Modified ECC by Means of Internal Impregnation

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Abstract

Concrete structural elements of bridges or tunnels may be in contact with water containing chloride during the winter. Furthermore, marine structures are permanently exposed to seawater containing chlorides. In all these cases, penetration of chlorides through the covercrete is a major risk and the service life of structures may be reduced considerably if permeability is too high. Early repair measures are both an economical and an ecological problem nowadays. By adding appropriate admixtures to the fresh concrete, it is possible to produce an internally water repellent material. It is shown that it is possible to substantially reduce chloride penetration through ECC (Engineered Cementitious Composites) in this way, thereby considerably extending the service life of new structures and of repair layers. The properties of the modified ECC are described in detail.

1. Introduction

Concrete structures are often under the influence of various environmental impacts, for instance aggressive chemical substances or a combination of hygral, thermal and mechanical loads. In many cases these loads lead to quick and serious deterioration of concrete structures. One reason for this is that durability has not been sufficiently taken into consideration in the process of design. The cost of restoring damaged concrete structures can be extremely high, in some cases higher than demolition and rebuilding. Not only can real costs and financial investment be extraordinary, but negative impacts on the environment also have to be considered. In addition to technical and economical reasons, it is becoming increasingly important to avoid restoration of concrete structures for environmental reasons (Wittmann 1998).

It has been shown that ECC can also be used in combination with conventional reinforcement (Fischer et al. 2000). Steel reinforced ECC structures show an impressive mechanical behaviour even at very large displacement levels. The security and performance of these structures is enhanced because of their high energy absorption capacity. The planned life span of such advanced structural systems can be achieved if the carbonation depth does not reach the reinforcement and/or the chloride content near the steel reinforcement does not reach critical values too rapidly. For this reason, steel reinforced ECC structures ought to be designed also according to durability aspects. Cement-based materials are porous with a pore size distribution ranging from several nm to several mm. Therefore such elements absorb considerable quantities of water or other liquids if their surface is in direct contact with them. Harmful dissolved chemical compounds such as sodium chloride or calcium sulfate can be transported into the porous structure of ECC in this way. To offer protection and to prevent the transport of harmful substances into the reinforced concrete structure, the crack width of ECC covercrete has to be as small as possible during the planned service life and the covercrete has to show low permeability and low capillary suction.

It is known that an efficient water repellent surface treatment can act as an effective barrier against penetration of aqueous solutions and hence protect concrete elements from early degradation (De Vries et al. 1996, Hassan et al. 1996). A reduction in the amount of water taken up leads, among other things, to reduced electrical conductivity and to increased frost resistance. A first possibility for the improvement of the life span of steel reinforced ECC structures can be realized by impregnation of the covercrete with water repellent agents (Wittmann 2001). In this way, the properties of the covercrete are optimized in a rational manner. Another possibility to reduce water permeability is to modify the ECC properties by adding a water repellent agent directly to the fresh mixture (Gerdes 1997). The effect of this modification on mechanical properties and capillary suction is presented in this paper.

For economic reasons, an ECC modified with a water repellent agent is particularly suitable as a repair material. The use of this very ductile material with an extremely low water absorption capacity efficiently protects the reinforcement and could more than double the life span of the repaired structure. It is also possible to apply modified ECC coatings as protective layers in order to shield new reinforced concrete structures. In this case, the structural concrete assures the load bearing capacity and the coating takes over the protection of the

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reinforcement (Wittmann 1998). This paper illustrates how ECC can be designed for high durability requirements.

2. Durability design of ECC

In a reinforced ECC element, ECC has to take over two completely different functions. First, ECC has to provide a structural element with the required strength, stiffness, and ductility and it has to anchor the steel reinforcement. At the same time, the ECC covercrete has to prevent corrosion of the steel reinforcement. The fulfillment of this second non-mechanical assignment is rarely taken into consideration adequately in the case of steel reinforced concrete structures. As a consequence of a low level of quality control at the time of execution, many concrete structures have to be repaired after a relatively short service life.

In the case of ECC material, the performance driven design has to be applied also on non mechanical assignments. In this way ECC is not only a unique cement based material because of strain hardening, high ductility, and large energy absorption capacity, but also for its durability. In other words, the ECC properties have to be modified in order to reach very high resistance against the penetration of ions.

The proposed step-by-step rational approach for the design of durable ECC structures is described with a flow-chart in Figure 1. First of all, it is important to analyze the boundary conditions and the loads acting on the ECC structure in order to define the requirements that form the guidelines for material design. A synergic combination between the tools of a virtual laboratory and experimental research methods (real lab) is suitable for the development of modern high-tech materials. Micromechanical models enable the prediction of the mechanical behaviour of the material. Neural networks can be used to advantage to optimize the mixture (intelligent mix-design), (Martinola 1992, Wittmann et al. 1993).

