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# STRENGTH DURABILITY MODELS FOR GLASS FIBRE REINFORCED CONCRETE AND THEIR APPLICATION FOR THE CALCULATION OF A TEXTILE REINFORCED STRUCTURAL ELEMENT.

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## Abstract

Concrete composites with high tensile strength and ductility can be obtained by reinforcing cement pastes or mortars with glass fibre strands. These concrete composites are however subject to degradation of their mechanical properties with ageing, especially in a wet environment. In this paper an overview is presented of the in literature available strength durability models. Not only a literature study is offered but also an in depth discussion. At the end of this paper a case study is provided in which the strength durability is taken into account during the design of a textile reinforced structural element.

**Keywords:** GRC; strength durability; modelling; design

## 1 Introduction

To by-pass the most important drawback of a cementitious material - the inherent brittleness, going together with a modest and unreliable tensile strength - high performance fibre reinforced cementitious composites were developed. One of the first load bearing concrete composites produced were reinforced by means of asbestos fibres. When health hazards were however associated with the use of these fibres substitution became imperative. Cheap E-glass fibres seemed to provide an adequate replacement. The glass fibre reinforcement can be applied under the form of chopped fibre strands (premix) or under the form of a textile reinforcement. For building applications this Textile Reinforced Concrete provides an interesting new load-bearing material [1]. Glass fibre Reinforced Concretes (GRC) are however subject to ageing and this especially in a wet environment. Loss of composite tensile strength is the most important manifestations of this ageing. The development of the at present well-known Alkali Resistant (AR) glass fibres [2] has greatly improved the durability. However, even concrete composites reinforced with these AR glass fibres are still subject to degradation of their mechanical properties with ageing [3]. Over the years many researchers have tried to model this strength loss.

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In this paper three of the in literature available strength durability models will be presented and discussed in some detail. These models are all based on the same idea that the loss of strength of a GRC component results from the deepening of flaws in the glass fibres. The different models will be calibrated using experimental data from literature. Once the presented models are calibrated a prediction of the remaining strength after exposure to 10 years of Belgian weathering will be made. This prediction will then be used for the dimensioning of a structural TRC element.

## 2 Strength durability models

Many have tried to determine which mechanisms govern ageing in order to be able to further improve the durability and to be capable to predict the strength durability. Early durability models [3] stated that if the rate of strength loss of the glass fibre is closely related to the rate of some chemical reaction, and if the time taken for the strength to fall to any given value ($\sigma_t$) can be regarded as an inverse measure of the rate of strength loss, that one may assume an Arrhenius type relation exists between the time taken for the strength to fall to any given value ($\sigma_t$) and the temperature at which the test was performed.

Other more recent models [4]-[5] state that a certain physical background is responsible for the strength loss recorded. They state that the failure stress will decrease with time due to the growth of flaws (nano-defects). The classical Griffith relationship between the free energy of a cracked body under stress and the crack size is used.

$$\sigma_t = \frac{K_{IC}}{A \cdot \sqrt{\pi \cdot a}} \tag{1}$$

Where: $\sigma_t$ is the tensile strength at time t
$K_{IC}$ is the critical stress intensity factor (Mode I)
A is a shape factor
a is the critical flaw size

This phenomenon can be accelerated due to the presence of moisture and pH. Starting from this basic assumption three models were constructed over the years, in this paper these models will be referred to as: (1) the Kinetic model, (2) the Combined model and (3) the Diffusion model.

### 2.1 Kinetic model

Some researchers [4] state that the growth of a flaw can be written as:

$$a = a_0 + k_1 \cdot t \tag{2}$$

Where: a and $a_0$ are the current flaw size and the initial flaw size
$k_1$ is a temperature dependant rate coefficient
t is the ageing time

This however is only valid when one assumes that the reaction between the glass and the environment is solely controlled by the reaction kinetics and that the flaw depth remains much smaller than the fibre diameter. When combining equation (1) and (2) the following expression can be found for the remaining strength divided by the initial strength (S).

$$S = \frac{1}{\sqrt{1 + k_1 \cdot t}} \tag{3}$$

It is assumed that one chemical reaction will control the degradation and that the $k_1$ parameter thus varies with temperature following an Arrhenius type relationship.

$$\ln(k_1) = \frac{-k_{c11}}{T} + \ln(k_{c12}) \tag{4}$$

## 2.2 Combined model

Some researchers [5] stated that the rate of strength loss gradually decreases with time. Some authors suggested that the removal of silicon atoms causing pitting of the fibre surface increases the relative zirconium content on the surface thus progressively reducing the available area for further attack. With time the surface might be covered with exposed zirconium ions or a layer of zirconia-rich reaction products which can slow down the reaction rate and consequently the rate of strength loss. Equation (5) presented below enables the user to model the slowing down as well as the acceleration of a chemical attack by stating that there exists a non-linear progression of the flaw depth.

