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Cathodic Protection of Concrete Ground Floor Elements with Mixed-in Chloride

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ABSTRACT

Corrosion of reinforcement in precast concrete ground floor elements with mixed-in chloride is a major problem for many privately owned houses in the Netherlands. Conventional concrete repair does not provide durable corrosion protection. Cathodic protection has been installed to protect these ground floors for their remaining service life. The method involves installing sufficient new reinforcement, activated titanium strip anodes and cementitious grouting and a transformer/rectifier in each house. Monitoring procedures have been adjusted to suit the needs of a large number of small CP installations. The materials and equipment used will provide a service life of at least 25 years. The cost of CP compares favourably with other solutions.

1. The Problem

Corrosion of reinforcement in precast concrete ground floor elements containing mixed-in chloride has become a major problem in The Netherlands (Fig. 1), potentially concerning about 100,000 privately owned houses. Concrete damage due to corrosion in some structures had been discovered over 20 years ago. Due to the particular circumstances of these structures it was not then appreciated that it would occur on such a large scale in houses. Specific solutions for privately owned houses have now become necessary.

Normally, carbon steel reinforcement in concrete is protected against corrosion by passivation due to the high alkalinity of concrete. Loss of passivation can only occur due to carbonation of concrete or the presence of chloride ions. In the houses discussed here, a crawling space of about 0.5 m height is present below the ground floor elements. The ground floor elements are supported by the foundation beams, with spans between 3 and 4 m. The soil below the crawling space is usually damp sand or clay, so the concrete is relatively wet. In such conditions, carbonation of concrete is slow. Penetration of chloride from external sources is not relevant. During the sixties and seventies, calcium chloride was mixed into precast concrete in many cases as a set accelerator at typical contents of 0.5 to 2% (total) chloride ion by mass of cement. Passivation is however compromised at some point in time, possibly because of some carbonation or seasonal movements of the evaporation front have increased the chloride content at the steel and active corrosion is initiated. Due to the

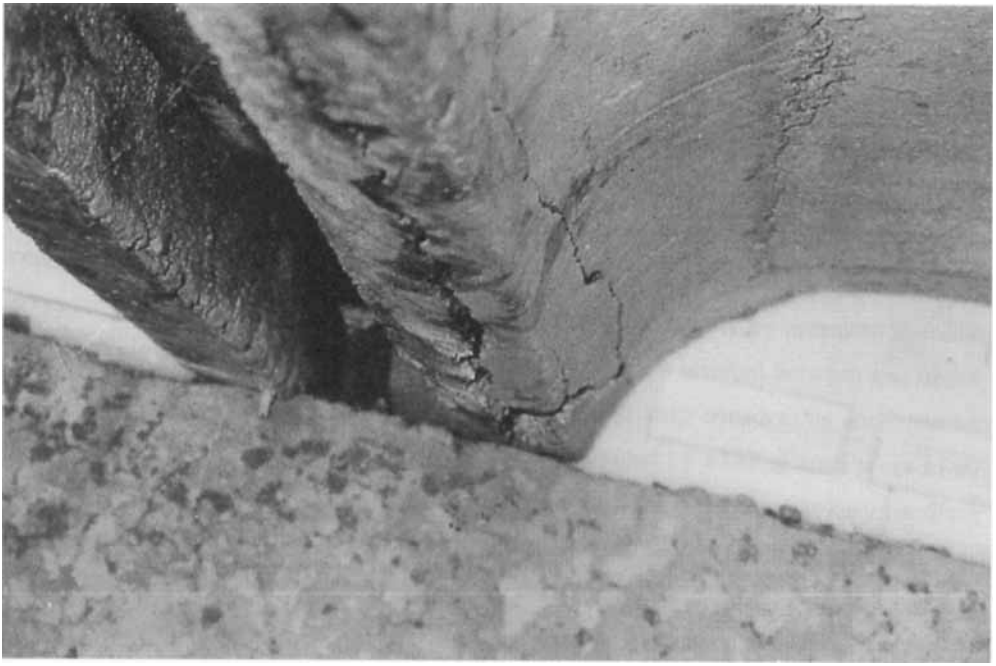

Fig. 1 Heavy corrosion damage in precast ground floor elements.

usually high humidity, subsequent corrosion rates may be quite high. The expanding corrosion products crack the concrete cover until it spalls. Because occupiers do not inspect their crawling space regularly, the problem is not discovered before it has caused a large amount of damage and by that time the steel cross section may have been reduced significantly. In typical cases, structural safety has become impaired after about 20 years service life. In a typical example that will be mentioned more often in this paper, 90% of the elements show corrosion-related damage of the concrete after less than 20 years.

