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Steel rebars corrosion investigation with strain gages

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Abstract

The presentation of a new laboratory, non-destructive method of detection and checking the corrosion of steel rebars in mortar specimens is discussed in this paper. The method uses extensive meter sensors, such as the well known strain gages (SG) and is based on the phenomena of tension state, in which the mortar mass comes near the rebar area, after the formation of corrosion products. The SG are embedded in reinforcing mortar specimens during casting. Specimens are immersed in a 3.5 wt% NaCl solution and a constant potential is applied between steel rebar and graphite electrode in order to obtain fast corrosion conditions. As the embedded SG are affected by volume changes, caused not only by corrosion products, all other disturbing parameters have been compensated for by the measurement method described. The method was applied in different types of mortar specimens in order to have test and verification results. The reliability of the technique was evaluated by measuring: (a) the gravimetric weight loss of the reinforcing steel bars; (b) the electrical charge flow through specimens; and (c) the porosity of mortar mass. The test results obtained indicate that the method is reliable and suitable for the laboratory study of the corrosion factors and the influence of concrete admixtures in corrosion protection. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Strain gage; Corrosion; Reinforcing rebars

1. Introduction

It is known that the high pH value (greater or equal to 12.5) of the pore solution of concrete causes the passivation of the embedded rebars, due to the creation of a Fe_3O_4 or γ-Fe_2O_3 tightly adhering very thin film [1,2]. This passivation can be destroyed by the diffusion of the aggressive species of the corrosion environment to the area of the reinforcement.

Penetration of the porous concrete matrix by chloride ions, water and oxygen leads to corrosion of the steel and forms corrosion products that are generally referred to as rust. Having significantly greater volume than the original iron the corrosion products may develop the tension in the steel rebar/concrete interphase.

Thus, the corrosion of reinforcements may cause the delamination and the spalling of the concrete cover, which may cause the intensification of the corrosion and finally the failure of the reinforced structure. Therefore, the early detection and the checking of the condition of reinforcing bars by nondestructive techniques are very important.

Regarding the laboratory techniques studied to check the corrosion of steel reinforcement, we could point out the electrochemical methods such as polarization curves which have been widely used, mainly to compare the effect of concrete admixtures [3].

The polarization resistance technique Rp also developed by Stern and Geary, was applied to steel bars embedded in concrete or mortar specimens to study the corrosion rate, utilizing a number of variables related to the concrete and cement by Andrade and Gonzalez [4,5].

Recently John et al. and Venger et al. applied the AC impedance technique after the study and proposal of electrical models simulating the system steel in concrete [6]. The above techniques were generally accompanied by the gravimetric weight loss method, in order to confirm their accuracy.

Further, we note the method of electrical resistance, based on the weakening of the cross-section of the reinforcement and the subsequent increase of its electrical resistance, as a result of corrosion [7]. Recently this method has been improved using the so called corrosion sensor by Zivica [8]. This improvement overcomes some disadvantages of the former method due to the influence of ambient temperature changes amongst others.

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The technique presented is based on the mentioned tension appearance caused by steel corrosion products. This tension is monitored by embedded Strain Gage extensivmeters. Compensation is provided during measurement because of disturbing effects, such as, ambient temperature and specimen volume changes.

The method is evidently a nondestructive one, directly related to the corrosion products formation and for the time being it is a laboratory technique.

2. Materials and methods

2.1. Materials

The chemical composition of OPC, CKD, P35 (OPC with pozzolans as flying-ash or Santorini Earth) and steel used in casting the reinforced specimens are shown in Tables 1 and 2. Sand (BS 4550: Part 6), drinking water and corrosion inhibitors are also used.

CKD (Cement Kiln Dust) is a by-product of the low-alkali cement manufacturing process, mainly containing calcium carbonate and is classified as a calcareous additive.

Two types of corrosion inhibitors of steel in concrete are used: Inhibitor-A is a corrosion inhibitor based on aminoalcohol action; Inhibitor-D is a corrosion inhibitor based on $Ca(NO_2)_2$ action.

2.2. Specimens casting

The mortar test specimens were in the form of 80×80×100 mm prisms. The steel bars (diameter 12 mm) were machined on a lathe to a final diameter of 10 mm. They were washed with water, immersed for 15 min in a strong HCl solution with inorganic corrosion inhibitor, washed with distilled water, alcohol and acetone and then were weighed to an accuracy of 0.1 mg (ISO/DIS 8407.3).

