

## **INFLUENCE OF STRESS CORROSION ON FRACTURE ENERGY OF CEMENTITIOUS MATERIALS**

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### **Abstract**

Concrete structures such as bridges, are often under the influence of corrosive chemical substances. The attack of aggressive chemical substances like sulphates or chlorides may lead to serious deterioration of the concrete. In reality, this chemically induced corrosion often occurs in combination with mechanical stresses. It can be shown that the rate of deterioration of concrete which is under mechanical stress and at the same time attacked by chemical substances is higher as compared to that of concrete under chemical attack alone. This type of corrosion is called stress corrosion. For a clarification of this type of corrosion, different experimental investigations have been carried out in order to characterize the influence of stress corrosion on fracture energy and strain softening. In this paper, first results of these investigations will be presented.

## **1 Introduction**

It is well-known that concrete will fail after a certain time if loaded at a level higher than 80 % of the short term strength (Wittmann and Zaitsev, 1974). This delayed failure is commonly called static fatigue. It has been suggested that water may cause or at least accelerate the delayed failure by stress corrosion (Wittmann, 1989). A series of chemical compounds such as sulfates and chlorides attack the structure of concrete (Metha et. al. 1992). This may lead to strength reduction in an aggressive environment and in several cases to total destruction of the material.

Schneider and Nägele (1986 and 1993) and Nägele (1991) have shown that combined mechanical and chemical load lead to an accelerated loss of strength of cementitious materials. According to the fictitious crack model (Hillerborg et. al., 1976) a real crack is formed by the extension of a fracture process zone (see f.e. Hu and Wittmann, (1990) and Hu (1990)). First results of a project with the major aim to study the influence of aggressive chemicals on fracture energy and strain softening shall be presented in this contribution.

## **2 Preparation and conditioning of test specimens**

In order to be able to condition test specimens in a reasonable time comparatively small specimens had to be prepared and the dimensions have been chosen to be 40x40x160 mm. It was decided to determine fracture energy and strain softening by the three point bending test similar to the RILEM Recommendation 50-FMC. One mortar mix was used throughout. The composition and the properties of the fresh mortar are given in Tab. 1.

In a first series mortar specimens have been stored in water and they have been tested after 7, 28 and 90 days. In the second series mortar specimens have been stored under water for 5 days, then dried under d-drying conditions for 24 hours and resaturated with a solution of 10 % ammonium sulfate under vacuum. Finally a third series was prepared on which the specimens were again stored for 5 days under water, then dried under d-drying conditions for 24 hours and finally resaturated with tap water.

Table 1: Composition and properties of fresh mortar

Composition of mortar	
Quartz powder > 125 $\mu\text{m}$ [ $\text{kg}/\text{m}^3$ ]	53.7
Sand, 0-4 mm [ $\text{kg}/\text{m}^3$ ]	1448.8
Portland cement [ $\text{kg}/\text{m}^3$ ]	483.9
Water [ $\text{kg}/\text{m}^3$ ]	289.8 (w/c ratio 0.6)
Properties of fresh mortar	
Flow table test [cm]	$20.50 \pm 0.71$
Air content [%]	$4.10 \pm 0.18$
Density of fresh mortar [ $\text{kg}/\text{dm}^3$ ]	$2.226 \pm 0.046$

### 3 Experiments and results

With the first series the influence of age on flexural strength and strain softening has been tested. Results are summarised in Table 2.

For the second and third series a special loading device has been built. This apparatus is schematically shown in Fig. 1. Preconditioned specimens can be loaded at different load levels while being stored in a chemically aggressive liquid.

Table 2: Flexural strength and fracture energy of mortar prisms stored in water

Age of the specimen [d]	Flexural strength [ $\text{N}/\text{mm}^2$ ]	Standard Deviation	Number of Specimen N	Fracture Energy [ $\text{N}/\text{m}$ ]	Standard Deviation	Number of Specimen N
7	4.00	0.29	6	63.94	5.35	4
28	4.89	0.11	6	87.49	-	1
90	6.25	0.36	11	77.50	6.18	4

