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STEEL CORROSION MONITORING IN NORMAL AND TOTAL-LIGHTWEIGHT CONCRETES EXPOSED TO CHLORIDE AND SULPHATE SOLUTIONS PART I: POTENTIAL MEASUREMENTS

Giulia Baronio°, Mario Berra°°, Luca Bertolini°°°, Tommaso Pastore°°°°
°Dipartimento di Ingegneria Strutturale del Politecnico di Milano
°°ENEL SpA/CRIS, Milano
°°°Dipartimento di Chimica Fisica Applicata del Politecnico di Milano
°°°°Facoltà di Ingegneria, Università degli Studi di Bergamo

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ABSTRACT

The paper reports on long time testing of reinforcement corrosion in normal and total-lightweight concretes exposed to cycles consisting of 4 phases: chloride salt fog, drying, sulphate solution immersion, drying. Potential monitoring evidenced a passive condition for all reinforcements embedded in normalweight concretes. The initiation of the corrosive attack in total-lightweight concretes could not be evidenced, although low potential values were found on corroding reinforcements.

Introduction

Corrosion of reinforcing steel is one of the main causes of reinforced concrete structures degradation. It can reduce the "service life", i.e. the period of time during which the structure can maintain the minimum requirements regarding safety, stability and functionality. Recent experience shows that structures, designed for a service life of several years, show worrying degradation symptoms just few years after their construction.

This work deals with the evaluation of the protective properties of several types of concrete, mixed with different types and contents of cement and aggregate, as far as corrosion of reinforcement in concrete structures exposed to very aggressive marine environments is concerned (1–3). Concretes with normalweight aggregates as well as concretes cast with coarse and fine sintered fly ash lightweight aggregates have been considered. Total-lightweight concrete could be suitable to decrease the density and increase the specific strength of concrete for floating structures. Reinforced concrete specimens have been exposed to cycles of chloride-salt fog and sulphate solution. Results of free corrosion potential monitoring are here reported. Part II (4) will discuss the polarisation resistance measurements.

TABLE 1
Characteristics of Concretes

Type of cement	Aggregate (kg/m^3)	Max dim. aggregate (mm)	Cement + silica fume (kg/m^3)	w/c[1]	Density (kg/m^3)
Normalweight concretes					
Portland slag	1780	30	400 + 40	0.42	2407
	1840	30	340 + 34	0.49	2402
	1730	15	400 + 40	0.46	2366
Portland+ PFA	1750	30	400 + 40	0.44	2355
	1800	30	350 + 35	0.49	2362
	1700	15	400 + 40	0.48	2324
Total-lightweight concretes					
Portland slag	1053	12	400 + 40	0.31	1781
	1092	12	340 + 34	0.36	1757
	1132	12	280 + 28	0.44	1730
Portland+ PFA	1034	12	400 + 40	0.33	1755
	1068	12	350 + 35	0.38	1748
	1129	12	300 + 30	0.44	1731

[1] (free water+additive)/(cement+silica fume)

Experimental

Twelve types of concrete were prepared. Six were ordinary (normal density) concretes with crushed limestone normalweight aggregate and six were total-lightweight concretes with sintered fly ash aggregate (fine particles were obtained by crushing the lightweight coarse aggregate).

The mixture proportions are described in Table 1. Two types of cement were utilised: a portland slag cement (CEM II/B-S 42.5R according to ENV 197/1, containing 30% slag) and a portland cement (CEM I 42.5R) mixed with 30% pulverised fly ash (PFA). Both portland + PFA and portland slag cements were added with silica fume in the concrete mix (10% by weight). A superplasticizer and air-entraining admixture, especially developed for lightweight concrete (1), was used (5% by weight of cement + silica fume) and a commercial superplasticizer based on a mix of naphtalene and melamine compounds was used in the normalweight concretes (2% by weight of cement + silica fume). The concretes were designed in order to obtain a workability of 4–5 s Vebe. Thus, (water + additive)/(cement + silica fume) ratio varied within 0.31 and 0.44 for lightweight concretes and within 0.41 and 0.49 for normalweight concretes. Further and more detailed information about materials, mix design and the physical and mechanical behaviour of the different concretes is reported elsewhere (3). 28-day compressive strength (determined on 15 × 15 × 15 cm cubes) varied between 40 and 60 MPa for total-lightweight concretes, whereas normalweight concretes exhibited values ranging from 60 to 90 MPa.

