Durability enhancements using fabric formwork

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ABSTRACT
By replacing orthogonal concrete moulds with flexible sheets of fabric the construction of optimised, variable cross section concrete elements that provide material savings of up to 40% when compared to an equivalent strength prismatic member is now possible. This paper details the results of recent tests undertaken at the Building Research Establishment Centre for Innovative Construction Materials (BRE CICM) at the University of Bath that demonstrate additional durability advantages for fabric cast concrete.

Using accelerated test methods a 50% reduction in the non-steady state chloride diffusion coefficient and a 51% reduction in the coefficient of carbonation were found when comparing fabric and timber cast concrete samples. The combined results demonstrate that fabric formwork may be used to create optimised structures where strength and durability are provided only where they are needed.

Key words: Fabric formwork, durability, carbonation, chloride ingress.

1 INTRODUCTION

Fabric formwork describes a construction method and design philosophy by which optimised concrete elements of a variable geometry are created (Orr *et al.*, 2010). Often used in underwater and offshore construction fabric formwork allows complex shapes to be cast and its simplicity has generated significant architectural attention. Research into the structural behaviour and construction of fabric formed elements has been undertaken in Europe and North America, with significant savings in concrete being achieved through simple optimisation routines (Lee, 2010). Less work has considered the changes in concrete properties that arise as a result of casting concrete into fabric formwork (Figure 1).

By allowing water and air to be expelled from a concrete element as it cures, permeable formwork systems provide concrete with improved durability due to its denser microstructure and reduced *water:cement* ratio in the cover zone (McCarthy *et al.*, 2001). However, commercially available permeable formwork systems require the fixing of permeable and draining layers to the inside of conventional structural formwork. The use of a single flexible fabric formwork system for the creation of optimised, durable structures therefore offers real advantages for designers.

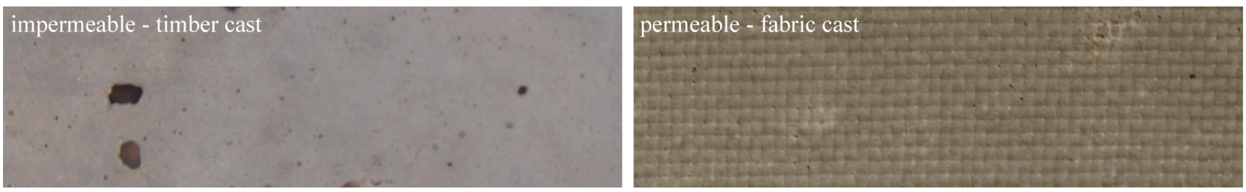

Figure 1 – Identical concrete cast in impermeable (left) and fabric (right) moulds.

2 DURABILITY TESTING

Accelerated testing of resistance to carbonation and chloride ingress was undertaken. The same concrete mix and fabric was used in all tests. The concrete mix used had an average compressive strength at 28 days of 43.8MPa, and the fabric was a woven polyester fabric with a pore size of 423µm and tensile strength in warp and weft directions of 54kN/m.

2.1 Series 1 – Carbonation resistance

Steel reinforcement is protected from corrosion by the formation of an oxide film on its surface as a reaction to the alkaline environment inside concrete. However, the penetration of atmospheric carbon dioxide into any exposed concrete surface will reduce the protective alkalinity to such a level that corrosion of the reinforcement may begin. The process of carbonation is primarily caused by the diffusion of carbon dioxide gas through the structure, as described by Liang *et al.* (2002).

In Series 1, the relative resistance to carbonation of concrete cast in fabric and concrete cast against steel was compared. Modified 100mm cube moulds were used in which one face was cast against a drained fabric surface. The resulting specimens were cured in water (20ºC ±2ºC) for 14 days, before being cured in air (50±5% relative humidity, 20ºC ±2ºC) for a further 14 days. Four sides of the cube that were not to be tested were then coated in paraffin wax before the specimens were exposed to an atmosphere containing 4% carbon dioxide with a relative humidity of 60±5% by placing them in a carbonation chamber. The available literature (Dunster, 2000) suggests that under such a regime, one week in the carbonation chamber is equivalent to 12 months curing under natural exposure conditions. Carbonation depths were recorded at 7, 14, 28, 90 and 180 days (representing 1, 2, 4, 12.8 and 25.7 years) exposure by splitting the cubes in half. The exposed surfaces were then sprayed with a Phenolphthalein solution to reveal the carbonation depth. Carbonation depths at four equally spaced points along each of the exposed faces were recorded using calipers. The results of 240 such measurements are summarised in Figure 7.