Table 1
Chemical composition of materials (%)

	OPC	CKD	P35
SiO_2	20.67	13.68	27.38
Al_2O_3	4.99	4.36	9.10
Fe_2O_3	3.18	2.30	5.65
CaO	63.60	42.59	45.39
MgO	2.73	1.23	2.73
K_2O	0.37	0.79	0.94
Na_2O	0.29	0.28	0.56
SO_3	2.44	0.10	2.71
LOI	1.52	–	5.04
IR (ISO)	0.21	–	–
CaO (f)	2.41	–	2.67

Table 2
Chemical composition of steel (wt%)

Fe	Mn	S	C	P
99.23	0.56	0.07	0.11	0.03

The bars were embedded in the mould up to a depth of 15 mm. Thus, the area of bars active to corrosion was 26.7 cm^2. The mortar moulds were stored in the curing room. The specimens, after being demoulded, were cured in water at 20° for 7 days and then left to dry for 24 h. A copper wire cable was connected to each steel bar and the specimens were covered with epoxy resin Araldite to protect the connection of steel with copper cable against corrosion, as shown in Fig. 1. Then they were immersed in a 3.5% NaCl solution.

Six categories of specimens were cast. The proportion of materials used and their code names are shown in Table 3. Different specimens of the same category are marked with (′), such as SGH′ and SGH or SGS′, SGS″ and SGS.

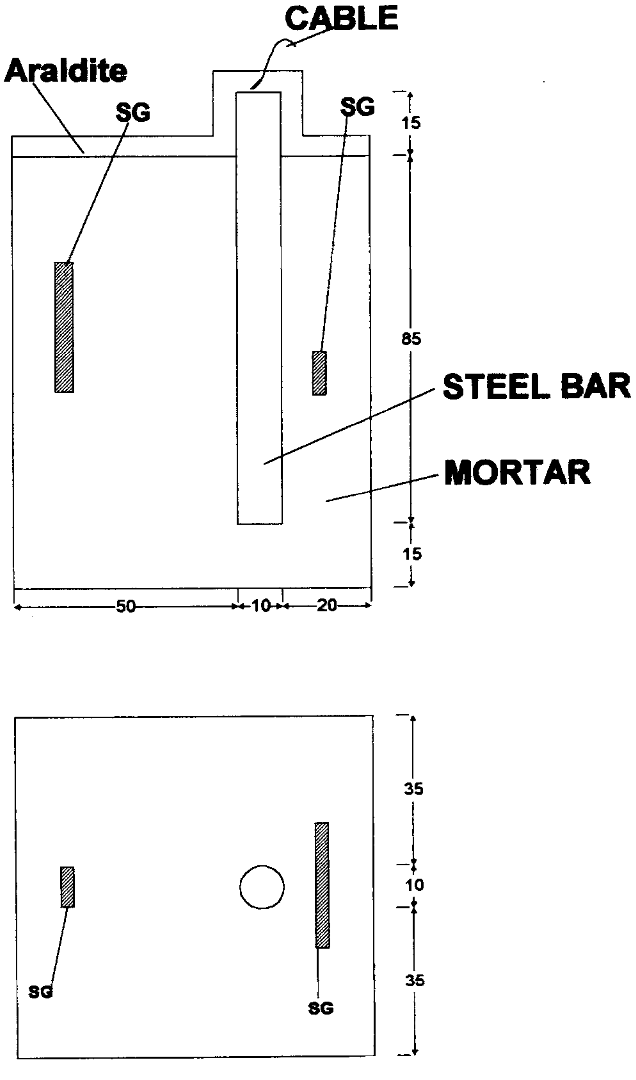

Fig. 1. Dimensions of specimens.

Table 3
Categories of specimens – composition ratio (wt)

Code name	P35	OPC	Sand	Water	3.5% NaCl sol	Inhibitor-D	Inhibitor-A	CKD
SGH	1	–	3	0.5	–	–	–	–
SGS	1	–	3	–	0.5	–	–	–
SGO		1	3	0.5	–	–		–
SGC		1	2.94	0.5	–	–	–	0.06
SGD		1	3	0.47	–	0.03	–	–
SGA		1	3	0.47	–	–	0.03	–

2.3. Methods

The sensor used for the measurement of corrosion rate of reinforcing steel was a special type of strain gage (SG), with characteristics given in Table 4. Two SGs were embedded in mortar specimen during casting. The deposition of SGs into the mortar was done by hand and their alignment was aided by the lead wire cable. Distances and directions between the SGs are shown in Fig. 1.

One of the SG (horizontally mounted) was used for corrosion results measurement and the other (vertically mounted) for compensating the temperature and other parameters (creep, wetting) influencing specimen volume.

A third SG was also used in all the experiments, free in the working area, for temperature compensation of the electrical circuit. The test set-up, including a potentiostat for applying the corrosion potential, a SG bridge-amplifier circuit and a multimeter for SG resistance, is shown in Fig. 2.

The application of the corrosion potential to the specimen by the potentiostat is made by means of a working bar electrode, 80×100×20 mm graphite auxiliary electrode and a reference saturated calomel electrode (SCE).

