. Lastly, the samples were placed in boiling water for 5 hours and left to cool for 14 hours and the final mass recorded. The change between oven dried mass and mass after immersion in boiling water defines the amount of voids within the hardened concrete.

ASTM C1585 sorptivity test

The ASTM C1585 sorptivity test measures the capillary suction rate of cement composites. Capillary suction is one of the three dominant mechanisms by which chlorides are transported into concrete. Cube samples were used in the sorptivity test, using the same dimensions as the samples used in the void test. Cube samples were extracted from the panels and each sample was placed in an environmental chamber for 15 days, where the temperature was maintained at 50±2°C and a saturated solution of potassium bromide was placed within the oven to control the relative humidity (RH) at 80±5%. Once removed from the environmental chamber, each surface of the cube (except the top and bottom) was sealed. A plastic sheet was placed around the top surface and tightened with elastic bands, while the bottom surface remained uncovered. The uncovered surface was then placed in contact with water.

ASTM C1556 bulk diffusion test

The ASTM C1556 bulk diffusion test determines the apparent chloride diffusion coefficient (the rate of chloride ingress) of the cement composite. As for the void and sorptivity tests, cube samples were extracted from the panels. With the exception of the bottom surface, all other surfaces of the samples were coated with polyurethane to prevent chloride ingress from surfaces other than the bottom surface. Samples were then immersed in a saturated solution of calcium hydroxide until constant mass was measured, following which the samples were immersed in NaCl solution with a concentration of 3.5% for a period of 35 days. After the samples were removed from the NaCl solution, the polyurethane coating the surface was ground off and samples were placed in a lathe. Layers were then ground off the sample at two millimetre increments and the powders collected (see Figure 2). Ten layers were ground off each sample so that the maximum depth the layers were ground off from was 20 mm. After all samples were ground off and collected, they were filtered through a 600 μm sieve so that the larger aggregates particles were removed as these typically contain no chloride particles, and would lower the apparent chloride content if they were kept within the sample. The larger particles contributed to approximately 10% of the total mass of the samples. 4±0.05 g of powder was extracted from each of the samples collected, with the method of extraction being adopted from [12], where samples were poured into a cone shape. The cone mass is then measured and cut into equal portions. The benefit of adopting this method is that the particle size distribution is consistent between the used and unused samples. If 4 g were poured directly out of the sample container then it is likely that only the lighter particles would be analysed. After 4 g was measured from a sample and placed in a beaker, the total acid soluble chloride concentration was determined by means of potentiometric titration with 0.1 M of silver nitrate. The chloride concentration against depth plot was then produced to determine the apparent diffusion coefficient.

Figure 2: Grinding layers of bulk diffusion samples

3. RESULTS

Void test

The results from all tests and the compression strength measured on all mixes are shown in Table 2, which shows that the majority of ECC-mixes had a void percentage of between 21.0 to 25.0%, which was relatively high when compared to a void percentage of 12% measured on the 40 MPa concrete. Studies conducted in [13] have also found the void percentage of high performance concrete (with 28 day compression strengths varying between 33.5 to 40.9 MPa) to be within the ranges of 10.2 to 12.0%, which verifies the percentages measured in this test. The higher percentage of voids measured in the ECC mixes was likely a result of the spraying process. As ECC is sprayed onto the wall, air is trapped within the mix material, and when the material has hardened the air remaining within the composite becomes the voids. However, there were fundamental differences in the voids, with the voids in the ECC mixes smaller and more uniformly distributed across the sample, while the voids in the concrete sample were significantly larger and more concentrated. Mix ECC-Zn had the lowest void percentage of 4.5%. From observation there was no distinct difference between the physical appearance of ECC-Zn and other ECC mixes. Therefore the metallic soap incorporated within the ECC-Zn mix was effective in repelling water, so even though the voids exist, water could not penetrate into the sample. The results of the void test indicate that ECC-Zn may have the best performance in resisting chloride penetration, while other ECC mixes will perform worse than concrete.

Table 2: Test results

Mixes	Void test results	Sorptivity test results		Bulk diffusion test results	Compression test result (MPa)
	Average void %	Initial sorptivity (mm/√min)	Secondary sorptivity (mm/√min)	Apparent diffusion coefficient ($10^{-12}m^2/s$)	
ECC-S	24.6	0.039	0.013	3.2	39.2
ECC-IFA	25.0	0.033	0.010	2.0	36.0
ECC-CH	21.4	0.027	0.0083	4.1	37.5
ECC-Si	21.0	0.025	0.0080	2.0	34.0
ECC-Zn	4.5	0.0027	0.0031	1.7	30.5
ECC-RH	22.3	0.036	0.016	13.4	56.8
OCM-40	12.0	0.019	0.0063	19.0	39.5

Sorptivity test

From Table 2, it can be observed that ECC-Zn had the lowest initial and secondary sorptivity. It was also physically observed that ECC-Zn was the only mix where no water vapour was observed on the top surface of the sample (where a clear plastic sheet was used to prevent water from escaping), which indicates that the amount of water uptake into the sample was minimal. The results obtained for the ECC mixes and for the concrete mix correspond to the results obtained using the void test, where the other ECC mixes had higher sorptivity than concrete. This observation suggests that there is a relationship between void testing and the sorptivity test, andwhen the results from the two tests are plotted together the relationship was linear and had a regression of 90.5%.

