Pergamon

Cement and Concrete Research, Vol. 26, No. 5, pp. 691-696, 1996
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0008-8846/96 $15.00 + .00

PII S0008-8846(96)00043-9

STEEL CORROSION MONITORING IN NORMAL AND TOTAL-LIGHTWEIGHT CONCRETES EXPOSED TO CHLORIDE AND SULPHATE SOLUTIONS
PART II: POLARISATION RESISTANCE MEASUREMENTS

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(Communicated by F. Massazza)
(Received December 13, 1995; in final form Feburary 26, 1996)

ABSTRACT

The paper reports on long time testing of reinforcement corrosion in high strength normal and total-lightweight concretes exposed to cycles consisting of 4 phases: chloride salt fog, drying, sulphate solution immersion, drying. Polarisation resistance monitoring performed for evaluating corrosion rates confirmed passive condition for all reinforcements embedded in normalweight concretes. The initiation of the corrosive attack was detected in all the reinforcements in total-lightweight concretes. Corrosion rates up to 400 μm/year were detected.

Introduction

Suitable measures should be adopted to cope with chemical, physical and mechanical degradation of concrete and with reinforcing bar corrosion phenomena in reinforced concrete structures. A proper mix design is the basic requirement for providing enough low permeability to concrete, so that its degradation can be avoided and reinforcement can be protected.

This work deals with the evaluation of the protective properties of different types of normalweight and total-lightweight concrete (1,2), as far as corrosion of reinforcement in concrete subjected to exposure cycles of sulphate solution and chloride salt fog is concerned. The results discussed in Part I (3) showed that potential of reinforcement embedded in total-lightweight concrete was remarkably affected by exposure conditions and it was impossible to detect the initiation of corrosive attack by potential monitoring, owing to a wide overlapping of the potential ranges indicating active and passive conditions. Furthermore, it is well known that potential monitoring is aimed only at detecting the corrosion condition of steel in concrete, but no information can be obtained regarding the corrosion rate, which can be evaluated, for instance, by polarisation resistance measurements.

In this second part, the results of polarisation resistance monitoring are discussed and compared to potential measurements in order to clearly assess the corrosion condition of reinforcements and to evaluate the degree of attack in relation to the concrete mixture.

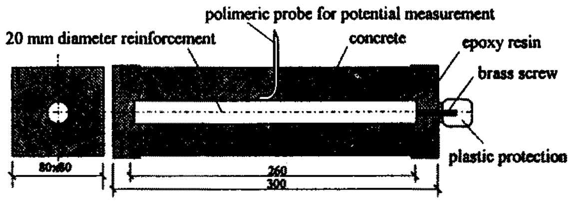

FIG. 1.
Reinforced concrete specimens for corrosion tests (dimensions in mm).

Experimental

Tests were performed on the reinforcement concrete specimens described in Part I (3). Corrosion rate was evaluated by measuring the polarisation resistance (R_p). R_p was calculated as the average slope of the straight part of the potential/current density curves drawn in range ± 10 mV Vs the corrosion potential, both in forward and in reverse potentiodynamic polarisation.

This type of test was performed on one specimen for every type of concrete. These specimens were equipped with membrane probes (4) in order to obtain a measurement of the potential close to the reinforcement (Fig. 1), so that ohmic drop due to the current flowing through the concrete was negligible. A scan rate of 0.2 mV/s was adopted. Corrosion current density (i_{cor}) was then evaluated with the relation: $i_{cor} = k/R_p$, assuming 26 mV for the constant k.

At the end of each cycle of exposure, profiles of total chloride content were measured on 10 × 10 × 10 cm concrete specimens made with the same concretes of the reinforced specimens and submitted to the same curing and exposure conditions. The profiles were determined, up to a depth of 4 cm, by dry cutting concrete slices with about 1 cm of thickness, crushing them and determining the total chloride through the chemical analysis procedure described in Part I (3).