Table 4
Strain gage characteristics

Type KYOWA	Sensing alloy	Backing	Operating temp. range compensated (°C)	Resistance (Ω)	Gage factor	Dimensions (mm)
KM-30-120	Cu–Ni	Acryl	0–150	120	1.8	30 × 10 × 3

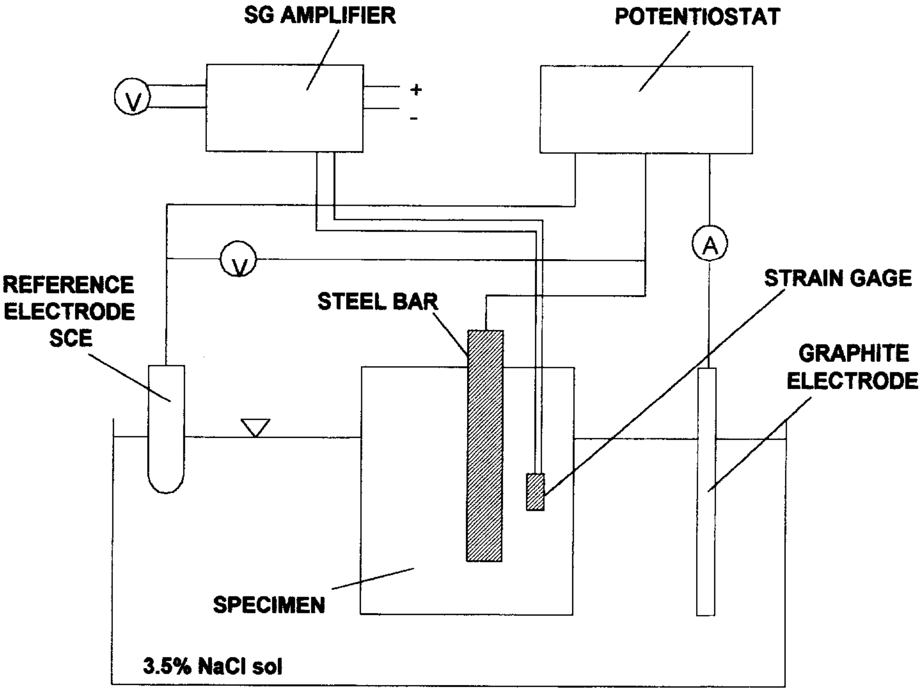

Fig. 2. Schematic diagram of test set-up.

Before applying a corrosion potential to the specimen immersed in 3.5 wt% NaCl solution, the output voltage of each SG is measured [common (E), volume changes compensation (T) and corrosion (*)] and these are the initial values as SGE_0, SGT_0 and SG^*_0. After the application of an equal corrosion potential to the specimens in the given time (t), with recorded feeding electrical current (I), the output voltage of the SG amplifier for each SG (SGE_t, SGT_t, SG^*_t) makes it possible to indicate the corrosion of the steel bars.

The following differences were calculated:

$SGE_t - SGE_0$, corresponds to the circuit temperature changes.

$SGT_t - SGT_0$, corresponds to the specimen volume changes and circuit temperature changes.

$SG^*_t - SG^*_0$, corresponds to the corrosion plus volume changes plus circuit temperature changes.

$(SGT_t - SG^*_t) - (SGT_0 - SG^*_0)$, corresponds to the compensated corrosion status.

As shown in Fig. 3, for each SG with initial electrical resistance R, included in a Wheastone bridge it is known [10] that:

$$\mathrm{SG} = \frac{V_i}{4}\frac{\mathrm{d}R}{R} \quad \text{and} \quad \frac{\mathrm{d}R}{R} = G \cdot \frac{\mathrm{d}L}{L}$$

where V_i is the input voltage, R is the electrical resistance of the strain gage, $\mathrm{d}R$ is the resistance change, L is the resistance length of the strain gage, $\mathrm{d}L$ is the resistance length change, G is the gage factor and SG is the output voltage.

From the values SG measured in the test it is possible to calculate the change in the length of SG resistance which corresponds to the tensions developed by corrosion products formation in the specimen. The internal forces in the near area of the corroded steel bar, if volume changes from temperature and other disturbing parameters are compensated, indicate the production of oxides, i.e. corrosion.

The values of SG (mV) obtained in the given time (t) were plotted.

At the end of the test, specimens were broken, pieces of mortar and the Araldite were removed. The steel bars were immersed in inhibited hydrochloric acid for 15 min, washed with water, alcohol and acetone, weighed, and their weight loss was found. The comparison of weight loss and SG* values for different specimens enables us to confirm the degree of corrosion.

3. Results and discussion

The test results obtained for the six given categories of the specimens by the SG technique, are illustrated in Figs. 4–10 and Table 5 as a function of time. The initial time is the moment of application of anodic potential to the specimen.