Adaptive models can be used for the prediction of the long term behaviour of ECC materials or structures. On the other hand, experiments and observations with sophisticated instruments and the use of new technology and material processing methods complete this approach. Modern structural design is possible by combining tools such as FEM and existing standards and specifications. The results of the design have to be compared with the required performance defined a priori. In this approach, two groups of required properties are given. The mechanical and protective assignments are treated separately. When all the imposed requirements are fulfilled, an ultra high durability ECC structure is obtained.

Minimizing the width of the cracks that occur in ECC structures is very important. The use of micromechanical models enables one to identify the material properties that have to be modified. As mentioned before, the optimization process is only powerful if the theoretical analysis is combined with experiments. In order to fulfill the physical requirements, it is very important to modify the matrix characteristics in order to minimize capillary suction. As noted in the introduction, it is possible to add water repellent agents to the fresh mix for this purpose.

Ref. presents test results from experiments with internally treated cement-based materials (Gerdes 1997). Calcium stearate, siloxane and silane emulsions were added to a standard concrete mix in the fresh state. Then

![Fig. 1 Proposed concept for design of ultra high durability ECC structures.](image1.png)

![Fig. 2 Chloride concentration profiles of internally treated and standard concrete.](image2.png)
the capillary uptake of a 3% sodium chloride solution was determined during seven two-day periods. The untreated concrete specimens absorbed approximately 9 kg/m² of solution after seven cycles. The internally treated samples absorbed only approximately 10% of this amount. Figure 2 shows the chloride concentration profiles at the end of the cyclic exposure to salt solution. While chlorides penetrate the untreated concrete up to a depth of 40 mm, penetration of the hydrophobic specimens is restricted to a layer of 5 to 10 millimeters only. These results clearly show that chloride penetration can be significantly reduced by using water-repellent agents to modify cement-based materials.

If this does not adversely affect the properties of the matrix and the fiber-matrix interface and hence multiple cracking continues to prevail, this modified ECC should benefit from full protection for at least 80 to 100 years.

3. Experiments

3.1 Mix composition
To study the influence of the matrix composition (cement to fly ash ratio) and the addition of an internal water repellent agent on strain capacity and capillary suction of an ECC, three types of mixtures were prepared and tested. The mix compositions of the investigated ECC materials, J5, JH, and JO are given in Table 1. To reduce hygral shrinkage and hence the width of potential surface cracks compared to basic composition J5, two thirds of the cement was replaced with fly ash in the case of JH and JO. JH additionally contained 2 weight-% of an aqueous Silan-Siloxan dispersion (2:1:1) supposed to reduce capillary suction even if surface cracking occurs. The fiber reinforcement consists of PVA fibers named REC15 with a fiber length of 12 mm. The mixtures were prepared in a 20-liter mixer, cast into steel moulds and consolidated with a table vibrator. The specimens were demolded after 24 hours and stored in an environment of 90% R.H. and 20°C. All tests were performed at an age of 28 days.

3.2 Mechanical properties
In addition to flexural stress versus strain curves derived by deformation controlled 4-point-bending-tests (see Figure 3), modulus of elasticity E, 3-point-bending strength ftb (span = 220 mm), compressive strength fc and splitting tensile strength fts were determined. The dimensions of the specimens were set to 70/70/280 mm and 70/70/70 mm, respectively. Three specimens per mixture were tested. The results of the 4-point-bending tests are given in Figure 4 while the other mechanical properties are summarized in Table 2. From the data for mixes J5 and JO given in Figure 4, it can be seen that the replacement of two thirds of the cement with fly ash reduced the first crack strength to approximately 45% while the ultimate strain increased by a factor of approximately three. This is due to the fact that the number of cracks that develop during loading of the specimen depends on the relation between matrix strength and maximum fiber bridging stress and the variation of these parameters within the area of constant stress. While the latter is quite similar for both mixtures, the probability density functions of matrix strength and bridging stress have better correlation in the case of J5. For this reason, ultimate strain is small compared to JO as matrix strength exceeds the value of maximum fiber bridging strength at lower strains. A visual check of the crack planes also discloses another phenomenon. The number of fibers that suffer rupture during loading is higher in the case of J5 as the maximum bond strength...
between fiber and matrix depends on the matrix strength. The addition of a dispersion of silan and siloxan leads to an interesting modification of the load-deflection curve. The slope of the hardening branch is steeper and the crack width remains smaller compared to J5 and JO. Even though the density of JH is smaller due to the air entraining effect of the dispersion, the values of splitting tensile strengths show that the matrix strength of JH is increased by the polymerization of the water repellent agent. (See mechanical properties of PCC.) As the number of broken fibers in the case of JH lies in between that of J5 and JO, the bond strength is expected to reach higher values when polymers are added. Even though the slope of the hardening branch and the crack width are coupled, the latter is much more important as far as durability is concerned.