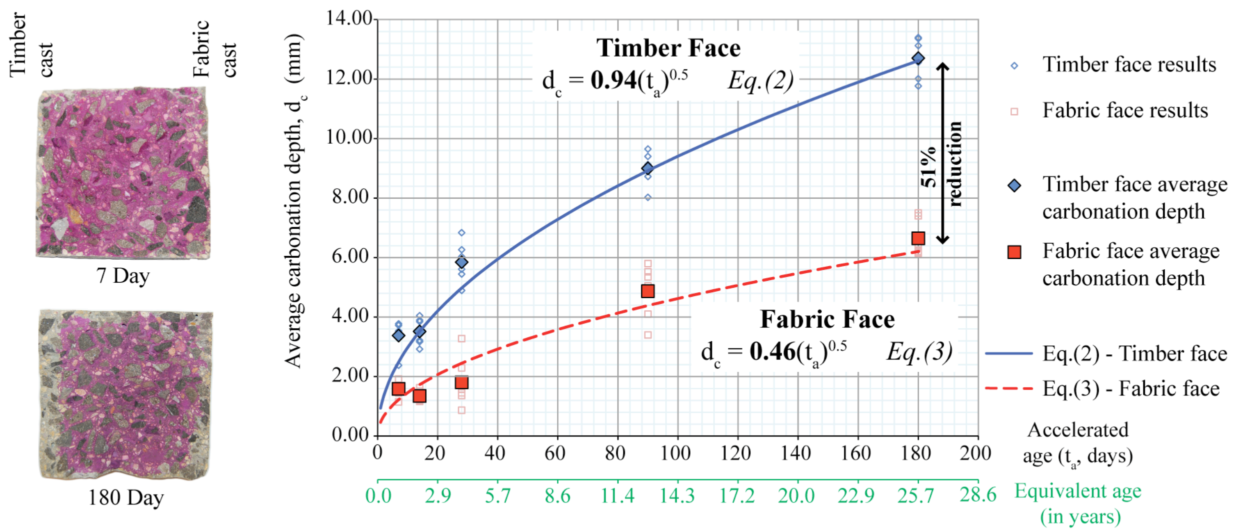

Figure 2 – Graph showing changes in carbonation depth.

Analysis

Many of the available models for the prediction of concrete carbonation depth with age (Liang *et al.*, 2002) can be summarised by Eq.(1). From the results presented above, two equations were determined to compare the rate of carbonation in timber and fabric cast concrete members.

These are given by Eq.(2) and Eq.(3) and are plotted on Figure 2. Values for the coefficients of carbonation B_{timber} and B_{fabric}, calculated by curve fitting against the accelerated test data, are also given in Figure 2, wherein a reduction in the coefficient of carbonation of 51% is seen for concrete cast against fabric formwork. Where estimated in-situ carbonation depths are required, Eq.(2) and Eq.(3) should be modified to account for the accelerated nature of the tests.

$$C_i = B_i \, t_a^{0.5} \quad (1)$$

Where C is the carbonation depth in *mm* and B is the coefficient of carbonation for the face i (fabric or timber cast); t_a is the accelerated exposure time in days.

Conclusions

Accelerated carbonation testing was carried on specially prepared cubes with a maximum exposure time of 180 days, which was estimated to represent an in-situ structure after 25 years service life. The results presented above show considerable improvements in surface durability and resistance to carbonation. After 180 days, the fabric cast surface had an average carbonation depth 48% less than the equivalent timber cast concrete. These remarkable results suggest that fabric cast concrete may have a durability against carbonation of almost double that of its conventionally cast counterpart. Alternatively, fabric cast concrete may be used to provide concrete structures with reduced cover distances that retain the same service life as one with greater cover but cast against an impermeable mould. Further work is now underway to quantify the improvements shown here for a range of concrete strengths and fabric types in order to provide complete guidance for designers.

2.2 Chloride ingress

When unsaturated concrete is exposed to a chloride solution, it can be absorbed into unfilled spaces in the surface by capillary action (Bamforth and Price, 1997). Upon drying, water in the chloride solution evaporates, leaving the salts behind which then build up over time. A range of factors affect the rate of chloride ingress into concrete structures, including the concentration of the chloride solution to which the structure is exposed and the resistance of the concrete cover zone to chloride penetration. Changes to the surface permeability of fabric cast concrete may therefore be beneficial in increasing resistance to chloride ingress.

