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Patch repairs on reinforced concrete structures – Model investigations on the required size and practical consequences

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Abstract

For various reasons, world-wide numerous concrete structures have to be repaired due to corrosion problems of the steel reinforcement. In some cases, frequent use of road salt in past winters, not foreseen during the planning of older traffic structures, has led to damage; in other cases the causes lay in deficient planning and execution, as for example

- irregular, insufficient concrete cover of the reinforcement;
- unsuitable concrete mixture proportions for outdoor structures;
- insufficient concrete curing, subsequently bad concrete quality in the concrete cover.

The model investigations described in this paper relate to construction practice, in which local damages due to reinforcement corrosion, e.g., spalls and cracks, are repaired solely in the area of visible surface damage. When damage is dealt with in this way, the carbonated or chloride contaminated concrete is often not removed completely, to avoid stability problems in the structure. In consequence, even after the repair measure there are areas of the reinforcement where there is no guarantee of sufficient protection against corrosion and a high corrosion risk remains. The reinforcement in the repaired area may even accelerate corrosion in unrepaired areas adjacent to it.

1. Introduction

Fundamentally, reinforcing steel in concrete structures is durably protected against corrosion. Protection is based on the alkalinity of the concrete pore solution (pH values > 12.5). In this environment, a passive layer of ferro-oxides is formed on the steel surface. The passivity of the steel surface may, however, be lost as a result of two mechanisms:

- A decrease in the pH value of the pore solution to values lower than 10, as a result of carbonation.
- Reaching a critical limit for the chloride content at the steel surface.

After losing the corrosion protection (depassivation) corrosion at the reinforcement can occur, provided that sufficient oxygen and moisture are available.

Corrosion of steel in concrete is an electrochemical process, in which anodic and cathodic regions are formed on the steel surface, where different subprocessess of corrosion occur (Fig. 1).

In the anodic subprocess (dissolution of steel), positively-charged ferroions are dissolved while electrons pass through the steel to the cathode. At the cathode, the electrons compound with water and oxygen to form hydroxide ions (OH^-). In the electrical field between the anode and the cathode, the negative charge of these ions is transported to the anode through the pore solution of the concrete. Depending on the available amount of oxygen and moisture, corrosion products are formed at the anode.

When carbonation has reached the surface of the reinforcement, the anodic and cathodic regions are so small that

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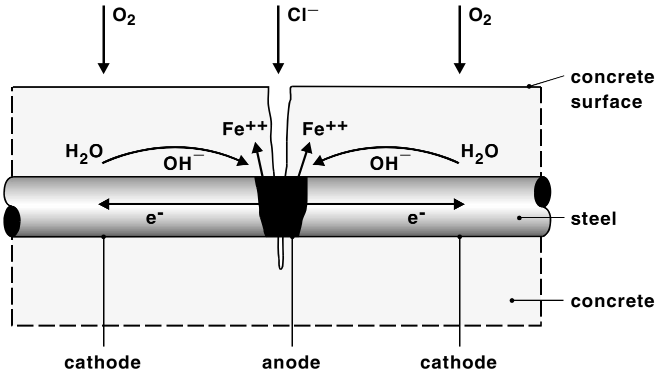

Fig. 1. Electrochemical process of steel corrosion in concrete shown for chloride induced corrosion in the area of a crack.

it is impossible to distinguish them with the naked eye. Such local corrosion elements are formed with very small interrelating anodic and cathodic areas. Dissolution of the steel takes place uniformly over the entire surface. In the vicinity of cracks in the concrete and after local repairs, macrocell corrosion may also occur in carbonated concrete.

The mechanism is quite different in the case of chloride-induced corrosion. Normally, local depassivation of the reinforcement takes place. Macrocells with locally separated anode and cathode, possibly at a considerable distance from one another, are formed. The cathodic regions of the reinforcing steel are extremely large in relation to the surface of the anode, leading to high dissolution rates at the anode. Corrosion then progresses rapidly inside the steel (pitting corrosion), weakening the cross-section.

The conditions necessary for corrosion to continue are that there should be sufficient chloride ions in the vicinity of the steel surface and that transport of chloride ions to the pits should be possible. The mobility of chloride ions in concrete has a decisive effect on the stabilisation and growth of chloride-induced pits, while the electrolytic conductivity of the concrete has a decisive influence on the formation of macrocell elements.

