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DETERIORATION OF REINFORCED CONCRETE REPAIR MORTAR LAYERS

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Abstract

A large number of repaired structures indicate that the rehabilitated reinforced concrete structures can suffer further corrosion. This problem should be considered by the design of rehabilitation and by the selection of the repair material. Since the thickness of the mortar cover over the reinforcing bar is about 20–50 mm, the resistance against the effect of the volume expansion due to steel corrosion cannot be neglected. The aim of our experiment was to investigate the deterioration mechanism of repaired reinforced concrete structures caused by corrosion of the reinforcing bar. We maintained corrosion defects in repairs to occur in four different ways, among them the crack trapping mechanism seems to be the less damaging.

Keywords: corrosion, repair mortar, crack trapping mechanism.

1. Introduction

Reinforced concrete is the most frequently applied structural material. That is explainable with its easy use, its advantageous mechanical properties which develop after hardening, etc. The commonly held view, that concrete is a durable, maintenance-free construction material has been changed in recent years. Several examples can be shown where concrete did not perform as well as it was expected. These are the results of the insufficient consideration of durability during the design process, the inadequate execution and the maintenance. Fortunately, the new prEN 206/1999 Code – which comes this year into force – will take those effects into account, which influence the service life of the structure. This is the future, but recently we have to deal with plenty of deteriorated reinforced concrete structures.

Whatever the source of deterioration and the mechanism of its development, corrosion of embedded reinforcement is recognised as the major problem affecting the durability of concrete structures.

The typical indication of corrosion in reinforced concrete are the cracks along the bars, spalled-off corners on beams or columns, or areas on slabs. The reason of these phenomena is explainable with the mechanism of corrosion. When reinforcement corrodes, the corrosion products generally occupy considerably more volume than the steel. The magnitude of this increase in volume varies approximately 2 or 3 times the volume of the original material. As a result, the corrosion products from quite small reduction in the cross-sectional area of a bar will produce an internal stress that destroys the neighbouring concrete under tensile stress. Thus, the thickness and the properties of the concrete cover have the most important function with regard to the mechanism of corrosion.

Many repair materials and techniques have been developed to provide strong, durable rehabilitation, such as the replacement of the overlay, cathodic protection, corrosion inhibitors, surface protection, etc. Among the different methods, replacement of the deteriorated concrete cover with repair mortar is the most frequently applied repair method. The physical and the mechanical properties of the mortar have the most important function with regard to the service life of rehabilitated reinforced concrete structure. Thus, the repair mortar has to fulfil the following requirements:

- collaboration with the concrete,
- resistance against aggressive ions,
- resistance against CO_2 and other gases,
- the E modulus of mortar has to be relatively small,
- the adhesions strength of mortar has to reach at least 1.5 N/mm^2.

These requirements are well-known, but beside them there is another very important effect, which is not so known. This effect is the volume expansion as a result of the further corrosion of the embedded reinforcement. It is assumed that the reinforcement will be not corroding after the replacement of the covering concrete overlay. However, the practice contradicts this assumption. The causes of the further corrosion are explainable with the following effects:

- during the rehabilitation process the reinforcement cannot be cleaned rust-free, further corrosion might occur,
- the reinforcement will be embedded into two different materials – with different mechanical properties – the repaired concrete and the repair mortar. It conduces to the so-called contact corrosion,
- the remaining concrete structure might still contain Chloride and other aggressive ions.

It means that we have to consider that the rehabilitated reinforced concrete structure will suffer further corrosion. This problem should be considered by the design of rehabilitation and by the selection of the repair material. Since the thickness of the mortar cover over the reinforcing bar is about 20–50 mm, the resistance against the effect of the volume expansion due to steel corrosion cannot be neglected.

2. Stresses Caused by Corrosion

To initiate electro-chemical corrosion, an electrolytic cell has to be established. Three basic components comprise the cell: the anode, the cathode as the dissimilar metals and the electrolyte. For corrosion to occur the anode and the cathode have to be electrically connected in a manner that permits electron flow. The current, which drives the anodic and the cathodic reaction, flows through a medium called the electrolyte. During the corrosion process in reinforced concrete structures the anodic part of the reinforcement breaks down, rust will be produced. The amount of rust, which is equal to the corrosion rate depends on the amount of current actually following, as calculated by Faraday's law:

$$W = k \cdot I \cdot t, \tag{1}$$

where W is the weight of corroded metal, k is the electro-chemical equivalent, I is the current and t denotes the time of corrosion process.