A constant potential of 1000 mV was applied to SGH, SGH′, SGS, SGS′ specimens and measurements of SG values versus time were plotted, as shown in Fig. 4. There was also a plot of electrical charge flow through specimens (Fig. 5).

In all cases there was an increase in SG values, related to the corrosion, with a significant difference between SGS (80 mV/day) and SGH (10 mV/day) specimens. Evidently, NaCl addition in SGS and SGS″ mortar was the cause for the higher corrosion rate of this kind of specimen.

The electrical charge plot shows a relatively good agreement with SG plot and could be considered as

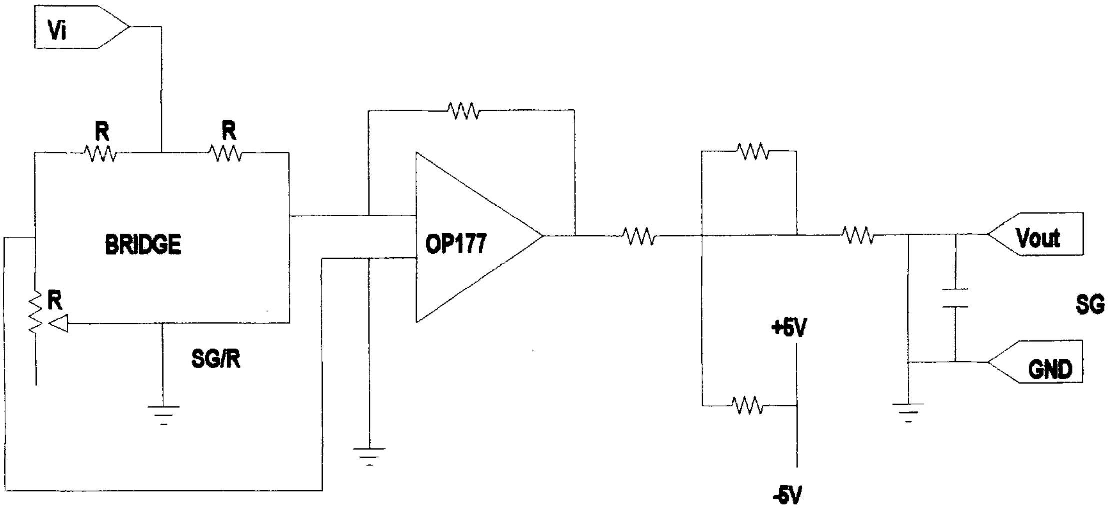

Fig. 3. Strain gage bridge–amplifier circuit.

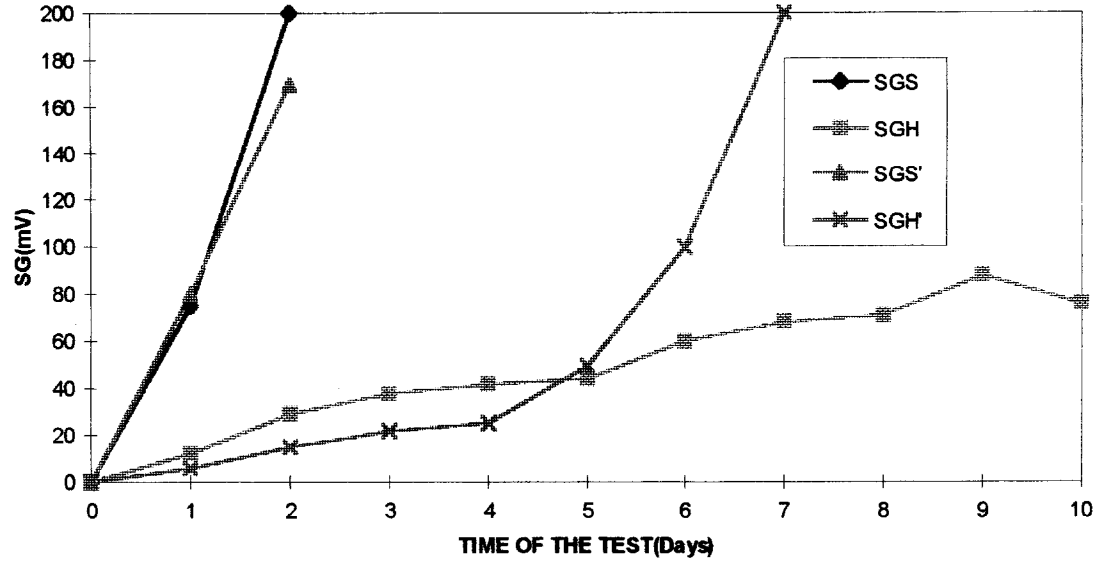

Fig. 4. SG values versus time for SGH, SGH′, SGS, SGS′ specimens.

an initial confirmation of reliability of the SG measurements.