Fig. 2 shows the special corrosion mechanisms for the situation of local depassivation before and after local repair. The situation before repair shows a quite uneven depth of carbonation or critical chloride content, resulting in certain steel surface areas being depassivated and neighboured areas without depassivation. Such an uneven distribution of carbonation front or critical chloride content is, e.g., typical for areas with locally bad concrete quality or locally low concrete cover. Provided that sufficient oxygen and water are available, anodic dissolution will take place in the centre of the depassivated steel surface area. As soon as the first pits are growing, a macrocell will develop with cathodically acting steel surface areas besides the pits. These areas are cathodically protected by the anodic dissolution of iron shown in the centre of Fig. 2. Due to this cathodic protection effect, the cathodically acting areas will not corrode, even if the depth of carbonation or critical chloride content has reached the steel surface.

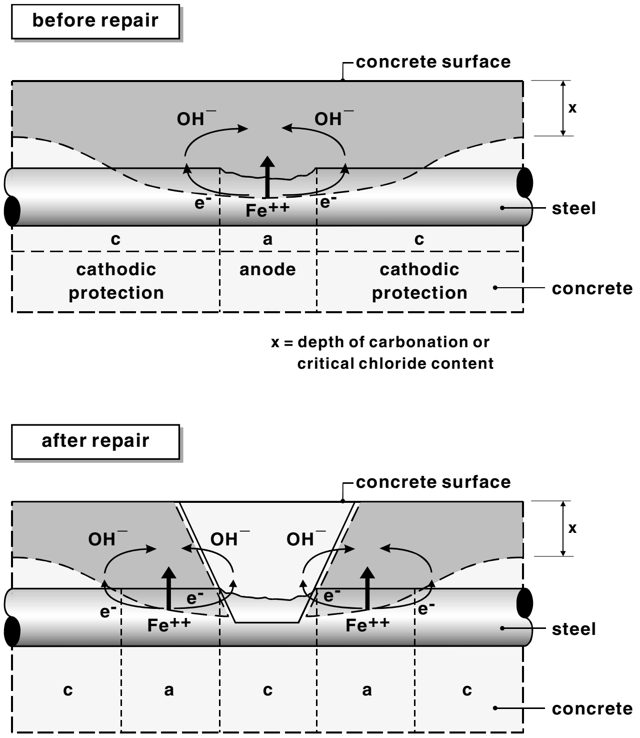

Fig. 2. Possible corrosion mechanisms before and after patch repair.

This situation changes after repair, provided that only the area is repaired, which shows structural damages which, for example, could be detected by a hammer test from the steel surface. This situation is also shown in Fig. 2: Only the area of rust formation is set free and filled with repair mortar. The alkalinity of the repair mortar will insure a passivation of the former anodically acting steel surface area. This means, that the "sacrificial anode" is removed by the repair work. As consequence the neighboured areas are not longer cathodically protected by the former corroding areas. Without cathodic protection all areas, where the depth of carbonation or critical chloride content has reached the steel surface, can start to corrode. This is shown in Fig. 2 for the situation after repair. Now the neighboured areas from these new corrosion sports are acting as cathodes, including the patch repaired area. In the cause of time this corrosion will lead to corrosion damages like cracks and spalling, and sometimes it can be seen that even the whole patch brakes off by corrosion of the surrounding area.

To be able to prevent such corrosion problems after local patch repair, it has to be investigated, under which conditions the mechanism showed in Fig. 2 may occur in actual practice.

2. Laboratory tests on the corrosion mechanisms before and after local patch repair

2.1. General

Already in the nineties several research projects have been carried out at the Institute for Building Materials

Research of Aachen University (e.g. [1,2]). In this paper only a model test is shown, which has been performed to find out whether the mechanisms shown in Fig. 2 will occur under practical conditions. As the main testing method, macrocell current measurements have been carried out at a special specimen with different pieces of steel embedded in concrete at defined locations. In the following section the model test is described and discussed and in Section 4 the consequences for the practical patch repair work will be worked out and discussed basing on these tests.