2. Re-installing Structural Capacity and Conventional Repair

An option is to reinstate the strength of the floor elements by an alternative structural system: steel profiles or prestressing cables in plastic ducts (unbonded tendons), supporting the floor fields. The poor accessibility makes practical application of steel beams difficult and consequently expensive. Applying prestressing cables is only economically attractive if at least a number of houses in a row use this method. Another possible option to be considered is conventional concrete repair. Conventional repair requires a high quality of steel cleaning before the application of new chloride-free concrete. This cannot be achieved in practice with sufficient reliability due to the limited working space. Some chloride ions may migrate from the old concrete into the new repair material, so there will always be the risk of new corrosion of rebars. Besides, the rebars in the old concrete are still suffering from corrosion, although this may not yet be visible. Thus, it may be concluded that conventional repair only fights the symptoms and does not solve the real problem. The Dutch Building Decree requires durable safety for the full remaining service life, typically 25 years, which cannot be guaranteed with conventional repairs.

3. Cathodic Protection

The only reliable method to stop the corrosion is provided by electrochemical means. As part of a Eureka research project, cathodic protection (CP) for ground floors was developed and for about 20 years CP of concrete structures has been a practical and effective method. Many apartment buildings with mixed-in chloride in The Netherlands have been successfully protected using CP [1]. However, specific procedures are required for this completely new application to private homes. In comparison to 'normal' concrete CP installations, these systems are small (50 to 100 m^2 concrete surface). Of course, CP cannot bring back the steel which has corroded away so that, where necessary, new reinforcement must be installed.

4. Applying Cathodic Protection to Ground Floor Elements

In the precast ground floors, each element consists of two ribs and a web with a total width of 500 mm. Each rib contains one main rebar of about 12 mm dia. The elements are repaired and CP is applied as follows. First, loose concrete is removed and where heavily damaged, new bars are fixed by welding, so that the amount of steel will meet the original design requirement. The old concrete and the steel are cleaned superficially by means of a needle hammer. Then 20 mm wide activated titanium strip anodes are inserted between and below adjacent ribs as shown schematically in Fig. 2. Anode strip connections are made by spot-welding bare titanium wires. Steel continuity is provided by welding steel wires to all bars in the ribs. Semi-tubular

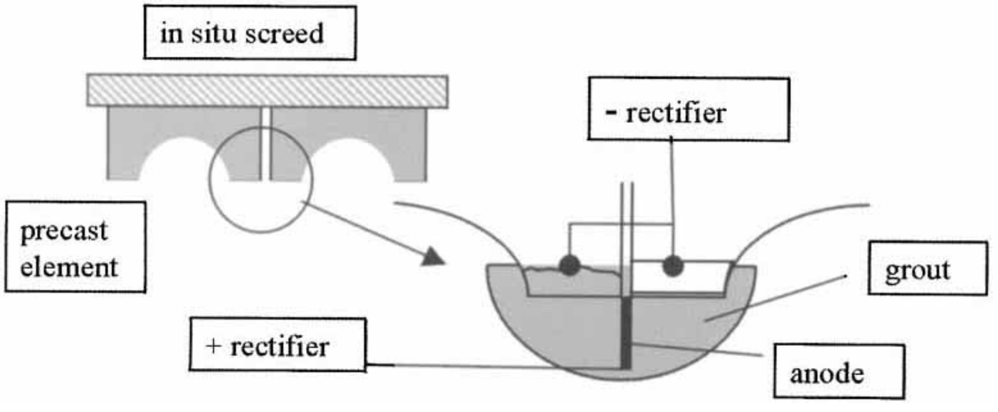

Fig. 2 Schematic cross-section of cathodic crotection for precast ground floor elements.

plastic forms with such a length as to provide easy handling are put together below the ribs to shape a continuous form. The form is filled with flowable cementitious grout from a pump placed outside, completely embedding the anode and any damaged rib parts. The new mortar tightly adheres to the old concrete. Wires connecting anode strips and reinforcement from the floor fields (parts separated by foundation beams) are connected at the transformer/rectifier, which is placed in a cabinet near the front door (also containing the gas and electricity meters).

For economical reasons, the existing regulations for design of CP installations could not be met on all issues. This was dealt with as follows. According to the Dutch recommendation for CP of concrete, CUR 45 [2], the current should be fed into the anode network at a minimum of two points to provide redundancy in case of cable failure. However, connecting the anode strips by spot-welding titanium wire was found to be very reliable in other installations. Moreover, the possibility of damage to the wires is very small due to the closed nature of the crawling space. It is therefore considered acceptable to use just one connection to each anode field. Similarly, CUR 45 prescribes a double connection from the steel cage to the power supply. Again, because of the small possibility of damage to the cables, in these cases it is acceptable to use only one connection per floor field.