The quick increase in SG values is an indication of mortar cracking, and this was confirmed by visual inspection. (This was observed in Day 1 for SGS, SGS″, Day 5 for SGH′ and Day 9 for SGH).

The test results for different composition specimens SGH′ and SGS″, obtained by the application of a suitable different corrosion potential so that the electrical charges would be similar, are slightly different (see Fig. 6). The SG values rapidly increase after 4 and 6 days respectively.

This view supports the fact that SG measurements are in agreement with the electrical charge flow through specimens, e.g. the corrosion caused, until the moment of mortar destruction.

The simultaneous testing of specimens SGO, SGC, SGD and SGA, with expected different corrosion behavior due to their composition, is confirmed by the SG measurement curves, by the electrical charge flow and also by weight loss determination of specimen bars. (Figs. 7 and 8). The admixture CKD acts protectively against corrosion but with lower efficiency in comparison with Inhibitor-D and Inhibitor-A. The corrosion

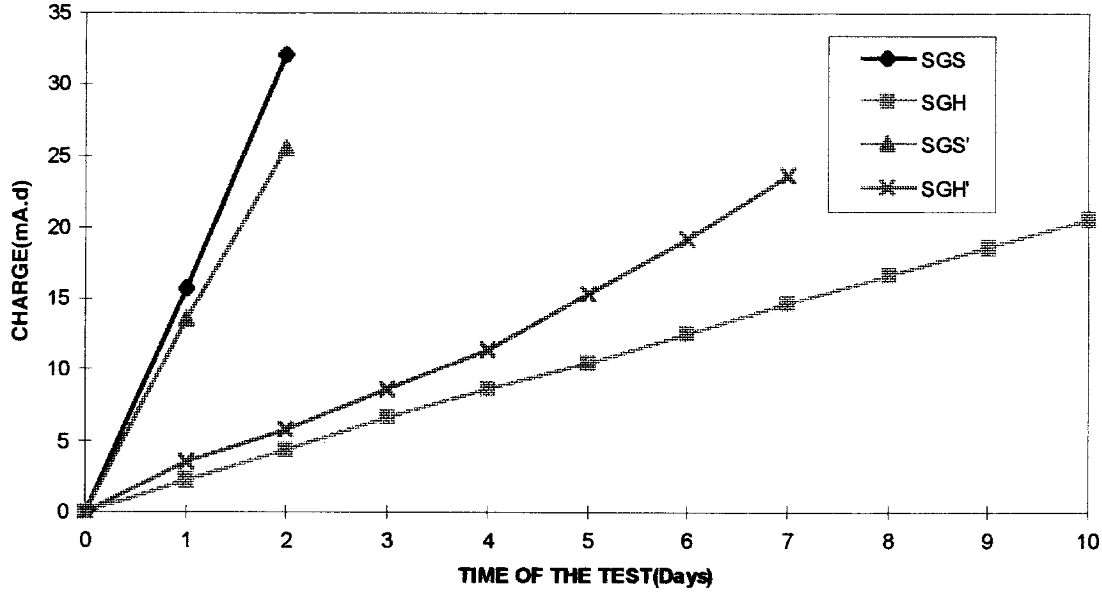

Fig. 5. Charge verus time for SGH, SGH′, SGS, SGS′ specimens.