2.2. Situation before repair

Fig. 3 shows the specimen for the laboratory tests for the simulation of a local patch repair. This specimen consists of three areas, in the centre an area with higher chloride content than at the sides and with bad concrete quality, representing a local area with bad compaction of the concrete. The concrete at the sides has been produced with a certain amount of mixed in chlorides. At each side two pieces of reinforcing steel have been embedded and into the centre three pieces of rebars, each with a length of 5 cm. This situation is shown schematically in Fig. 4. For the specimen described in this chapter in the centre 1.6% of chlorides relative to the cement content have been added and at the sides 0.8% of chlorides relative to the cement content. This leads to the situation, that the centre part will corrode, while it is uncertain whether the reinforcement within the sides of the specimen will corrode, because the chloride content is only slightly above the critical chloride content for the given conditions. As shown in Fig. 4 the pieces of rebars are connected with external cables so that the electrical currents can be measured between them by an external amperemeter. In this case resistors have been inserted into the cable connection enabling to measure the electrical current indirectly by measurement of the voltage drop across the resistor. The cables and resistors can be seen in Fig. 3.

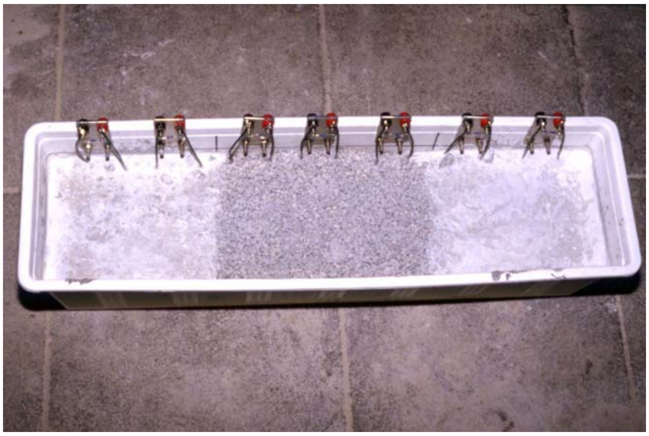

Fig. 3. Specimen for the simulation of a patch repair.

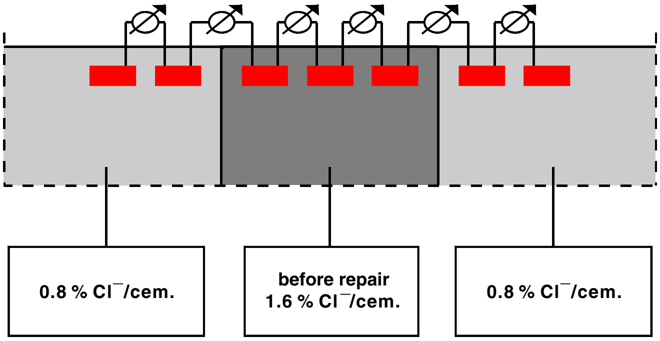

Fig. 4. Chloride distribution within the specimen before repair.

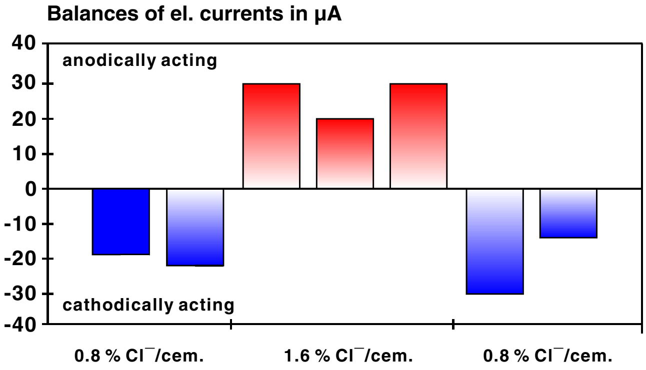

Fig. 5. Distribution of electrical currents before repair.

Fig. 5 shows the distribution of the electrical currents before repair. By the direction of the electron flow it can be calculated, whether the pieces of rebars are acting more anodically or cathodically. Fig. 5 shows the situation 28 days after production: As to be expected the pieces of rebar in the centre of the specimen are acting anodically, while the pieces of rebars at the sides of the specimen are acting cathodically. The intensity of cathodic reaction is decreasing with the distance from the anode, due to the effect of the longer distance resulting in a higher electrolytic resistance. This figure shows that the pieces of rebar at the sides of the specimen are cathodically protected by the anodic action of the pieces of rebars in the centre of the specimen, even at a chloride content of 0.8% relative to the cement content. After this situation has stabilised, the local patch repair has been simulated.