When reinforcement rusts, the corrosion products generally occupy considerably more volume than the steel. The magnitude of this increase in volume varies approximately 1 or 3 times the volume of the basic metal. As a result, the corrosion products from quite small reduction in the cross-sectional area of a bar will produce an internal tensile stress that may destroy the surrounding. To consider the effect of corrosion, an elastic ring model loaded with internal pressure is used (*Fig. 1*).

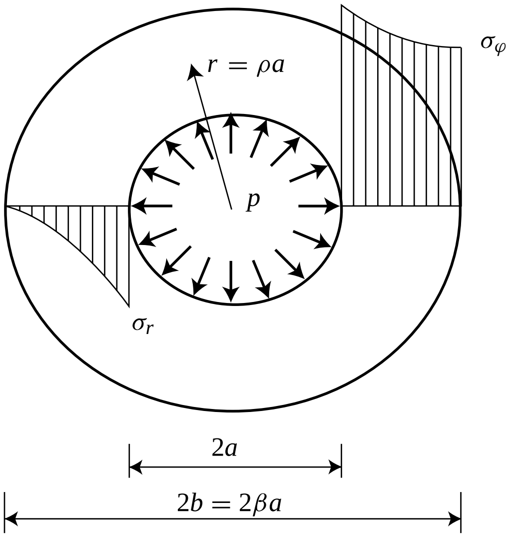

Fig. 1. Stresses caused by internal rust pressure

When the value of the circumferential stress (σ_φ) reaches the tensile strength of concrete (f_t), cracking will occur. In an elastic stage, the value of the stress depends only on the ratio of the internal and the outer ring:

$$\sigma_\varphi = \frac{p}{\beta^2 - 1}\left(1 + \frac{\beta^2}{\rho^2}\right). \tag{2}$$

The maximal value of (σ_φ) is obtained when $\beta = 1$ at the interface of the bar and the concrete. From this equation we can get the maximum value of the rust pressure:

$$p_{\max} = f_t \cdot \frac{\beta^2 - 1}{\beta^2 + 1}. \tag{3}$$

This value is the so-called critical rust pressure, which depends on the β ratio and the strength of the surrounding concrete.

3. Deterioration of Rehabilitated Reinforced Concrete Structures Caused by Corrosion

Since the environment around the reinforced bar in the rehabilitated structure is inhomogeneous, the elastic-ring model is not an effective approximation. The concrete structure with the replacing repair mortar is a 3-phase material, such as the concrete, the repair mortar and the interface between the two materials. All the 3 phases have their own mechanical, physical properties which are very different (*Fig. 2*).

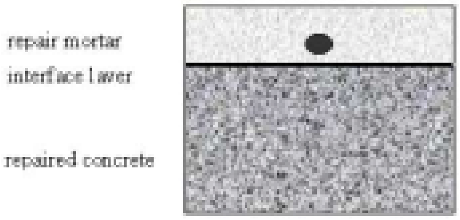

Fig. 2. Schematic picture of the repaired reinforced concrete member

When the internal forces due to volume expansion reach the critical rust pressure, microcracks around the reinforcement will be induced. The propagation of microcracks is characteristic only for a limited area called microcracking zone. Generally, the microcracking zone takes place in the repair mortar inside of an inelastic ring.

With further increase of rust pressure microcracks start to localise into some major cracks, which may lead to deterioration of the rehabilitated structure. The space distribution and development of the localised cracks depend on the mechanical properties of the 3-phase. Experiments were carried out at the Department of Construction Materials and Engineering Geology, Budapest University of Technology and Economics for better understanding the above questions.

4. The Experiments

The aim of the experiment was to investigate the different deterioration mechanisms of reinforced concrete structures with replaced repair material, using different repair mortars. Repair mortars with different strength and toughness were used. To obtain different tensile strengths, dispersion powder was added to the mortars, however, to obtain different toughness, short micro fibres were used. However, the amount of aggregate, cement and water applied by the different mortars were the same. The composition of the five different mortars can be seen from the *Table 1.*

Table 1. The compositions of the mortars

No. of probe	I. Original	II. steel	III. plastic fibre	IV. disp.+steel fibre	V. disp.+ plastic fibre
CEM I 42.5	290	290	290	290	290
adm. ($d$max=4)	695.5	680.5	694.5	679.5	665.5
silicafume	10	10	10	10	10
calciumformiat	3	3	3	3	3
plasticiser	1.5	1.5	1.5	1.5	1.5
RE 545 Z disp.	–	–	–	15	15
steel fibre	–	15	–	–	15
plastic fibre	–	–	1	1	–
$\Sigma(g)$	1000	1000	1000	1000	1000

The repair mortars were applied to concrete test specimens. The schematic drawing of the test set-up is shown in *Fig. 3.* The thickness of the repair mortar cover was 25 mm. The diameter of the deformed reinforcing bar was 10 mm, which was placed directly to the surface of a concrete prism. The prism was cast 28 days before placing the mortar on it. Average compressive strength of the concrete at the age of 28 days was 20 N/mm^2. The bonding strength on the concrete surface was 1.5 N/mm^2. Before placing the mortar, the pores of the concrete were opened by brushing with a steel brush.

