- Technical paper -

INVESTIGATION OF ELECTROCHEMICAL PROPERTIES OF SHEATH-GROUT-TENDON ELEMENT

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ABSTRACT: In order to investigate the electrochemical properties of sheath-grout-tendon (SGT) element in post-tensioned PC bridge, five SGT specimens with various grouting degrees/styles were tested in tap water by half-cell potential (HCP) and electrochemical impedance spectroscopy (EIS) method. It is concluded that corrosion status of galvanized steel sheaths can be determined by HCP method, but not the inner tendons due to the shielding effect. Grouting degrees can be evaluated by fitting measured EIS data to the equivalent circuits provided that no electrical connection exists between sheath and PC tendon.
KEYWORDS: half-cell potential (HCP), electrochemical impedance spectroscopy (EIS), sheath-grout-tendon (SGT) element, equivalent circuit (EC)

1. INTRODUCTION

Previous investigations on the post-tensioned prestressed concrete (PC) bridges with internal grouting tendons reveal a variety of deteriorations due to the imperfect grouting conditions ranging from minor voids to complete loss of grout [1]. Corrosion of steels embedded in cementitious materials, such as cement paste, does not occur because of the formation of a passive film on the steel surface due to high alkalinity of pore water. However, this passive film is compromised if the grout pH in the steel surface falls below about 10 and/or the chloride concentration rises above a threshold. The chloride-induced corrosion is ascertained to be the predominant deterioration mechanism in almost all damage cases of PC bridges according to a literature survey [2]. Passivity is not expected where steel is exposed at grouting voids although a thin paste layer may cover the steel surface. Without the passive film, the active corrosion commences provided that adequate moisture and oxygen are present irrespective of grout pH and chloride concentration.

In order to evaluate the durability of existing PC bridges, it is indispensable to examine the corrosion status of sheath and PC tendon and the degree of grouting within the sheath. Various kinds of non-destructive testing (NDT) methods for examining the degree of grouting have been proposed in the past few years. Among others, X-ray penetration and impact elastic-wave methods are widely used at present. Until today, electrochemical method is seldom applied in site for evaluating the corrosion behavior and grouting degree of post-tensioned PC member because of the existence of sheath and complex displacement of PC tendons. Research in this aspect is also limited.

Sheath-grout-tendon (SGT) element is an important part in post-tensioned PC member. For purpose of investigating the electrochemical properties of SGT element, SGT element specimens with different grouting degrees and styles were tested in tap water by two electrochemical techniques, namely half-cell potential (HCP) and electrochemical impedance spectroscopy (EIS) measurements. It is concluded that HCP measurement can only provide available corrosion information of the galvanized steel sheath when lead wire is connected to sheath. Those of inner tendon cannot be obtained because of the shielding effect of steel sheath. A random electric potential difference exists between sheath and tendon due to the variation of distribution of water-content in the pore of grout material and/or corrosion products and the moisture in void. Grouting degrees can be evaluated quantitatively by fitting the measured EIS data into

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the equivalent circuit (EC), provided that no electrical connection exists between sheath and PC bar.

2. EXPERIMENTAL DETAILS

2.1 SPECIMEN PREPARATION

Five SGB specimens S1~S5 with five kinds of grouting degrees/styles simulating the real grouting styles are schematically shown in Fig.1. PC bar (SBPR 930/1080, D13mm) was carefully displaced at the center of the galvanized steel sheath (JIS G 3302, D26mm/28.5mm) and disconnected with it at two ends. Lead wires were connected to the sheath and PC bar separately. Cement properties and mix proportion of grouting materials are listed in tables 1 and 2. After grouting, they were cured in a room of constant temperature of 20^{0}C and 60%RH for one week. Afterwards, salt spraying was performed twice a day for 1month.