2.3. Situation after repair

Fig. 6 shows the chloride distribution within the specimens after simulation of the local patch repair. The three pieces of rebars in the centre of the specimen have been set free, cleaned from rust and installed again by embedding into a mortar made of OPC without polymer admixtures. This mortar shows a high pH value resulting in passivation of the three pieces of rebars in the centre of the specimen. After repair the electrical currents have been measured until corrosion started again. Fig. 7 shows the result of the electrical current measurements 300 days after simulation of the local patch repair. As to be expected the

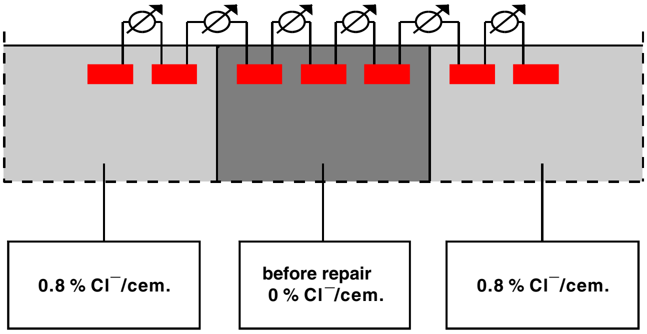

Fig. 6. Chloride distribution within the specimens after repair.

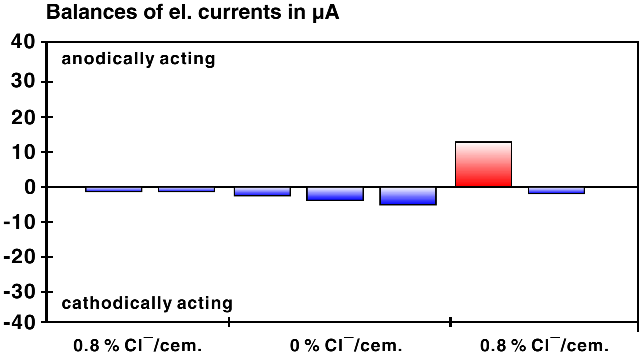

Fig. 7. Distribution of electrical currents 300 d after repair.

balances of the electrical currents of the pieces of steel in the centre are acting cathodically, because they are in the passive state. However, one piece of rebar besides the local patch repair has started to corrode. It can be assumed that the piece of rebar opposite to the centre will also start to corrode after a certain time, because the cathodic protection from the newly corroding area is quite small due to the distance from the new corrosion spot.

This result shows, that the mechanisms shown in Fig. 2 can be simulated in laboratory at specimens, which are designed to be representative for the situation in actual practice.

2.4. Discussion of the result

The results of the model tests described in the previous chapters show clearly, that the mechanism of corrosion shown in Fig. 2 has been verified for situations comparable to conditions in actual practice. As consequence the criterion for the design of the required size of a patch area is not visible spalling or adhesion, which can be checked by the hammer test, but all steel surface areas, and show a critical amount of chlorides or carbonation which could start to corrode after the sacrificial anode has been removed by the patch repair work.

In [2] it has additionally been investigated, whether coating of the steel surface would be able to prevent such macrocells after local patch repair, but it has clearly been shown, that such a coating is not able to prevent the cathodic action for the newly corroding areas, because other areas of the steel surface will act as cathodes for the new macrocell.

However, this conclusion is only valid in cases, where no additional measures are carried out during repair like coating of the concrete surface or other measures like cathodic protection. To take the influence of the different repair principles into account, further points have to be considered as described in the following section.

3. Practical consequences taking the different repair principals into account

As mentioned above the consequences of the corrosion mechanisms shown at the previous sections are different for the various possible repair principles. A systematic overview of possible repair principals for the protection and repair of concrete structures can be taken from the new European standard EN 1504. This standard is based on the RILEM technical recommendation 124-SRC “Strategies for Repair of Concrete Structures Damaged by Steel Corrosion”. Table 1 shows the structure of EN 1504, consisting of ten main standards and about 65 standards for test methods. More details on this European standard are given in [3].