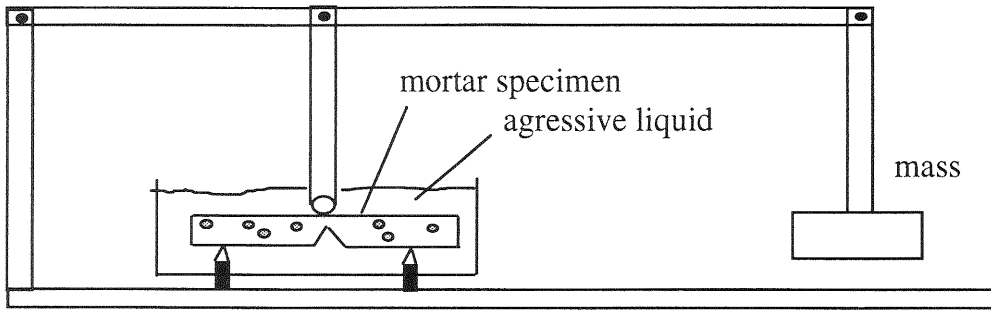


Fig. 1. Loading device for applying combined chemical and mechanical load

Samples which had been preconditioned with a 10 % solution of ammonium sulfate have been loaded at 60 % and 80 % of their respective bending strength for periods up to 15 days. For comparison identically treated mortar prisms have been kept in ammonium sulfate solution without being loaded. The immersion in the aggressive liquid was immediately followed by an embrittlement. For this reason most specimens failed in a brittle way and fracture energy could not be determined. A more sensitive experimental device will be used in the future.

In Fig. 2 the flexural strength is plotted as function of the immersion time. Flexural strength increases first significantly and later decreases. This strength decrease is more pronounced for highly loaded specimens. The experimental results are fitted with the following function:

$$f(t) = f_0 \left[ 1 + \frac{A t}{B + t} + C t^2 \right] \quad (1)$$

$f_0$  stands for the bending strength at the beginning of the combined chemical and mechanical load and  $f(t)$  is the strength as function of time.  $A$ ,  $B$  and  $C$  are parameters which have to be determined experimentally.  $A$  and  $B$  describe the amount and the time-dependence of the strength increase due to the chemical interaction.  $C$  finally describes the decrease of strength by stress corrosion.

In the example shown in Fig. 2  $A$  and  $B$  have been found to be 0.278 and 0.257 respectively. The parameter  $C$  as obtained by a least square fit is plotted in Fig. 3. It can be seen that  $C$  increases sharply with the applied sustained load beyond a load level of about 50 % of the initial strength.

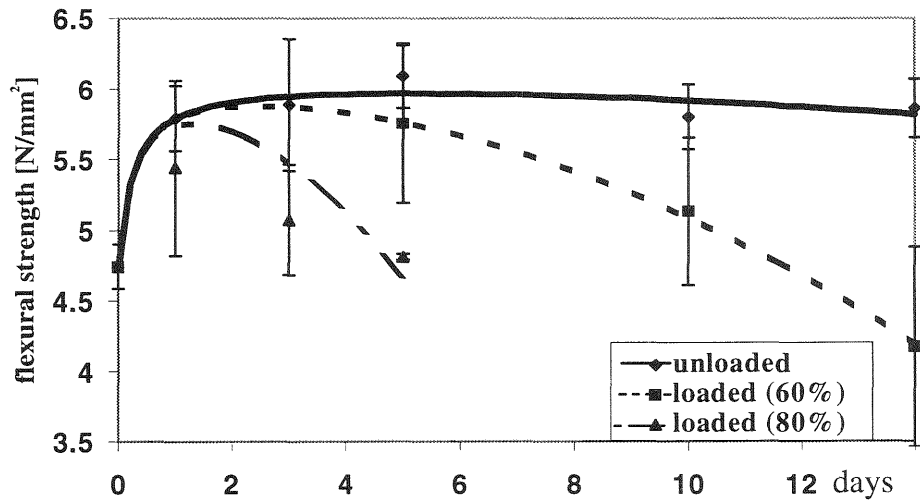


Fig. 2. Flexural strength of specimens, immersed in 10 % ammonium sulfate solution with a load level of 0%, 60% and 80 %,

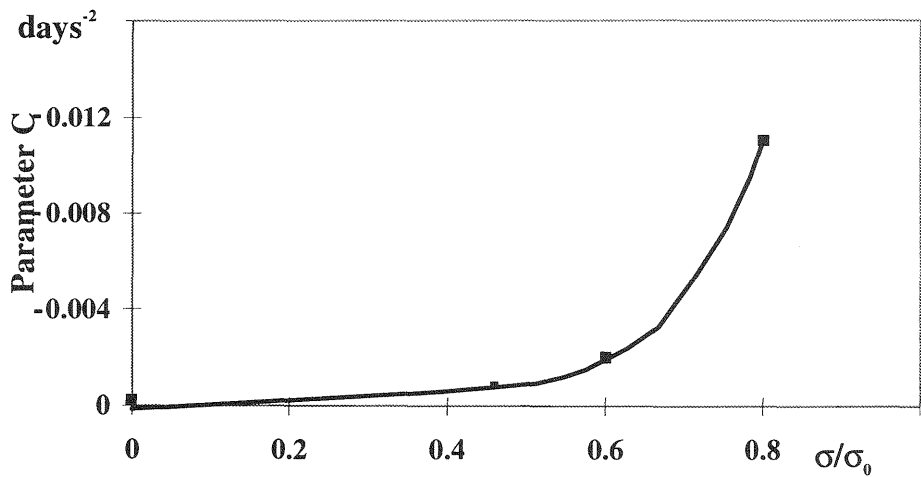


Fig. 3. Parameter C of equation (1) as function of the applied related load

For the conditions chosen in this study equation (1) can be rewritten as follows:

$$f(t) = 4.75 \left[ 1 + \frac{0.278 \cdot t}{0.257 + t} + a \left( \frac{\sigma}{\sigma_0} \right)^n \cdot t^2 \right] \quad (2)$$