Results

Polarisation resistance measured on the reinforcements embedded in normalweight concrete specimens (Fig. 2) was roughly constant during the entire test period and showed values approaching 100 $\Omega \cdot m^2$ corresponding to a very low corrosion rate, lower than a fraction of a micrometer per year (Table 1). Actually, chloride content at the reinforcements depth was lower than the usual critical chloride threshold of 0.4–1% by weight of cement for corrosion initiation.

Reinforcements embedded in total-lightweight concrete exhibited initially stable polarisation resistance values around 20–30 $\Omega \cdot m^2$ denoting corrosion rates 3–5 times higher than rates observed in normalweight concrete. After about two years of exposure, the polarisation resistance started to decrease, reaching values lower than 1 $\Omega \cdot m^2$ (Fig. 2) which correspond to very high corrosion rates, above 25 µm/year. The decrease in polarisation resistance is due to the initiation of localised corrosion when the critical chloride content is reached in the vicinity of the reinforcement surface. Fig. 3 confirms that the critical content is between 0.4% and 1% of cement weight. Anomalous results were obtained on specimens with the intermediate cement content (340 kg/m^3) both for portland slag cement and for portland cement + PFA, where R_p measured on reinforced specimens only slightly decreased although a chloride content above 1% was observed at 3.5 cm depth in non-reinforced specimens.

Very low potential and R_p values, i.e. very high corrosion rates, were reached when corrosion propagation gave rise to longitudinal cracks in the concrete cover. After 13 cycles all the total-

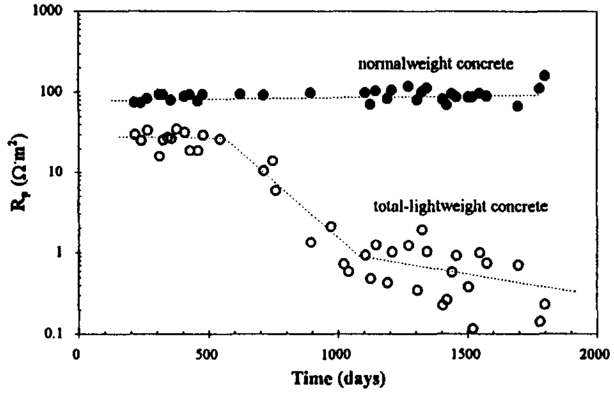

FIG. 2.
Example of polarisation resistance of reinforcements in total-lightweight and normalweight concrete as a function of time (specimens with 400 kg/m³ of portland cement + PFA).

lightweight concretes were cracked. Some specimens were completely cracked and their corrosion current densities were very high, close to 100 mA/m² or even higher (Table 1) denoting that the cracked concrete was not able to further protect the reinforcements from the external environment. However the specimens with the intermediate cement content were only slightly cracked.

Fig. 4 shows that corrosion initiated since the 7th cycle (about 900 days of testing) in the specimens with a 280 kg/m³ cement content. Reinforcements in concretes with the highest cement content (400 kg/m³) reached polarisation resistance values lower than 10 Ω · m² after just 5 cycles (about 600 days) when portland slag cement was used and 6 cycles (700 days) for specimens with portland cement + PFA. Specimens with a cement content of 340 kg/m³ exhibited only a slight decrease during the 13th cycle (1700–1800 days) and the polarisation resistance decreased slightly below 10 Ω · m².

TABLE 1
Average Corrosion Rate (mA/m²) Measured After Exposure to Sulphate Solution in Different Periods by Polarisation Resistance Measurements (1 mA/m² = 1.17 µm/year)

Type of cement	Cement	Testing time (days)			
	(kg/m³)	430	1030	1440	1800
Normalweight concretes					
Portland slag	400	0.3	0.3	0.3	0.2
	340	0.3	0.2	0.3	0.2
	400	0.3	0.2	0.2	0.2
Portland + PFA	400	0.8	0.6	0.3	0.8
	340	0.6	0.2	0.2	0.3
	400	0.5	0.3	0.4	0.3
Total-lightweight concretes					
Portland slag	280	1.4	36.4	45.0	182.5
	340	0.8	2.0	2.1	5.1
	400	1.4	4.7	422.1	307.0
Portland + PFA	280	1.1	88.4	99.3	102.3
	340	1.1	0.9	1.2	4.7
	400	0.8	47.0	168.8	444.3