Within EN 1504-9 altogether 11 principles are described for protection and repair of damages from corrosion of the concrete or corrosion of the reinforcement. Principles 7–11 are dealing with repair and protection of damages induced by reinforcement corrosion. Table 2 shows an overview of the principles 7–11 and corresponding methods based on the principles. Table 2 shows also the relevant parameters to design the size of a patch repair. For all methods, where corrosion protection is only insured by replacing the contaminated or carbonated concrete or by painting of critical steel surface areas, the concrete has to be removed in all

Table 1
Structure of EN 1504

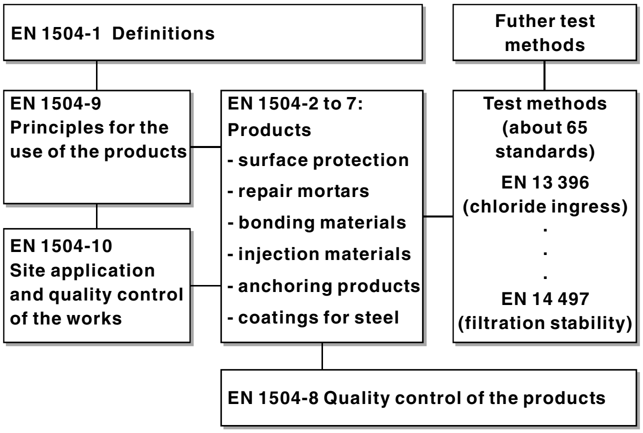

Table 2
Relevant parameters for the design of the size for patch repairs

Principle no.	Principle and its definition	Some examples of methods based on the principle	Size of patch repair
Principle 7 [RP]	Preserving or restoring passivity	7.1 Increasing cover to reinforcement with additional cementitious mortar or concrete	Carbonation/chlorides
	Creating chemical conditions in which the surface of the reinforcement is maintained in or is returned to a passive condition	7.2 Replacing contaminated or carbonated concrete	Carbonation/chlorides
		7.3 Electrochemical realkalisation of carbonated concrete[a]	Structural damages
		7.4 Realkalisation of carbonated concrete by diffusion	Structural damages
		7.5 Electrochemical chloride extraction[a]	Structural damages
Principle 8 [IR]	Increasing resistivity Increasing the electrical resistivity of the concrete	8.1 Limiting moisture content by surface treatments, coatings or sheltering	Structural damages
Principle 9 [CC]	Cathodic control Creating conditions in which potentially cathodic areas of reinforcement are unable to drive an anodic reaction	9.1 Limiting oxygen content (at the cathode) by saturation or surface coating[b]	Actually no methods available
Principle 10 [CP]	Cathodic protection	10.1 Applying electrical potential[a]	Structural damages
Principle 11 [CA]	Control of anodic areas	11.1 Painting reinforcement with coatings containing active pigments	Carbonation/chlorides
	Creating conditions in which potentially anodic areas of reinforcement are unable to take part in the corrosion reaction	11.2 Painting reinforcement with barrier coatings	Carbonation/chlorides
		11.3 Applying inhibitors to the concrete[a,b]	Carbonation/chlorides

[a] These methods may make use of products and systems not covered by the EN 1504 series.
[b] Inclusion of methods in this prestandard does not imply their approval.

steel surface areas, where the carbonation front or the depth of the critical chloride content has reached the steel surface. In this case in Table 2 the short mark "Carbonation/Chlorides" has been noted. In other cases, where the corrosion protection is insured by other measures like limiting moisture content or electrochemical methods, which protect the whole steel surface area, patch repairs can be reduced to the absolute minimum, which in practise means all areas with structural damages, i.e., where adhesion of the concrete surface is damaged or where the concrete quality is unacceptable. In these cases the depth of carbonation or critical chloride content is not the relevant parameter for the design of the size for the patch repair.

However, in certain cases also different approaches may be adequate, which has to be decided by the designer of the measures for protection and repair of the concrete structure.

4. Conclusions and outlook

In cases, where the concrete has to be removed in all areas, where the critical chloride content has been reached, the designer has always to evaluate, which chloride content is critical for the given conditions. As it is commonly agreed, the critical chloride content is not a fixed value, but depending on a lot of factors like:

- Composition of the concrete.
- Execution of the concrete, like compaction, curing, etc.
- Environmental conditions (temperature, humidity, exposition to chloride and carbonation).

Actually in Germany an extensive research project has been set up to investigate the parameters causing damages to the concrete by reinforcement corrosion like cracking and spalling [4]. Within this project not only the depassivating chloride content is investigated, but especially the chloride content initiating damages as mentioned above. The results of this research will be published within the next years as a basis for the designer to decide on the chloride content, which might be left within the concrete without causing any damages.

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