5. Life Time Considerations

The service life of this CP system has been estimated as follows [3]. For a design current density of 20 mAm^{-2} steel surface (2 bars of <12 mm dia., see Fig. 2), the titanium anode strip has to deliver 1.5 mA per running metre. The maximum anode current density is 110 mAm^{-2} anode surface, corresponding to 5.5 mAm^{-1}. This leaves a 'safety factor' of over 3, so the lifetime of the anode material itself will be much more than 25 years, probably 100 years or more. The current exchange at the anode will produce acid. In the long term acid attack of the grout may occur, potentially causing failure of the system. The amount of acid generated can be calculated according to Faraday's law. The amount of alkaline substance can be calculated from the cement content of the mortar and the calcium oxide content of the cement. The design current density of 20 mAm^{-2} steel surface would cause dissolution of the cement paste to a maximum of 25% of the grout volume surrounding the anode in 25 years. This is considered to be acceptable as a worst case scenario. Practical experience shows that two effects will mitigate the amount of acid attack that occurs in reality. Firstly, the real current density in the long term is probably 2 to 5 times lower than the design value. Secondly, the net acid production is 5 to 10 times lower than that calculated theoretically, due to migration to the anode of hydroxide ions produced at the cathode [4]. Based on the transport numbers of the ions involved, it can be argued that about 80% of the current is carried by hydroxide ions (produced at the steel), neutralising the acid produced at the anode. Consequently only about 20% of the current will actually cause acid to be formed. The combination of both effects reduces acid production in the anode region at least by a factor of 10, so only about 2.5% of the grout around the anode may be dissolved and consequently acid attack is no threat to a service life of well over 25 years.

The power supply is a specially designed type with a MTBF (Mean Time Between

Failures) of at least 100,000 h at full capacity of 3 A. This means that after an average period of 11.4 years the power supply may fail. The lifetime of this type of electronics is inversely proportional to the temperature, corresponding to the current delivered. In practice the average current is 1 A or less, so the expected lifetime is much longer than 25 years.

6. Test Programme

The CP system described above was installed and tested in one house (the example mentioned above) in November 1998. Subsequently similar systems were installed in 30 houses of the same type during 1999. An intensive test programme is being carried out in some houses, in order to establish safe operating criteria for the whole group. Activated titanium (Ti*) reference electrodes have been installed in these houses. The objective is to determine the average and the maximum (worst-case) current necessary to obtain between 100 mV and 250 mV depolarisation in 24 h. In the activation stage, each installation is tested for anode to cathode resistance and steel polarisation using external silver–silver chloride reference electrodes. Usually, over 100 mV polarisation is obtained in a short time (15 min) after energising. Table 1 reports decay measurements for the first house after three months of CP at 1.4 V driving voltage, resulting in 0.4 A protection current. At three locations there is already a good depolarisation after just 4 h. After the measurements, the voltage was increased to 2.0 V. Table 2 gives average data of three houses measured six to twelve months after energising. Future measurements will include depolarisation over 24 h.

7. Control and Maintenance

The CP system is guaranteed for 10 years full corrosion protection. The guarantee contract requires the owner to check the front panel displays of the power supply once a month and to warn the contractor if they are outside specified 'normal' voltage and current ranges. Once a year full control measurements will be made in order to check the quality of protection and the complete system. The criterion will be:

Table 1. *Depolarisation in 4 h; test house 1 after three months operation at 1.4 V, March 1999; E steel potentials (vs activated Ti, similar to Ag/AgCl), measured 'on', 'instant off', '5 min' and '4 hour'; D depolarisation*

Location	E (on)	E (inst off)	E (5 min)	E (4 h)	D (in 4 h)
1 front door 1	–550	–495	–495	–450	45
2 front door 2	–683	–625	–600	–470	155
3 garage 1	–244	–178	–168	–71	107
4 garage 2	–368	–312	–244	–78	230

Table 2. Average data of three houses (all 76 m² concrete floor surface), November 1999

House	Voltage (V)	Current (A)	Average D in 3 h (mV)
1 (Me)	2.0	0.37	95
2 (El)	2.0	0.55	112
3 (Ho)	2.0	0.24	168

depolarisation in 24 h within 100 and 250 mV. Regarding the frequency of measurements, the existing procedures had to be adapted. According to CUR 45, testing should take place at least twice a year. Because of the closed character of the system and the obligation for the owner to carry out monthly checks it is considered to be safe to use a lower testing frequency.

8. Economic Considerations

Because the CP system described here can be installed very efficiently, this method is about 30% more economic than the alternative structural systems mentioned above (steel beams, prestressing cables). Conventional repair is not acceptable because the problem (reinforcement corrosion) is not solved in a reliable and durable way. This view is based on many cases of failing conventional repair of structures with mixed-in chloride. In such cases, conventional repair will only cover up the damage. In fact, many CP systems in The Netherlands had to be installed because previous conventional repairs had failed after some 5 to 10 years [1]. The owner of the structure remains responsible for possible re-activation of corrosion and subsequent damage in the future. This reduces the economic value of the house. With CP the owner has a fully reliable solution which is acceptable under the existing regulations (Dutch Building Decree), for a lower price than other solutions.

9. Conclusions

From previous experience and research, cathodic protection was developed into a complete solution for corrosion damaged ground floor elements. For economic reasons, some design principles and test procedures had to be simplified. In each case, it was shown that such modifications were acceptable. The life time of the system is estimated to be more than 25 years, matching the legally required remaining service life of the houses. Testing in a few selected houses has shown CP to work well over a period of one year. In this project, CP systems are being installed (1999) in a total of some 30 houses.

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