In the third series ammonium sulfate solution was replaced by tap water. Results and a fit of the results are shown in Fig. 4. In this case the loaded and unloaded specimens showed a slow and steady increase of flexural strength. This further strength development is attributed to continuous hydration of the mortar specimens.

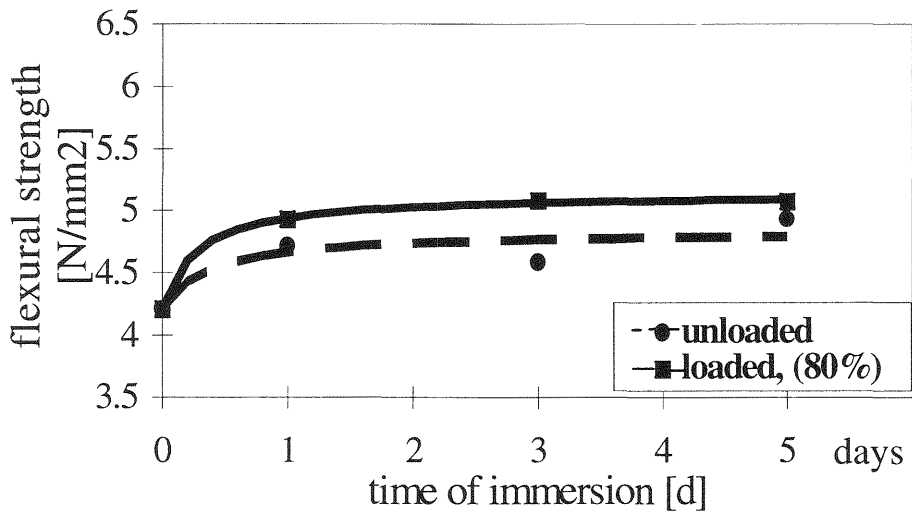
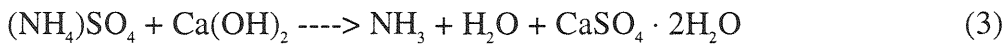


Fig. 4: Flexural strength of specimens, immersed in water

#### 4 Discussion and conclusions

If ammonium sulfate penetrates into the porous system of cementitious materials an exchange of ions takes place:



That means gypsum is formed in the pores of the mortar. As a consequence the outer layers of a specimen will tend to expand under this swelling action. In this way in the surface near zones which are rich in penetrated sulfates a compressive stress is built up. In Fig. 5 the superposition of bending and swelling stresses is schematically shown. It can be seen that the compressive stress created by sulfate swelling in preconditioned specimens has to be overcome before a crack can be formed.

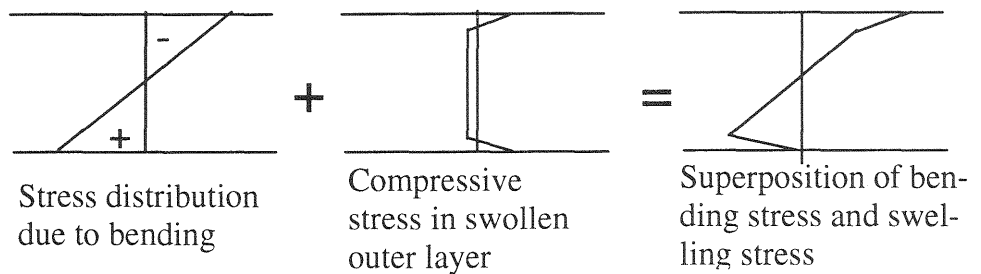


Fig. 5. Schematic representation of the superposition of pure bending and swelling stresses

This "prestressing" effect is also known as a hardening mechanism on glasses and it explains why the flexural strength of mortar increases rapidly when exposed to sulfate solution. Subsequent chemical reactions first compensate and then overcompensate the strengthening effect of ammonium sulfate. This behaviour has also been observed by Nägele (1991).

The strength decrease in chemically aggressive environment and under load has been called stress corrosion (Nägele, 1991). One possible mechanism is briefly described by Wittmann (1989). Further detailed studies are needed in order to be able to describe the different mechanisms which contribute to stress corrosion and in order to be able to describe a sound basis for a reliable prediction of service life of concrete elements under combined chemical and mechanical load.

## 5 References

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