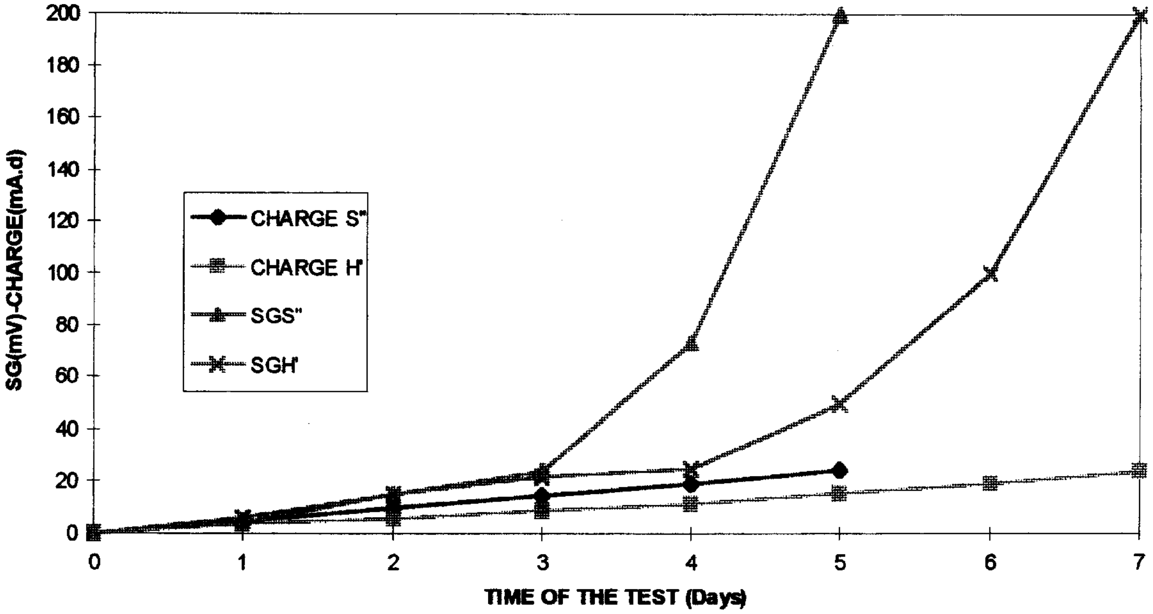

Fig. 6. SG-charge values versus time for SGS″, SGH′ specimens.

behavior of CKD as admixture in concrete has been studied in a previous paper [9]. Fig. 11. shows the corrosion behavior of specimens with 6% CKD in comparison with OPC and with 6% of another additive A.

Good agreement can be observed between the SG measurements plot and the electrical charge flow plot for specimens SGO, SGD and SGA. Regarding the electrical charge plot of specimen SGC, we should expect a corrosion lower than the actual measured corrosion rate. A possible explanation is that the CKD admixture mainly affects the mortar mass of the specimen, in contrast to corrosion inhibitors included in SGD and SGA specimens, which affect the passivating film of rebars.

For a further explanation of the results, the relationship between SG measurements before cracking and corrosion of steel bars was investigated via gravimetric weight loss determination of each specimen bar, as shown in Table 5 and Fig. 9.

In cases of specimens broken during testing the weight loss was estimated, based on the final determination and the electrical charge transferred through the specimen.

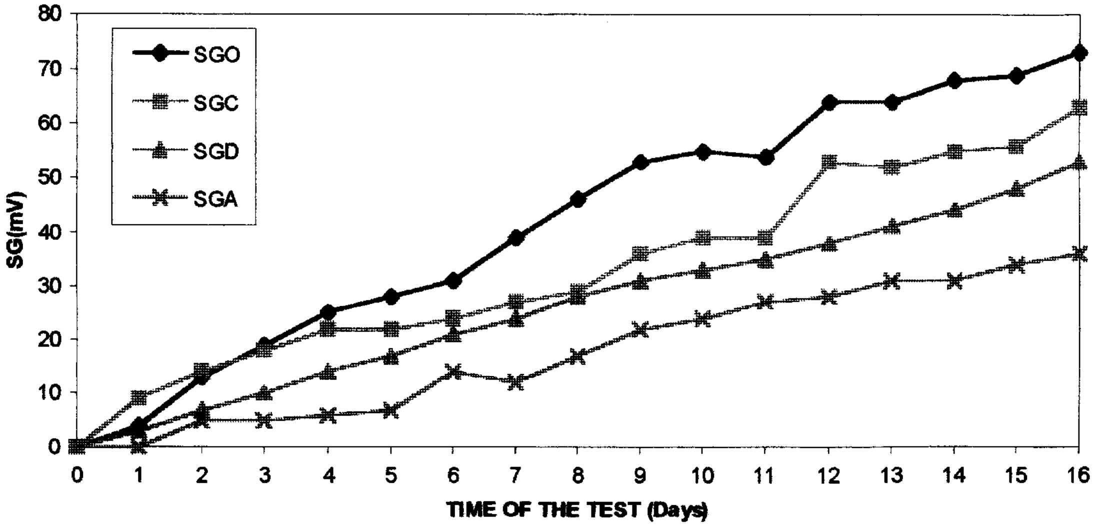

Fig. 7. SG values versus time for SGA, SGD, SGC, SGO specimens.

