Pergamon

Cement and Concrete Research, Vol. 25, No. 2, pp. 257-264, 1995

0008-8846/95 $9.50+.00

0008-8846(95)00006-2

COMPARISON OF RATES OF GENERAL CORROSION AND MAXIMUM PITTING PENETRATION ON CONCRETE EMBEDDED STEEL REINFORCEMENT

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(Communicated by C.D. Pomeroy)
(Received August 26, 1994)

ABSTRACT

Local attack of reinforcement is observed usually in chloride-contaminated concrete. When mechanical weakening of the concrete structure is affected by the bar section loss in the places where corrosion is intensified, the maximum penetration of the deepest pits happens to be a very relevant datum. In this work average corrosion values are compared with maximum pit depth values. Using natural corrosion tests and accelerated tests, it has been found that the maximum penetration of localized attack on steel embedded in concrete containing chlorides is equivalent to about four to eight times the average general penetration.

Key words: Chloride-contaminated concrete, reinforcement deterioration, maximum penetration of pits, average general corrosion, damage prediction.

INTRODUCTION

It is well known the harmful role that corrosion of reinforcement plays in the service life of reinforced concrete structures (1,2). This calls for routine assessment of any corrosion process developed on them, preferably by using non-destructive techniques. Nowadays, the continuous or periodic monitoring of corrosion is mainly based on electrochemical measurements. These measurements are referred both to corrosion potential (E_{corr}) and corrosion current (I_{corr}). E_{corr} is related to the likelihood that reinforcements suffer active corrosion (3), and therefore fails to provide an accurate measurement of corrosion rate. This problem is solved with I_{corr} measurements (4,5), although other problems arise in this case, such as those related to the correct interpretation of the measurements.

The values of I_{corr} experimentally determined in reinforcements, even the highest ones, do not seem to imply at first sight too much danger. Values of 1-3 $\mu A/cm^2$ are frequent in active corrosion and only seldom values of the order of 10 $\mu A/cm^2$ or higher are determined (6). Values of 1-3 $\mu A/cm^2$ are equivalent to corrosion rates of 11-33 μm per year, so that it is difficult to understand how from such a low figures a structure becomes unusable in a relatively short period of time, as so happens in some instances.

However, such values are only apparently small. Extrapolating from an assumed constant rate of 20 μm/year up to 50 years, an average attack penetration of 1 mm will be obtained, which means a loss of material equivalent to the 21 per cent of the cross-sectional area of a rebar of 9 mm diameter, which may exceed the safety coefficient. The presence of localized corrosion, with pit depths several times greater than the average corrosion attack, makes the situation worse, especially in prestressed structures. Similar consequences concerning structural safety and serviceability come from the point of view of the concrete cover cracking. So, it has been established (7) that the amount of iron oxide generated during the corrosion of 10-50 μm of metal (depending on rebar diameter) is enough to crack a concrete cover of 2-3 cm. This means that many concrete covers will be cracked after 1-3 years as a result of corrosion rates of only 10-30 μm/year.

The values of I_{corr} are average values referred to the overall reinforcement surface. The integration of these values over the exposure time allows estimate of an average penetration of corrosion (P_{av}), but it does not inform at all about the maximum penetration (P_{max}) of the deepest pits when the attack is very uneven. For life predictions, this P_{max} value may have more importance than the average value when the mechanical weakening of the structure is affected by the bar section loss in those places where corrosion is intensified. P_{max} could be estimated from I_{corr} provided that a ratio (R) between P_{max} and P_{av} could be established.

Despite the practical interest of the matter, little systematic work has so far been done to the writers' knowledge on pitting of reinforcements. A study by Tuutti (8), who determined values of R = 4-10, makes an exception, although he did not include the effect of chloride additions to cement and used an external voltage source as a corrosion accelerator. Some more information on pit depths is found in a number of papers on atmospheric and soil corrosion of bare metals. From these data, values of R ≈ 3-5 for mild and low-alloy steel (9-13) and R ≈ 8-10 for aluminium alloys (14), exposed to different atmospheres, as well as values of R 3.5-15 for buried uncoated steel and cast-iron pipe samples (15,16), have been estimated.

Determination of R in natural reinforced concrete corrosion entails important experimental difficulties, such as to have (a) to break up the concrete sample in order to examine pitting on the reinforcement surface, (b) to wait for a long time (many years) to get, through a natural corrosion process, a sufficient attack to facilitate the survey, and (c) to handle concrete samples of large dimensions (big enough for the examination of an extensive reinforcement surface) in order to arrive at statistically sound conclusions regarding the distribution and size of pits.

These difficulties have, no doubt, contributed to delays in testing this particular aspect.

Both natural and accelerated corrosion testing will be used in this investigation, the latter to verify the feasibility of using a small impressed current (of the order of I_{corr}) to accelerate pitting in laboratory testing of chloride containing reinforced concrete samples.