For the purpose of establishing and accelerating the rebar corrosion, direct-current generator was connected to the reinforcement. A copper bar was connected to the positive pores of the generator, which had a cathodic function during the experiment. The test specimens were placed underwater in a fibreglass tank and the direction of the current was arranged such as the reinforcing steel served as the anode while the copper bar was positioned in the tank to act as cathode. A constant current density of 2 mA/cm^2 was passed over the reinforcement surface. Appearance of the first crack was monitored very carefully, as this formed a reference time. The total time of the current load were 72 hours, when the specimens were taken out of the electrolytic liquid and cut into slices for the microscopic investigation of the developed cracks.

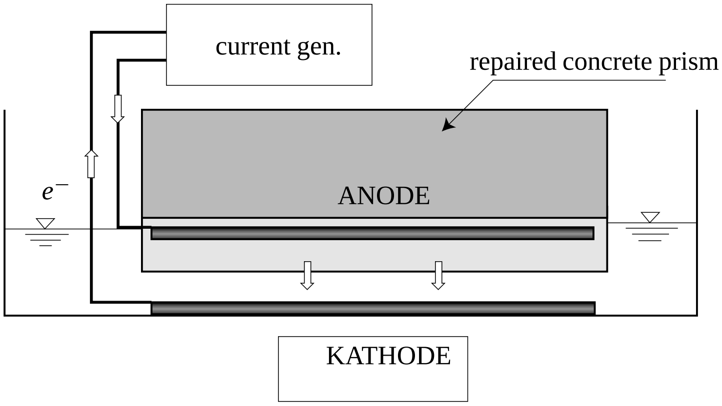

Fig. 3. The schematic drawing of the test set-up

5. Experience Made during Testing

We observed the following effect on the surface of the probes, before cutting them into slices. Except on probe IV, every prism has developed cracks, along the whole body of the probe. The cracks developed within the range of ±5 mm over the reinforcement bars, and produced widths between 0.2 mm to 1 mm, in case of dispersion enhanced mortars, or, between 1 to 2 mm, in case of mortars not improved by dispersion (*Fig. 4*). Over the surface of these probes, iron stains appeared. Iron stains appeared also over the surface of steel fibre reinforced probes, which did not develop cracks, still, stains would appear around steel fibres near the surface, within circles of 1 to 2 mm diameter.

Fig. 4. The schematic drawing of the test set-up

Photos made of the sliced prism are on display in the *Figs. 5* to *9*. The rate

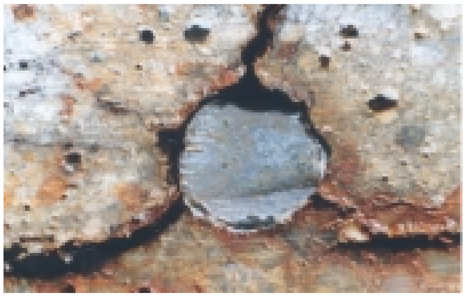

Fig. 5. The schematic drawing of the test set-up

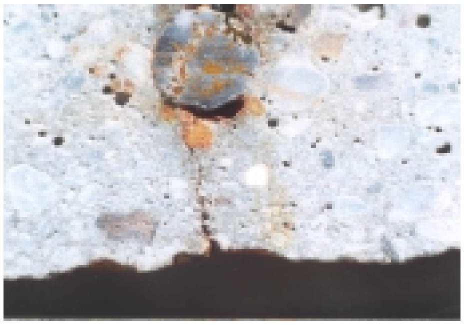

Fig. 6. The schematic drawing of the test set-up

of cracking development is highest on probe No. I which served for basis. This probe has developed three wide (1 mm to 2 mm) cracks. First, a crack running up to the surface appeared on the probe, then one of the other cracks developed and ran towards the adhesive layer, while the other intruded into the repaired concrete component (*Fig. 7*).

The two probes not modified by dispersion but reinforced by steel fibre displayed cracks running to the surface, too. However, the widths did not exceed 1 mm, at maximum. In both cases, radial cracks in the concrete appeared, starting from the surface of the reinforcement. Cracks, which reached neither to the surface of the mortar nor on to the transition surface in the repair material or on the repaired concrete itself, were absorbed by the mortar (probe No. II, *Fig. 6*, probe No. III, *Fig. 7*).