Three prismatic specimens with dimensions of 8 × 8 × 30 cm for every type of concrete mixture were used. The reinforcement was a sand blasted carbon steel rebar with a diameter of 20 mm and was placed in the centre of the specimen, the minimum concrete cover thickness being 30 mm. Both ends of the specimens were coated with epoxy resin. Specimens were demolded one day after casting and cured at 20°C and 95% R.H. for roughly 1 year.

Specimens were subjected to aggressive cycles, at room temperature, alternating exposure to salt fog with a 3% NaCl solution to immersion in a 14,78 g/l Na_2SO_4 solution, spaced by drying periods at 50% R.H. The length of each period was at least 15 days. The exposure to sulphate solution was realised with a partial immersion of the specimens in the sulphate solution so that the top of the specimen was exposed to 50% R.H.

The free corrosion potential of reinforcement was measured at the end of each exposure period, in a the NaCl solution for the measurements carried out before and after the salt fog

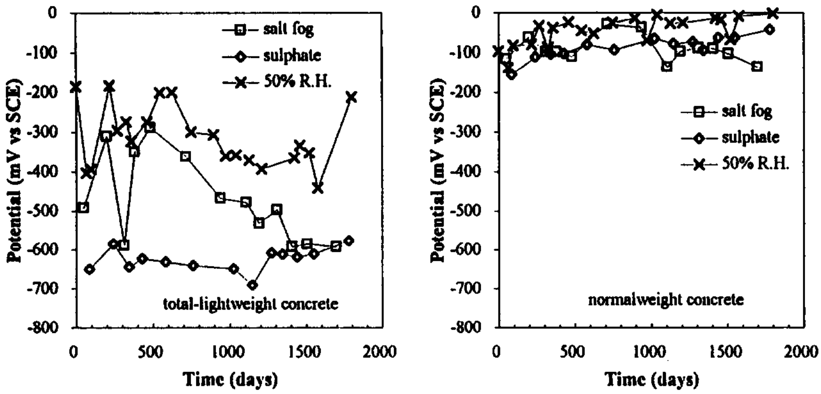

FIG. 1.
Example of the effect of exposure condition on the potential of rebars embedded in total-lightweight and normalweight concrete (400 kg/m3 of portland cement + PFA).

period or in the Na_2SO_4 solution for the measurements carried out before and after the sulphate period, by using a saturated calomel reference electrode (SCE).

The chloride content of concrete was evaluated by means of chemical analysis on 10 × 10 × 10 cm unreinforced specimens subjected to the previous exposure condition. The total chloride content was determined by precipitation with a surplus of silver nitrate solution and titration of residual silver nitrate with ammonium thiocyanate solution, using ammonium iron (III) sulphate salt as indicator.

Results

The rebar in ordinary concretes exhibits noble free corrosion potentials which do not change substantially with the exposure environment. On the contrary, the corrosion potential of specimens with total-lightweight concrete shows wide fluctuations, even higher than 400 mV, and very low potentials are reached after immersion in the sulphate solution, whereas the noble values are only observed after drying periods at 50% R.H. (Fig. 1).

The different behaviour can be pointed out also by a statistical analysis (Figs. 2 and 3). The distribution of potentials measured on specimens with normalweight concrete shows a 200–240 mV wide peak around -150 mV for portland slag cement and -70 mV for portland cement + PFA. Anomalous values, below this range, were measured during the first cycles and only on a few specimens; however, even on these specimens, the potential progressively raised to reach potential within the peak range. Potential distribution is quite similar in the different exposure conditions. Only the central value of the peak slightly changes: at the end of periods of exposure to sulphate solution potential values tend to be about 40 mV lower compared to those observed at the end of the exposure to 50% R.H.; values observed at the end of exposure to salt fog exhibit an intermediate behaviour.