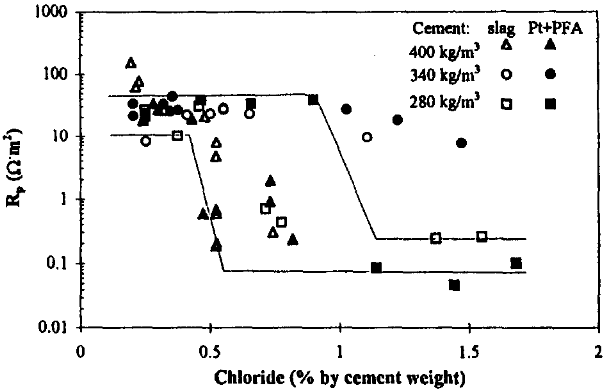

FIG. 3.
Polarisation resistance of reinforcements embedded in total-lightweight concrete as a function of chloride content at 3.5 cm depth, measured in non-reinforced specimens (after 50% R.H. exposure).

Discussion

Data from polarisation resistance measurements are in good agreement with potential measurements reported in Part I (3). However, the polarisation resistance data gave clear information on the corrosion evolution also for total-lightweight concrete specimens whereas potential monitoring was ambiguous.

Passive condition of reinforcement are pointed out by both high potential and high R_p values and the active corrosion conditions progressively reached on reinforcements in total-lightweight concrete is denoted by a decrease of free corrosion potential and R_p, as for instance shown in Fig. 5 which reports data obtained after exposure to sulphate solution.

Polarisation resistance measurements show that the total-lightweight concrete specimens have lower resistance against reinforcement corrosion in comparison with the normalweight concrete specimens. This can be attributed to the high porosity of the total-lightweight concrete (3) which allows the absorption of high amounts of salts during periods of exposure to moist environments (NaCl fog and sulphate solution). Ions remain inside concrete following the evap-

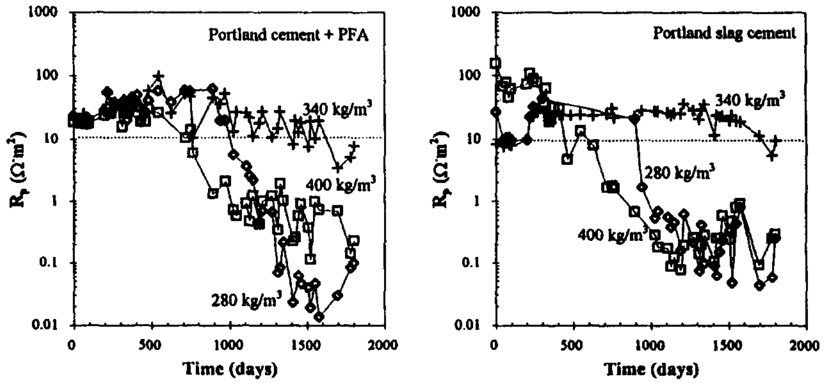

FIG. 4.
Polarisation resistance monitoring of reinforcements embedded in total-lightweight concrete.

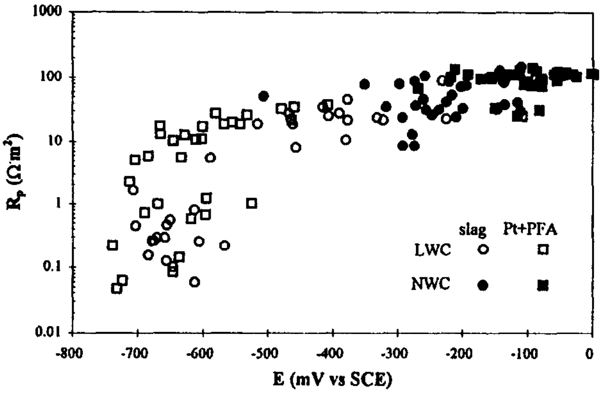

FIG. 5.