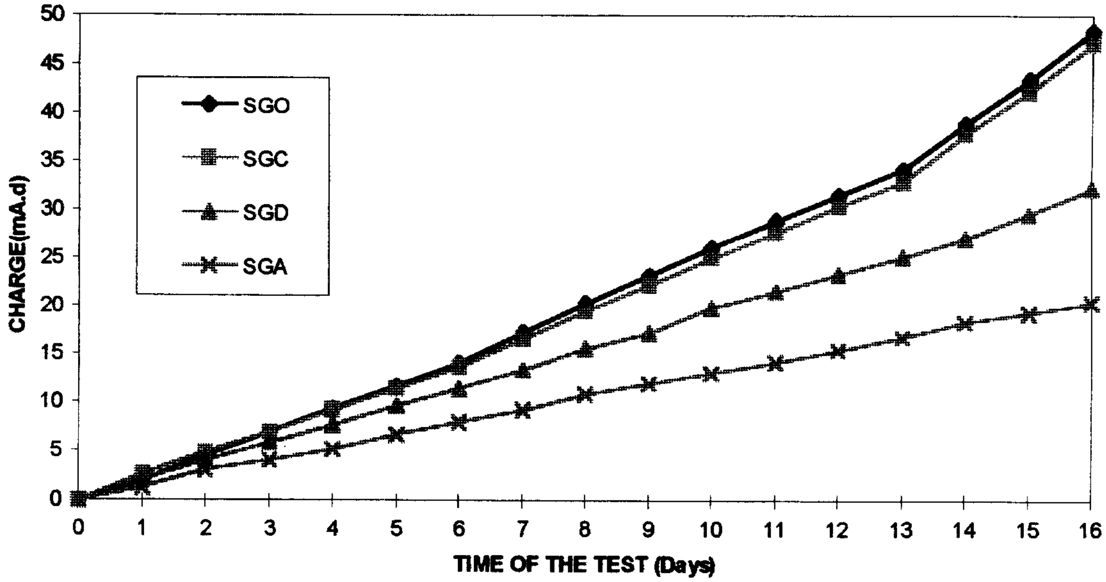

Fig. 8. Charge versus time for SGA, SGD, SGC, SGO specimens.

The weight loss values and the related SG measurements for each specimen (shown in Fig. 9) must be divided by the duration of test in order to give the corrosion rate.

A constant relationship between SG and weight loss values is observed and it is of the order of 200 mV per gram weight loss of steel. According to this relationship it is proven that the elongation of the SG sensor is related to the formation of the corrosion products and consequently the SG measurements correspond to the real corrosion caused in steel bars.

The corrosion rates for all specimens tested according to their weight loss of steel per day under the same conditions are given in Fig. 10. The differences shown between the specimens of the same category, such as SGS and SGS″ or SGH and SGH′, are explained by the fact that SGH′ and SGS″ specimens were tested with potential application different than SGH and SGS.

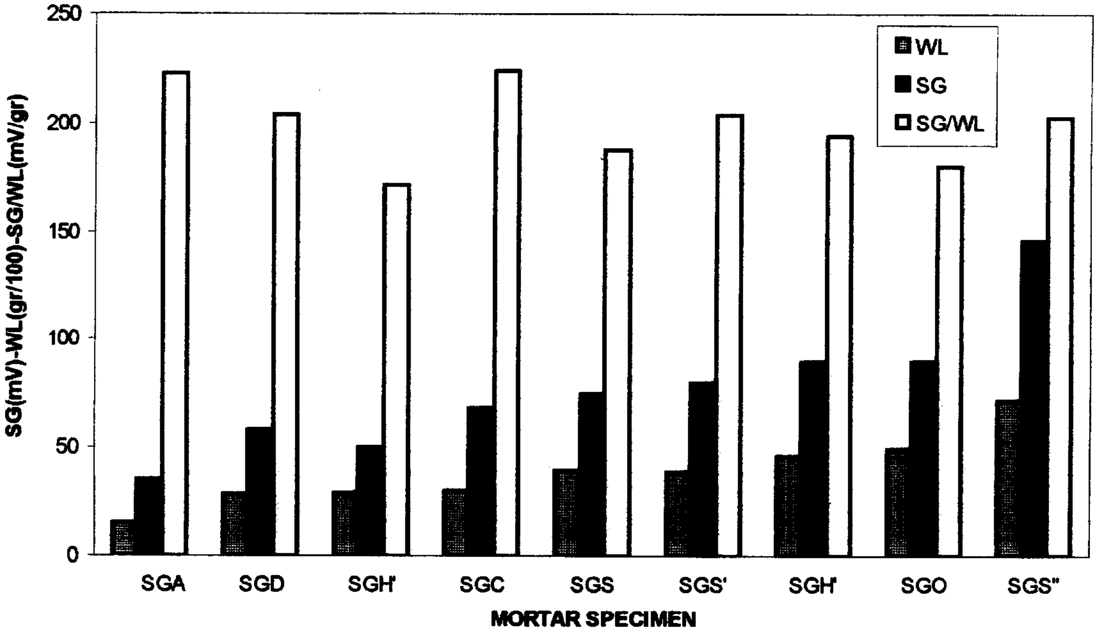

Fig. 9. SG values–weight loss comparison for different specimens.