More complex is the potential distribution on total-lightweight concrete specimens. Potential values are distributed within a wide range, between -700 and -50 mV. Potential distributions in the different exposure periods are quite dissimilar: potentials measured at the end of exposure

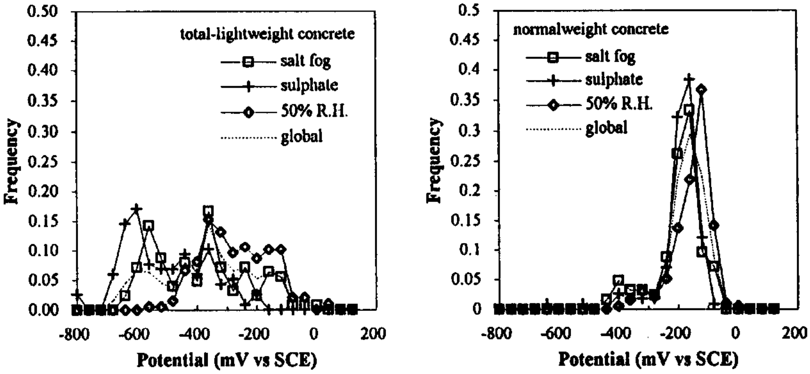

FIG. 2.
Statistical analysis of rebar potential of specimens with 400 kg/m3 of portland slag cement.

to sulphate solution tend to be lower and show a peak, particularly evident for portland cement + PFA specimens, around roughly -600 mV. At the end of periods of exposure to 50% R.H., potential values within -470 mV and -70 mV are observed, and after salt fog exposure intermediate values or values similar to those found after 50% R.H. are observed.

Discussion

Potential measurements show a passivity condition on all rebars of specimens cast with normalweight concrete, even after 13 cycles of exposure (carried out in 5 years). In fact, free corrosion potential is constant with time and, thus, being rebar corrosion unlikely in the first period, no corrosion initiation occurred. The range of potential below the peak in the statistical distribution can be assumed as representative of the variability of the potential for passive steel. Assuming the lower limit for the passivity range as the potential value above which 90% of measures fall, values of -200 mV SCE for normal concrete with portland cement + PFA and -280 mV for portland slag cement normal concrete can be obtained (Fig. 4). Furthermore, the potentials evi-

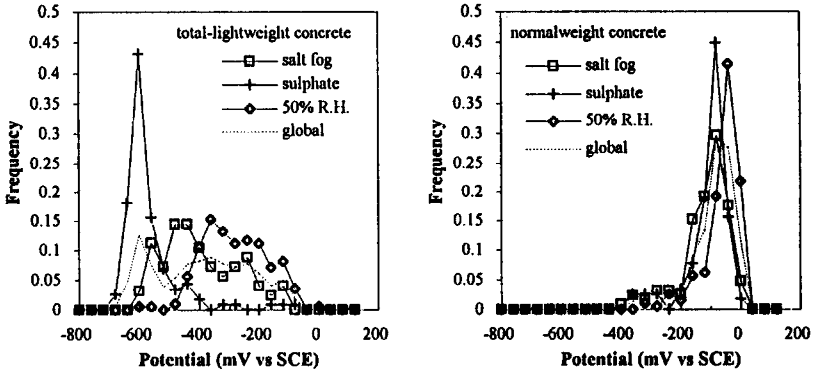

FIG. 3.
Statistical analysis of rebar potential of specimens with 400 kg/m3 of portland cement + PFA.

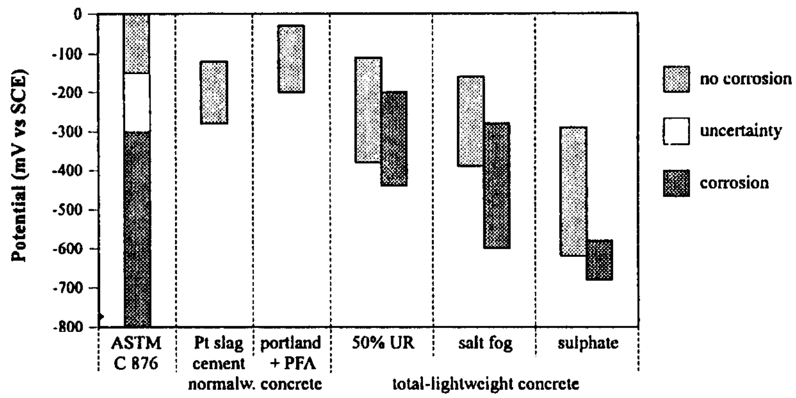

FIG. 4.
Potential ranges (10% to 90% of cumulative frequency) for rebars in active and passive corroding state as a function of concrete type and environment.

dence a major influence of cement type and a minor effect of the environmental conditions with potential changes less than 40 mV between the periods of exposure to different environments (Figs. 2 and 3).