$$a = a_0 + k_1 \cdot t^n \tag{5}$$

With the n value greater than 1 an accelerating reaction can be modelled and with the n value smaller than 1 decelerating reactions can be modelled. If one assumes that the slowing down of the chemical reaction is a sign of a reaction that becomes diffusion-controlled with progressing time following expressions for the rate of flaw size growth can be used.

$$\frac{dX}{dt} = \frac{1}{\frac{1}{k_1} + \frac{X}{k_2}} \tag{6}$$

With:

$$a = a_0 + X \tag{7}$$

When these formulations are used one states that the rate of degradation is initially determined by kinetics and becomes diffusion controlled in a later stage. The remaining strength can be calculated by substitution of equation (6) into equation (1). The formulation for $k_1$ presented in equation (4) is still valid. The Arrhenius type relationship is also assumed for $k_2$.

$$\ln(k_2) = \frac{-k_{c21}}{T} + \ln(k_{c22}) \tag{8}$$

## 2.3 Diffusion model

There also exists a possibility that the chemical reaction will be diffusion-controlled from the start [6]. In that particular case the flaw size growth can be expressed as follows:

$$\frac{dX}{dt} = \frac{k_2}{X} \tag{9}$$

Equations (1), (7) and (8) are still valid in this case.

## 3 Strength durability predictions

The 3 models presented above can now be used to predict the remaining strength of a structural element after exposure to a certain climate for a certain duration. To calibrate the different models results from literature will be used; more precisely the results obtained by Litherland and co-workers on SIC specimens [3]. These results were chosen since they are the most complete results currently available. It should however be emphasized that the material combination used for these measurements will result in relatively high degradations. With newer, more durable material combinations the reduction in strength is much more reduced.

The different models were fitted to the results. For each temperature the different temperature dependant rate coefficients were determined. In table 1 the Arrhenius relationships for the different models are listed. To this table the R² value is also added indicating the goodness of fit with the Arrhenius plot. As can be seen from the results presented in Table 1 we were not able to fit "the Combined model" on the results. The main problem with the fitting of this model is that it strongly depends on the starting values used for the fitting of the different rate coefficients. This finding does however not imply that this model is not a good model but that a certain knowledge is needed for determination the correct starting values.

| | **Kinetic model** | **Combined model** | **Diffusion model** |
|---|---|---|---|
| $kc_{11}$ (K) | 10628 | Not able to fit the results of Litherland *et al* | - |
| $kc_{12}$ (nm/day) | 2,595 E+13 | | - |
| $kc_{21}$ (K) | - | | 5891 |
| $kc_{22}$ (nm/day) | - | | 5,181 E+7 |
| $R_1^2$ (-) | 0,9986 | | - |
| $R_2^2$ (-) | - | | 0,9914 |

**Table 1** The Arrhenius relationships for the SIC results of Litherland *et al* [3].

The other 2 models are easier to fit and are not dependent on the starting values used. The Arrhenius fit is also very good, for both of the models a R² of more than 0,99 is registered. For what follows only the Kinetic and Diffusion model will thus be further used. In Figure 1 the fitted results obtained for these 2 models can be found.

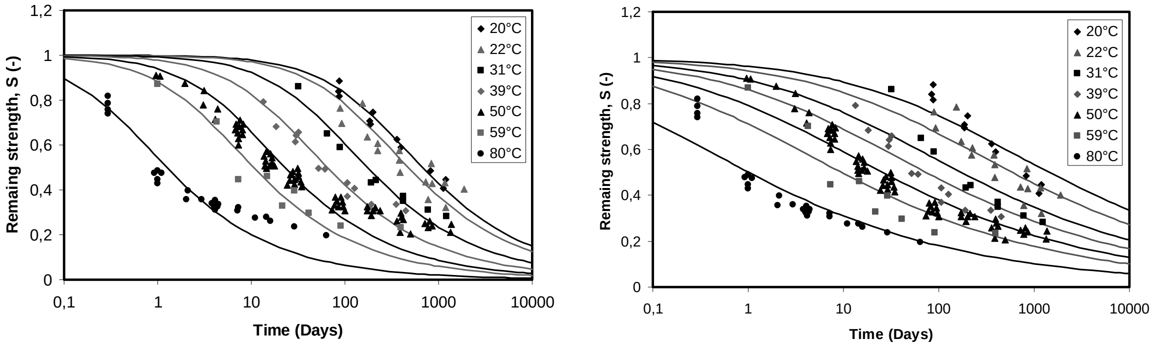

**Fig. 1** The results of Litherland *et al* [3] fitted with the Kinetic (left) and Diffusion model (right).

From figure 1 it can be seen that the Kinetic model seems to fit the results better at lower temperatures and at shorter exposure times at higher temperatures. This in contrast with the