Bulk diffusion test

The apparent diffusion coefficient of the mixes tested is shown in Table 2, showing that results from the bulk diffusion test do not correspond to the results obtained from the indicative tests. All the ECC mixes had a lower apparent chloride diffusion coefficient than that of concrete, thus indicating that ECC is more resistant to chloride ingress when compared with concrete. In the indicative tests only ECC-Zn showed better performance than concrete.

With the exception of ECC-RH, all ECC mixes had an apparent chloride diffusion coefficient of approximately an order of magnitude lower than the concrete mix, with mix ECC-Zn having the best performance. While mixes ECC-IFA and ECC-Si also had a comparable apparent diffusion coefficient to ECC-Zn, ECC-Zn also demonstrated the lowest void percentage and capillary suction rate in the indicative tests. Therefore it was determined that ECC-Zn should be selected as the ECC mix to be used as a chloride resisting barrier for concrete structures.

4. CONCLUSIONS

ECC is effective as a chloride resistance barrier when compared with 40 MPa concrete. The standard ECC mix has a chloride diffusion coefficient that is less than 20% of the diffusion coefficient of concrete. The diffusion coefficient further reduced to 10.5% when either fly ash was increased or silane water repellent was added. ECC was most effective when metallic soap was incorporated in the mix design, which reduced the diffusion coefficient to 8.9% of the concrete diffusion coefficient.

The two indicative tests (void and sorptivity) cannot be used alone to indicate the chloride resistance of a material but they can be used as a quality assurance test if a correlation is established with the bulk diffusion test. There is also a positive correlation between the ASTM C642 void test and the ASTM C585 sorptivity test and the relationship is linear.

ACKNOWLEDGEMENTS

The authors would like to thank David Nevans, Richard Leary, Gareth Williams and Mason Pirie from Reid Construction Systems for the assistance to produce the ECC samples. The authors would also like to thank Mike Botherway from Atlas Concrete for providing the concrete sample used in this study and thank Steve Lowery for cutting of the samples. Lastly the authors would like to thank the Foundation for Research, Science and Technology for the funding of this study.

REFERENCES

[1] NZS (2006). "Concrete Structures Standard Part 1-The Design of Concrete Structures." NZS 3101:2006. New Zealand Standards. Wellington, New Zealand.

[2] Kanda, T., Saito, T., Sakata, N. and Hiraishi M. (2003). "Tensile and Anti-Spalling Properties of Direct Sprayed ECC." *Journal of Advanced Concrete* **1**(3): 269-282.

[3] Li, V. C., Horii, H., Kabele, P., Kanda, T and Lim, Y.(2000). "Repair and retrofit with engineered cementitious composites." *Engineering Fracture Mechanics* **65**(2-3): 317-334.

[4] Lim, Y. M. and Li, V. (1997). "Durable repair of aged infrastructures using trapping mechanism of engineered cementitious composites." *Cement and Concrete Composites* **19**(4): 373-385.

[5] Kim, Y., Kong, H-J. and Li, V. (2003). "Design of Engineered Cementitious Composite Suitable for Wet-Mixture Shotcreting." *ACI Materials Journal* **100**(6): 511-518.

[6] Lin, Y., Lawley, D. & Ingham, J. M. (2010). Seismic Strengthening of an Unreinforced Masonry Building Using ECC Shotcrete." 8th International Masonry Conference. Dresden, Germany**:** 1-10.

[7] SINTEF Building and Infrastructure. (2008). Effect of Surface Treatment on Chloride Ingress and Carbonation in Concrete Structure - State of Art. Oslo**:** 1-38.

[8] Martinola, G., Bauml, M. F. and Wittmann F. (2002). "Modified ECC Applied as an Effective Chloride Barrier." JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC) - Applcations and Evaluation, Takayama, Japan.

[9] ASTM (2006). "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete." *ASTM C642-06*. Philadelphia, American Society for Testing and Materials.

[10] ASTM (2004). "Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic Cement Concrete." *ASTM C1585-04*. Philadelphia, American Society for Testing and Materials.

[11] ASTM (2004). "Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixture by Bulk Diffusion." *ASTM C1556-04*. Philadelphia, American Society for Testing and Materials.

[12] ASTM (2003). "Standard Practice for Reducing Samples of Aggregate to Testing Size." *ASTM C702*. Philadelphia, American Society for Testing and Materials.

[13] Bharatkumar, B., Narayanan, R. Raghuprasad, B. and Ramachandramurthy, D. (2001). "Mix proportioning of high performance concrete." *Cement and Concrete Composites* **23**(1): 71-80.