Fig. 4 also compares the potential ranges assessed on passive reinforcements in the normal concretes with ASTM C 876–87 criteria. It is evident that these criteria do not give a reliable interpretation of the potential measurements, inasmuch as both concrete mixture and environmental conditions are not taken into account.

Interpretation of corrosion potential measured in lightweight specimens is difficult. Statistical analysis reported in Figs. 2 and 3 is not itself enough to outline a reliable criterion. However, it demonstrates that rebar potential values remarkably vary with the exposure condition and are lower with respect to those measured in normalweight concrete.

After long time testing, an appreciable chloride concentration built up at the reinforcement depth and reinforcement corrosion initiated as showed by results of polarisation resistance mea-

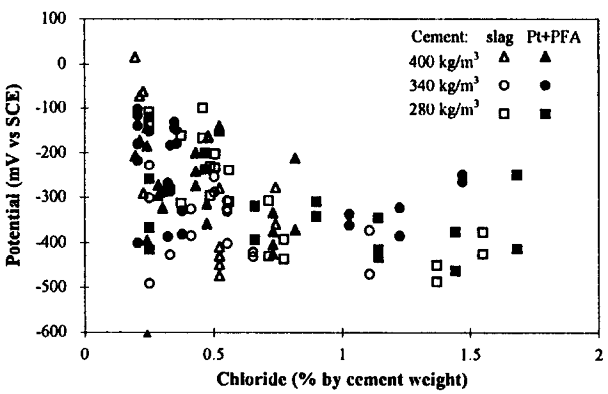

FIG. 5.
Potential of rebars embedded in total-lightweight concrete (after 50% R.H. exposure) as a function of chloride content measured in non reinforced specimens at a depth of 3.5 cm.

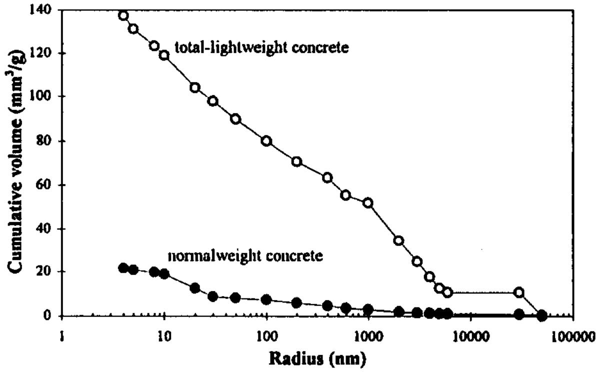

FIG. 6.
Porosity of total-lightweight and normalweight concrete with 400 kg/m3 of portland slag cement, measured with mercury porosimetry.

surements reported in Part II (4). Free corrosion potential approached very low values, as reported for instance in Fig. 5 regarding measurements carried out at 50% R.H.

In order to assess the potential ranges for active and passive conditions of rebars in total-lightweight concrete, the distribution of potential measurements performed during the first 500 days, representative of passive condition, and the distribution of potential measured after 1000 days of testing, representative of active corrosion conditions (see also the results discussed in Part II) has been considered. Fig. 4 reports the potential ranges within which are included 80% of measurements (from 10% to 90% of cumulative frequency). However, also considering that the activity range is below -200, -260 and -580 mV SCE respectively after exposure to 50% R.H., salt fog and sulphate solution and the passivity range is above -370, -380 and -620 mV respectively, it was not possible to detect the initiation of corrosive attacks by analysing the time evolution of free corrosion potential.

Regarding the remarkable influence of the environment on rebar potential in total-lightweight concretes, it can be noted that they exhibit a much higher porosity with respect to normalweight concretes (see example of Fig. 6). The higher total porosity and the different pore size distribution could promote a great variability of environmental conditions inside total-lightweight concrete (for instance, regarding oxygen presence) hence causing the high variability of free corrosion potential.

Conclusions

Free corrosion potential of reinforcement exhibited a variability related to the type of concrete and the exposure conditions. The variations induced by environmental changes were particularly evident in total-lightweight concretes. Consequently, potential measurements could not be analysed according to ASTM C 786–87 criteria. Interpretation criteria more appropriate to the specific situation were assessed by statistical analysis of potential values.

Fully passive conditions were outlined for all reinforcements in the normalweight concretes in five years testing. Nevertheless, potential monitoring could not give any evidence of corrosion initiation on reinforcement embedded in total-lightweight concrete, owing to the overlapping of activity and passivity range and the wide variability induced by environmental exposure.

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