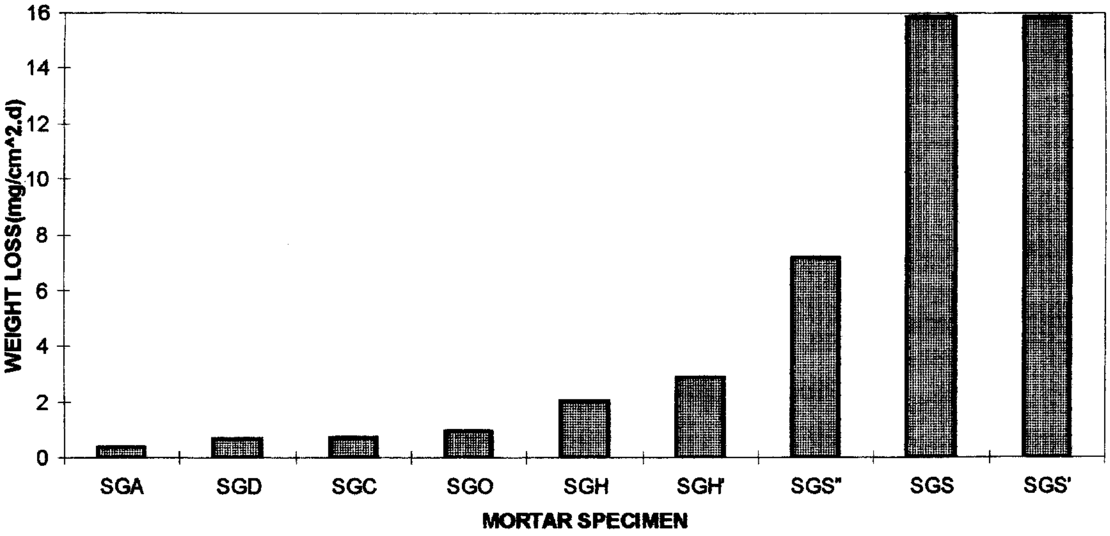

Fig. 10. Weight loss comparison for different specimens.

Table 5
Weight loss–Sg values comparison for different specimens

Specimen code	Weight loss $(g \times 10^{-2})$	SG value (mV)	SG per weight loss (mV/g)	Corrosion time (days)	Corrosion rate (mg/cm^2 day)
SGA	15.67	35	223	16	0.39
SGD	28.43	58	204	17	0.67
SGC	30.27	68	224	17	0.71
SGO	49.74	90	181	20	0.99
SGH	46.30	90	194	9	2.05
SGH′	29.00	50	172	4	2.89
SGS″	72.00	146	203	4	7.17
SGS	39.83	75	188	1	15.86
SGS′	39.28	80	204	1	15.86

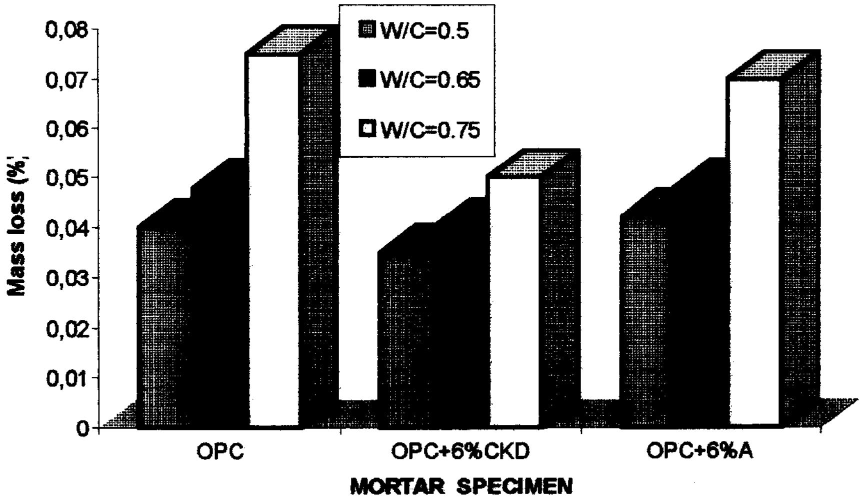

Fig. 11. Mass loss of steel bars after 6 months exposure in 3.5 wt% NaCl solution.

The porosity measurement (with mercury porosimeter Carlo Erba 2000) of the mortar of the above specimens with similar values (12.26 to 12.79) confirm that the different SG value plots of various specimens of the same porosity were caused by other factors influencing corrosion (chloride ions, passivating film).

The results have shown that the corrosion rate measurements by SG sensors enable a reliable inspection of the state of embedded steel in different categories of mortar specimens.

4. Conclusions

1. The test results obtained suggest that this method can be used for an efficient inspection of the state of steel reinforcement and for corrosion rate measurements.
2. This nondestructive technique is suitable for the laboratory study of corrosion factors, including the evaluation e.g. of various admixtures.
3. Although SG sensors used are temperature compensated, the main problem solved was the compensation of specimen volume changes during testing.
4. After the moment of mortar cracking, the SG values were affected mainly by the mortar composition and less by corrosion products formation.

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