From the group of probes modified by dispersion and reinforced by fibre repair mortar, only probe No. V, reinforced by plastic fibre developed cracks running out to the surface, the width of this was maximum 0,2 mm. In both cases, several radial cracks started, only to be absorbed in the repair mortar (probe IV, *Fig. 8,* and probe V in *Fig. 9*).

Fig. 7. The schematic drawing of the test set-up

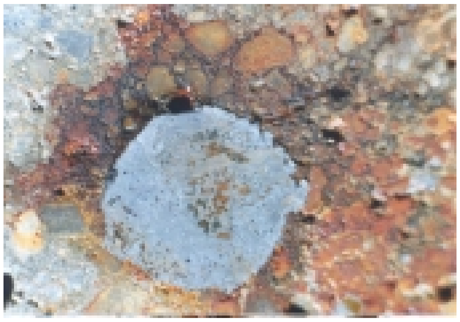

Fig. 8. The schematic drawing of the test set-up

6. Conclusions

On the basis of the tests, by review of the picture of the crack development in the reinforced concrete repair cases investigated as a three-phase sandwich structure, we maintained corrosion defects in repairs to occur in four different ways:

1. Similar to structures without a repair layer, defects may occur by effect of strains developing in radial directions out of the rust pressure, exceeding and breaking the tensile strength of the repair mortar. Consequently, cracks will develop in the mortar layer and extend along the reinforcement in the repaired section. This crack picture was obtained in repair sections, not modified by dispersion (see probes II and III), which means that the sole utilisation of fibre shall not influence the tensile strength of repair mortars substantially.
2. In practical occurrences, the reinforcements of repair sections are very close to the repaired part of the concrete, defects occur therefore often by pressure of the iron stain, destroying not the repair mortar itself, but this transition layer, which detrimental effect then continues to spread further out, over this

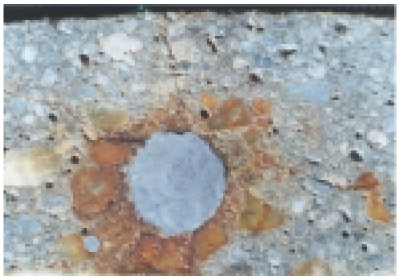

Fig. 9. The schematic drawing of the test set-up

layer. In such an event, the repair layer will come debonded from the repaired concrete. This type of defect occurs, if no sufficient adhesion forces are effected by the adhesion layer or the repaired concrete did not have sufficient adhesion strength (in specifications maintained to be 1.5 N/mm^2, typically). In this event, because of the small β value, higher radial tensile strength values occur, which the weak transition layer cannot withstand. This type of defect was on display on probe No. I, the basic probe.

3. Another type of defect development occurs, when initial cracking by the iron stain pressure would drive the crack through the transition layer over into the repaired basis, to cut off a piece of that. This type of crack mostly develops when the thick repair layer (capital b/a on the *Fig. 1*) produces higher strength and rigidity compared to the repaired concrete. Such crack has occurred in the original probe, too.
4. A rather favourable type of cracking would be, if the cracks do not appear on the surface of the repair mortar at all, they would be absorbed in the repair mortar. Such a situation could be produced by an optimum mixture of fibre reinforcement and dispersion. By adding dispersion, the tensile strength of the mortar increased substantially (compared to 5.4 N/mm^2 in the original No. I probe, mortars modified by dispersion produced an average of 9.5 N/mm^2), tenacity was increased by the fibres, further enhanced by the adhesion-increasing effect of dispersion. The fibres thus were able to accomplish a cracking limitation effect, they could absorb the growing cracks. This is the so-called trapping mechanism, which occurred in the probe IV and probe V.

7. Summary

A large number of deteriorated reinforced concrete structures prove that their rehabilitation is a common topic. A whole range of repair materials and several repair techniques have been developed and aggressively marketed by manufacturers and construction contractors. However, neither the material nor the application of repair techniques to concrete structures has been adequately investigated. Codes and specifications specify some requirements of the repair material properties, however, many important questions are neglected. One of them is the effect of the further corrosion of embedded reinforcement, which effect can destroy the rehabilitation. The aim of the experiment was to investigate the deterioration mechanism of repaired reinforced concrete structures caused by rebar corrosion. We maintained corrosion defects in repairs to occur in four different ways, among them the crack trapping mechanism seems to be the less damaging.

Acknowledgement

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