EXPERIMENTAL

For the natural testing, two types of concrete samples were made of 50 cm x 50 cm x 10 cm and 20 cm x 15 cm x 10 cm dimensions, respectively, having embedded 0.8 cm diameter steel reinforcement. The concrete used in the first type of samples contained 3% of $CaCl_2$ per weight of cement, in order to provoke an active attack on reinforcements. This sample was subjected to repeated periods of wetting-drying, by keeping a water moistened pad on its surface, which were followed by drying periods in the laboratory atmosphere (50-60% RH approx.). The second type of concrete samples contained no admixtures, and were submerged into a natural sea water tank located at the Instituto de Ciencias del Mar (CSIC) of Barcelona. The mean salinity of water was 28 g/l, temperature varied from 14ºC in winter to 24ºC in summer, and oxygen mean content was 5 ppm (17).

After 6 years testing, both types of samples were broken in order to assess the corrosion suffered by the steel reinforcement, i.e. weight loss, attack morphology and pit depth distribution. Weight loss was obtained by comparing the weight per unit length of attacked reinforcement (once all adhered concrete and corrosion products were removed), with that of the unattacked reinforcement. The depth of pitting was measured in different ways, according to convenience. Where pits were big enough a micrometer was directly used. In other cases, the depth was determined from the displacement of an optical microscope objective focussing the external surface and the bottom of the pit successively.

For the accelerated testing, two types of samples were also prepared: (a) mortar samples 2 cm x 5.5 cm x 8 cm, with mild steel bars embedded of 0.6 cm in diameter and a mortar cover of 0.7 cm, and (b) concrete samples 15 cm x 15 cm x 40 cm, with bars of 1.6 cm in diameter and concrete covers of 2 to 5 cm. Both series were prepared with 2 and 3% by weight of admixed $CaCl_2$ to provoke active corrosion from the beginning of test. Anodic currents ranging from 10 to 100 $\mu A/cm^2$ were applied to the reinforcement. A central graphite bar in samples "a" and an external metallic plate placed on the concrete surface (through a wet pad) in samples "b" were used as counterelectrodes. At the end of the test period, when cracking of mortar or concrete cover occurred due to the accumulation of corrosion products (oxide), the samples were broken and pits examined similarly to natural testing.

RESULTS

Natural testing

The examination of the reinforcement that had been part of the sample of dimensions 50 cm x 50 cm x 10 cm exposed to the laboratory atmosphere disclosed a great number of pits, distributed all over their surface, which is normal with highly chloride-contaminated concretes. The study of this specimen was mainly based on two reinforcements: one reinforcement "A" located in front of a crack in the concrete cover (the crack was detected on the third year of testing), and other reinforcement "B" that was all the time under an undamaged concrete cover. In the case of reinforcement "A", the weight loss after the 6 years was equivalent to an average penetration of the attack on all the surface of 0.265 mm (Table 1).

Table 1. Values of R obtained in natural conditions, when the concrete samples containing 3% $CaCl_2$ by weight of cement were submitted to wetting-drying cycles in the atmosphere.

Conditions	Average penetration of attack after 6 years (mm)	Maximum pit depth after 6 years (mm)	R value
Rebar in front of a crack in the concrete cover	0.265	1.20	4.4
Uncracked cover	0.085	0.50	5.9

The deepest pits showed penetrations of the order of 1.20 mm. In this bar, pitting was more abundant and deeper along the reinforcement generatrix coincident with the position of the crack on the concrete. If the average value (0.265 mm) is compared with the depth of the deepest pits, a ratio R between P_{max} and P_{av} of 4.4 is obtained. In the case of reinforcement "B", the weight loss after the 6 years was equivalent to an average penetration of 0.085 mm, which is lower than for reinforcement "A", most likely due to the higher protecting capacity of the undamaged concrete cover. The deepest pits showed depths in the order of 0.50 mm. In this case, R = 5.9.

During the six years of testing, I_{corr} measurements were highly influenced by wetting and drying conditions of concrete, ranging from about 0.1 $\mu A/cm^2$ for dry concrete up to some 7 $\mu A/cm^2$ for very wet concrete.

Table 2 summarizes the characteristics of the attack in samples that were continuously submerged in sea water. The average value of R for all the reinforcements examined gave a figure of 4.5 which is of the order of those previously found. Scatter of data seems to be normal in pitting attack. In these samples the value of I_{corr} increased gradually with time as the chlorides penetrate into the concrete, reaching values of 10-20 $\mu A/cm^2$ after 5-6 years. The total corrosion estimates from curves I_{corr} vs. time gave values in reasonable agreement with the measured weight losses.

<u>Accelerated testing</u>
Tables 3 and 4 show the values of R obtained when an anodic current is applied. They range from 3.2 to 16.1 with an average value of

Table 2. Values of R obtained in natural conditions when the concrete samples were immersed in natural sea water.