While the values of Young's modulus and the compressive and splitting tensile strength are obvious and correlate with the matrix composition, the determination of 3-point bending strength shows that the maximum bridging stress of JH exceeds that of both J5 and JO. In the case of J5, this is due to fiber rupture as a result of high bond strength, whereas in the case of JO, bond strength is rather low and so is the maximum bridging stress.

3.3 Capillary suction

The specimens used for measuring the amount of water taken up by capillary suction are cubes cut out of the middle section and the edge zone of the beams used for performing 4-point-bending tests. In the first case, water is sucked in by both cracks and capillary pores, whereas in the second case, only the capillaries of the pore system contribute to the suction process. During the test, the lower surface were in direct contact with liquid water while the other faces of the cube, except the face opposite to the sucking one, were sealed. This enables modeling water penetration into the samples as a one-dimensional phenomenon.

All specimens were predried at 45°C for 4 days to establish identical moisture conditions before the determination of capillary suction. This means that the measured values of the coefficient of water absorption A are in fact an upper bound. In reality, concrete elements will be in equilibrium with the humidity of their environment and hence A will be a smaller value. Figure 5 shows the increase in mass related to the absorbing surface and its dependence on the square root of time. The slope of the linear function that can be fitted to the measured values gives the value of the coefficient of water absorption A that is usually determined to describe capillary suction.

Figure 6 shows the crack patterns and the width of the cracks on the surface of the cubes from the middle
The J5 and JH specimens show fairly similar crack characteristics, while the JO specimens show more numerous and wider cracks. This leads to a higher value for the relation between water absorption coefficients with and without cracks.

Figure 7 compares the values of A of the three different ECC mixes. For comparative purposes, the A values of four concretes with different w/c ratios are indicated in the same diagram (Lunk 1998). The difference between JO and J5 is due to their different water-cement ratio, which is 0.63 for JO but only 0.21 for J5. Without special measures, value A cannot be reduced below 0.1 kg/m²/h₀.⁵ for uncracked surfaces (Lunk 1998). As far as capillary suction is concerned, J5 can be judged a rather dense cementitious composite with very low capillary suction. Even though the water-cement ratio of JH is similar to that of JO, its A value is less than half that of J5 for both cracked and uncracked surfaces. As the water repellent agent was added to the fresh ECC mix (JH), not only the capillary pore system but also the crack-surfaces became hydrophobic. The dependence of the water absorption coefficients on the existence of internal impregnation is greater than the dependence of the water absorption coefficients on crack width and w/c ratio. This is especially true considering that the cracks of all different specimens have been generated using the same load level.

The experimental series described in this contribution cover uncracked and cracked samples in the unloaded state. In reality, it is not unusual for concrete elements to be mechanically stressed and exposed to an aggressive environment. In the next stage, the coefficient of capillary suction A and chloride penetration will be studied by drying shrinkage for a long time. For a realistic assessment of durability, this phenomenon also has to be taken into consideration.

Concrete with a w/c ratio of 0.3 features a coefficient of water absorption of approximately 0.15 kg/m²/h₀.⁵ (Lunk 1998). Even though this value can be judged as rather low, high chloride charges will lead to complete penetration of a covercrete of 40 mm after 40 years (Hunkeler 2002). The addition of water repellent additives may allow us to reach A values that cannot be achieved with conventional methods in the case of cracked surfaces. Without surface cracks, it is even possible to reduce A to approximately 0.05 kg/m²/h₀.⁵, a level where capillary suction is practically impossible and moisture is mainly absorbed by diffusion processes. As a consequence, no dissolved ions will be transported by moisture movements. In addition to the positive effects of water repellent agents mentioned above in section 3.2, the combination of PVA-fiber reinforcement and internal impregnation leads to an enormous increase in the service life of reinforced concrete structures consisting of water repellent ECC or protected by a layer of water repellent ECC similar to mixture JH.

4. Conclusions

This paper presents a concept for the design of ECC structures and proposes the separate formulation of the mechanical and protective requirements of steel reinforced ECC structures. This allows the service life of reinforced ECC structures and the remaining service life of repaired structures to be considerably enhanced.

This paper demonstrates that ECC materials with pronounced strain hardening behaviour can be prepared with water repellent agents. Such modified ECCs show interesting mechanical behaviour and in particular a very low water absorption coefficient in both the uncracked and cracked state. Further investigation is needed in order to quantify the resulting changes in interface and matrix properties and their effect on the strain capacity of the composite.

As capillary suction is one of the main aspect of the durability of reinforced concrete structures, the results described above show that internally impregnated repair and protective coatings can increase the durability of reinforced concrete structures.

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