The potential for increased chloride resistance in fabric cast concrete was investigated by chloride ingress tests on ø100mm cylindrical concrete specimens, which were tested in accordance with the method described in NT Build 443 (1994). Volhards titration of the subsequently collected concrete samples was undertaken in accordance with NordTest 208 (1996). Seven cylinders (four cast in a fabric mould) were exposed to a solution of sodium chloride (165±1g NaCl per dm^3 purified water) for either 53 or 90 days. Nine samples were then taken at incremental depths (up to 20mm) from each cylinder and subjected to Volhards titration. Non-linear regression analysis of these results was used to determine the non-steady state chloride diffusion coefficient (D_{nss}) for the timber and fabric cast concrete. The results are summarised in Figure 3, where reductions in D_{nss} of 58% after 53 days and 41% after 90 days were seen when comparing the fabric and steel cast samples.

Conclusions

Concrete cylinders cast in steel and fabric moulds were used to determine the relative resistance to chloride ingress of fabric cast concrete. The results showed significant improvements in the fabric cast specimens. There is thus reasonable confidence that fabric cast concrete provides better resistance to chloride ingress by diffusion. However, it should be recognised that only sixty-three titration tests were undertaken, and only one fabric type and concrete mix was tested.

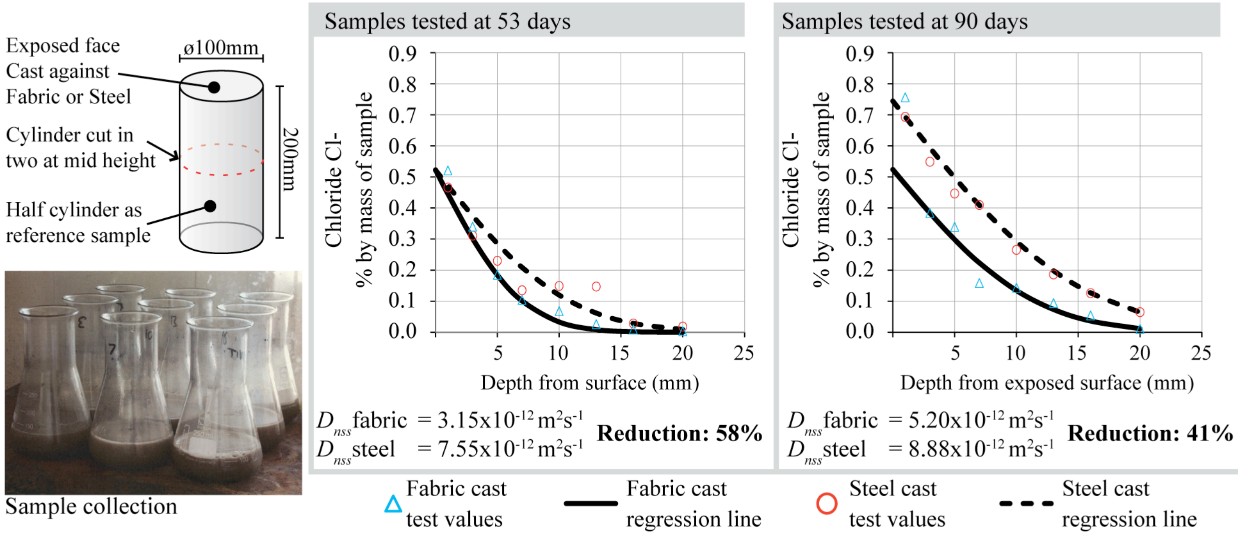

Figure 3 – Chloride ingress results

3 CONCLUSIONS

The tests outlined in this paper have demonstrated that by casting concrete into a fabric mould and allowing any excess pore water to bleed from the concrete during the curing process, a dense surface zone is formed which provides significant improvements in durability. Fifty percent reductions in carbonation depth and chloride diffusion coefficient may allow designers to reduce their cover requirements, or, in designs governed by durability concerns, to reduce the specified concrete grade. Such reductions may in turn facilitate savings in embodied carbon in addition to those that can be achieved by using fabric formwork to create structurally optimised concrete structures. SEM data is currently being collected to determine the mechanisms behind these improvements, and further work is required to classify the optimum fabric to act as both formwork system and drainage membrane to provide the dual advantages described above.

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