Relationship between polarisation resistance and free corrosion potential measured after the exposure to sulphate solution (LWC = total-lightweight concrete; NWC = normalweight concrete.

oration of water during dry periods (50% R.H). Thus a very high concentration of sulphate and chloride ion builds up and tends to migrate towards reinforcement owing also to capillary absorption phenomena.

Fig. 6 shows the apparent diffusion coefficient (D_e) and the chloride surface concentration (C_s) calculated by interpolation of chloride content profile determined at the end of the 13th cycle with the pure diffusion model (5), integrating the Fick's second law in the hypotheses that both C_s and D_e are constant during the testing period. Higher values of C_s and D_e are evident for the total-lightweight concrete in comparison with normalweight concrete. It should also be noted that these values are evaluated through the chloride content profiles measured in non-reinforced specimens and, thus, do not take into account cracking of concrete occurred in reinforced specimens after corrosion initiation, which favoured further chloride migration towards the reinforcement.

Concerning the type of cement, it can be underlined that, as far as the results presented in this paper are concerned, corrosion initiation on reinforcement embedded in total-lightweight concrete was not significantly different in specimens with portland slag cement or with portland cement + PFA.

Conclusions

The utilisation of lightweight aggregate both for fine and coarse aggregate instead of normal density aggregate brought about a reduction of protective properties of concrete with regard to reinforcement corrosion, owing to a greater porosity and, thus, to a higher absorption of aggressive solutions. As far as total-lightweight concretes utilised in this work are concerned, a similar behaviour was observed regardless of the specific mix design, although an early initiation of corrosion occurred on reinforcement in total-lightweight concretes with the highest binder content.

The evaluation of corrosion rate by means of polarisation resistance measurements pointed out the evolution of corrosion on reinforcements giving in all cases a clear interpretation even where potential monitoring was ambiguous, that is on total-lightweight concrete specimens.

Corrosion rate of reinforcements in total-lightweight concrete was higher compared to reinforcements in normalweight concrete even during the first period, in passive condition. After

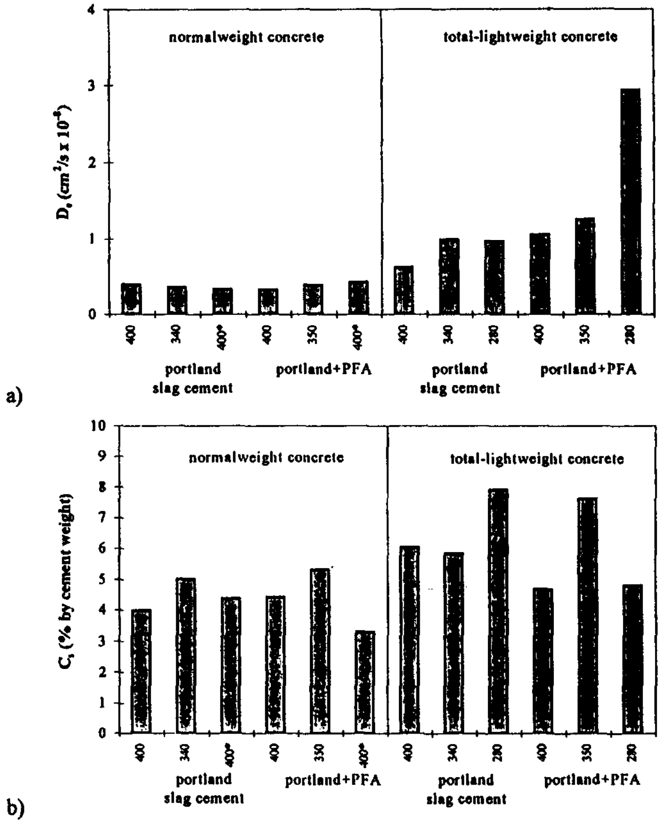

FIG. 6.

Apparent diffusion coefficient (a) and surface concentration (b) evaluated from total content profiles of chloride measured after 13 cycles of exposure.

corrosion initiated owing to chloride ions penetration, corrosion rate increased to values up to 25–400 μm/year.

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