Diffusion model which seems to fit the results at longer exposure times at higher temperatures better. This finding might have important consequence for predictions in real climatic conditions. For the prediction of the remaining strength we now use the calibrated models (see Table 1). Weather measurements in Brussels are used. The average temperature in Belgium is 11°C. For 10 years of Belgian weather this results in a remaining strength of 50% in the case of the Kinetic model and 40% in case of the Diffusion model.

## 4 Design of a structural element

To illustrate the effect of the limited durability an exemplary structural element will now be designed and discussed. One of the possible applications for TRC is the use of thin faces in sandwich structures for building applications. In [7] a more extensive series of sandwich panels is dimensioned, using a cement matrix which shows no degradation with time. In this paper, only one illustrative material combination will be discussed in order to show the effect of the limited durability on the design of structural elements.

A sandwich roof panel with a polyurethane foamed (40kg/m$^3$) core and TRC composites as faces will be dimensioned under own weight, wind load and snow load. It is assumed that the magnitude of the environmental loads is determined at the Belgian coast specifically. For a span of 3m the necessary thickness of the faces is determined such that the panels do not violate the design criteria in the ultimate limit state (ULS) and serviceability limit state (SLS). In ULS it is assumed that none of the components should fail and in SLS it is assumed that the deflection should not exceed span/250. The thickness of the TRC layers is increased in a discrete way by 2mm per extra layer of textiles. The TRC material is composed of a bi-directional textile in a fine tuned Portland cement based mortar, of which the mechanical properties are similar to the properties of the mortar discussed in [3]. The core material is assumed to behave linear elastic in shear as long as the maximum shear stress stays below 1/3rd of the failure shear stress (which was tested and found to be 0,2MPa). The shear stiffness of the core was 8MPa. The typical non-linear stress-strain behaviour of the TRC face in tension is can be found in [5] and is implemented as such in a FEM simulation. The design failure stress in tension was set to 14MPa. The behaviour of the TRC in compression is linear elastic until failure and the E-modulus was found to be 31GPa. The FEM-simulation program ANSYS, version 7, is used to dimension the TRC faces. Element “Shell 91” is used and the sandwich option is activated: the element stiffness and the evolution of the stresses along the thickness of an element are calculated according to the sandwich theory. The number of elements along the whole sandwich is increased until convergence is reached for the displacements and stresses.

| | **No strength loss** | | | **Strength loss** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *Kinetic model* | | | *Diffusion model* | | |
| Core thickness (mm) | 60 | 80 | 100 | 60 | 80 | 100 | 60 | 80 | 100 |
| Face thickness (mm) | 4 | 2 | 2 | 6 | 4 | 4 | 4 | 4 | 4 |
| ULS max stress (MPa) | 7,5 | 10,6 | 8,8 | 6,6 | 5,7 | 4,6 | 7,5 | 5,7 | 4,6 |
| SLS max deflection (mm) | 11,3 | 11,0 | 7,7 | 9,6 | 7,5 | 5,7 | 11,3 | 7,5 | 5,7 |

**Table 2** Results of the FEM simulations

Table 2 (see ‘no strength loss’) shows the necessary thickness for the faces and the corresponding maximum stress in tension and maximum deflection under ULS and SLS load combination respectively. If however 50% and 40% of loss of strength is to be expected according to the kinetic model and diffusion model respectively within a lifetime of 10 years of outdoor weathering, most of these panels need thicker faces. Table 2 show the new dimensioned results according to the kinetic and the diffusion model.

# 5 Conclusions

Different strength durability models for GRC’s have been developed over the years. The 3 models discussed in this paper are all based on a similar physical background. Results presented in this paper indicated that the Combined model requires an extensive inside knowledge of the user. The other two models on the other hand are much easier to fit on experimental results but provide distinct different strength evolution predictions. To establish the impact of the durability on the design of a structural element in the scope of this paper a sandwich structure was designed. The results of these calculations clearly indicated the necessity of including the strength reduction into the design. Also in some cases a slightly different design was obtained when using the Kinetic model or the Diffusion model.

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