Concrete type	Reinforcement	Average penetration of attack after 6 years (mm)	Maximum pit depth after 6 years (mm)	R value
OPC-400 kg/m^3	1N	0.62	5.50	8.9
	2N	0.41	1.51	3.7
	3N	0.41	1.51	3.7
w/c=0.38	5N	0.43	2.15	5.0
OPC-400 kg/m^3	17N	0.53	2.20	4.2
	19N	0.42	1.15	2.7
w/c=0.6	20N	0.47	2.50	5.3
OPC-400 kg/m^3 w/c=0.5	28N	0.38	1.72	4.6
OPC-300 kg/m^3	32N	0.54	2.19	4.1
w/c=0.6	33N	0.40	1.10	2.8

Table 3. Values of R obtained from accelerated tests in mortar samples containing 2% $CaCl_2$ by weight of cement. Application of a current of 10 $\mu A/cm^2$.

Conditions	Test duration	R mean value of 6 rebars
Samples immersed in water	1-3 months	3.2
Samples exposed to RH > 90%	1-3 months	3.7

Table 4. Values of R obtained from accelerated tests in concrete samples containing 3% of $CaCl_2$. Test duration, 1 month.

Concrete cover (cm)	Current ($\mu A/cm^2$)	Number of bars tested	Average penetration of attack (mm)	Maximum pit depth (mm)	R value
2	10	2	0.095	1.20	12.6
	100	3	0.276	1.68	6.1
3	100	5	0.314	1.86	5.9
5	10	1	0.090	1.50	16.1
	100	3	0.263	2.15	8.2

R = 8.2. In spite of the applied current, surface examination revealed a very uneven corrosion, with areas not corroded and others intensely attacked, reproducing in some way the appearance of natural corrosion of reinforcement in concrete.

DISCUSION

The frequent obtaining of $R = R_{max}/P_{av}$ values ranging from about 4 to 8 in natural corrosion, and from 5 to 13 in accelerated testing of reinforced concrete, is a fact of a great practical importance for prediction of residual life of concrete structures from electrochemical I_{corr} measurements. Accordingly, it can be expected that pit growth proceeds 4-8 times or so more rapidly than the instantaneous I_{corr} (average rate) measured. Similarly, the maximum total depth of localized attack will exceed by about 4-8 times the estimated average general penetration deduced from loss in weight after a given exposure time.

Certainly, the above conclusions are provisional while a meticulous statistical study on a large number of samples is not accomplished. It is interesting to note that the furnished data appear to agree among themselves and, as mentioned, with other data reported for bare metals in the atmosphere or in the soil. The resemblance among R values in different circumstances recalls other similarities between the mechanisms of concrete corrosion and atmospheric corrosion already emphasized (18).

A rigorous approach to pitting corrosion should involve the combined use of a great amount of field measurements, statistical analysis and mechanistically based modelling. Extreme value statistics may provide an approximate method of predicting the maximum pit depth in a given area (19). Analysis of many samples is required, where the number of pits and the depths of all of them have to be measured. In the statistical analysis, conflict with the physical limits on pit growth kinetics can exist and significant progress is still needed in the development of realistic models (20). In a general treatment, progress of pits with time should also be considered; especially the effect of time on the number, distribution, total area and volume of all pits.

The value of R depends on the penetration rate (V_{max}) for the deepest pits and the average corrosion rate (V_{av}) for the whole exposed surface. The complex nature of the pitting process makes it difficult to predict the effect of the different variables on R. It is foreseeable that V_{max} be more or less influenced, according to experimental circumstances, by (i) diffusion of corrosion products and species concerned in the pit propagation process, (ii) activation energies of the anodic and cathodic processes, and (iii) electrical resistance between the anodic and cathodic areas. On the other hand, V_{av} is a complicated function of (i) presence of heterogeneities that act as nuclei for pit initiation, (ii) alteration of potential distribution around a established pit in a sense unfavourable to the starting of new pits (anodic dissolution of metal within a pit renders the surrounding region insufficiently anodic for the beginning of fresh pitting), (iii) resulting total number of pits on the metal surface and distribution of pit shapes and sizes, (iv) pit growth kinetics, and (v) rate of attack of the remaining metal surface unaffected by the pits.

A theoretical justification of the observed values of R should include a study in depth of all the above points, and for this purpose essential information is lacking. Fortunately, the empirical fact that R values of 4-8 are often obtained, in spite of the number of variables that in theory will affect R, may be used as a basis for approximate predictions of residual service life.

CONCLUSIONS

1. It has been found that the maximum penetration of the localized attack on steel embedded in concrete containing chlorides is equivalent to about four to eight times the average penetration of the attack on the overall reinforcement surface. This relation does not differ too much from similar relations reported for the corrosion of metals in the atmosphere or in the soil.

2. The study of pitting corrosion on reinforced concrete can be accelerated by using an impressed anodic current. Values of R rather similar, although slightly higher, to those found under natural conditions have been obtained with the application of 10-100 $\mu A/cm^2$ to reinforcements in concrete containing chlorides.

3. The knowledge of R may be useful for estimation of the residual life of concrete structures from on-site I_{corr} measurements.

ACKNOWLEDGMENTS

This work was suported by the Comisión Interministerial de Ciencia y Tecnología (CICYT) of the Ministry of Education and Science of Spain. The authors are indebted to M. Teresa Gutierrez of "E. Torroja" Institute for careful and patient measurement of pits in reinforced concrete samples exposed to sea water.

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