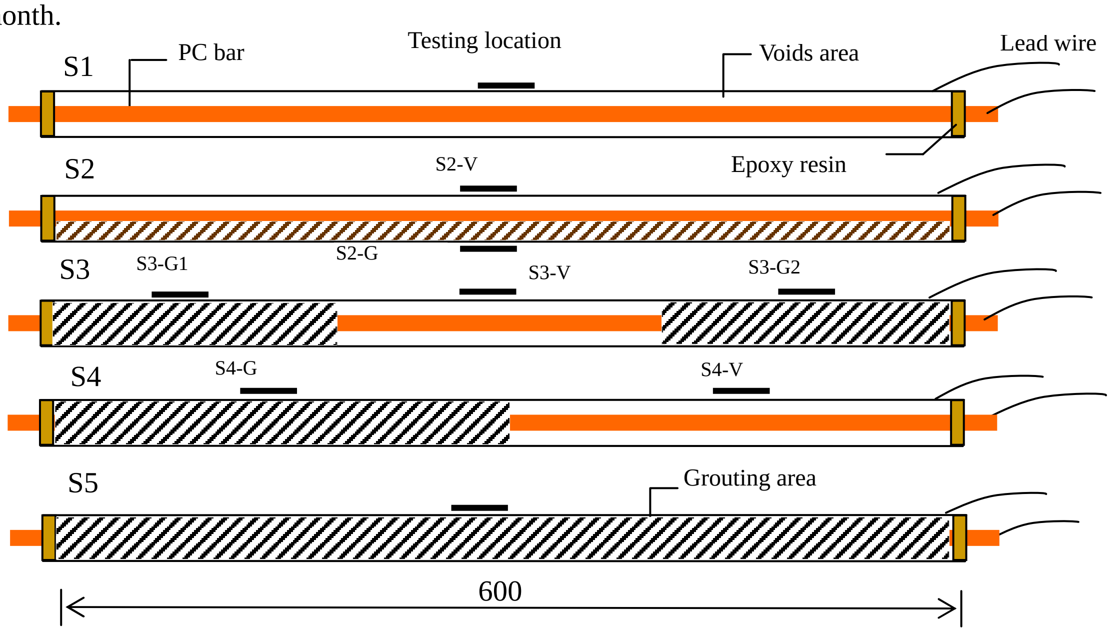

Fig.1 Grouting degrees/styles and testing locations of S1~S5

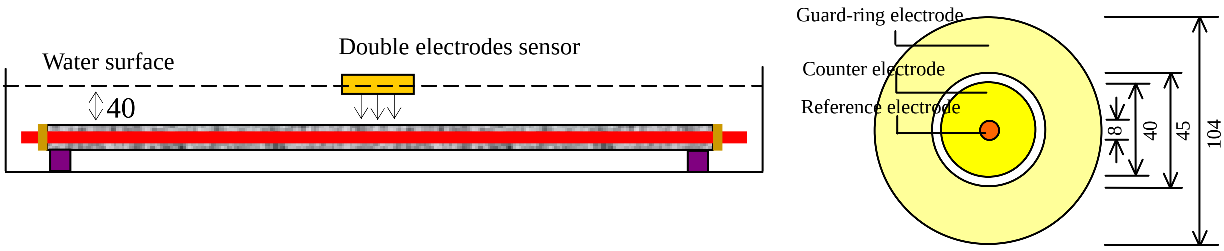

Fig.2 Setup of the EIS measurement in tap water and double electrodes

Table 1 Physical properties of Cement

Type	stability	Hardening time		Specific surface area (cm^2/g)	Compressive strength (Mpa)			
		Beginning	End		1d	3d	7d	28d
Early hard Portland cement	good	1h48min	2h45min	4550	25.6	47.0	57.7	69.0

Table 2 Mix proportion of grouting material

Cement (kg)	Water (kg)	Admixture/GF-700 (g)
10	3.5	150

2.2 ACQUISITION OF HCP VALUES AND EIS SPECTRA

Instead of embedding in concrete, SGT specimens S1~S5 were simply put in tap water for testing their electrochemical properties by measurements of HCP and EIS (Fig.2). Immersion in water for two hours before testing is necessary for stabilization. Saturated silver chloride electrode Ag/AgCl was used as reference electrode. It was put on the water surface 40mm above sheath. HCP values were collected several times in 1 month during corrosion development and EIS values were collected only at last time.

EIS spectra of sheath and bar were obtained by a portable rebar corrosion meter with double-electrodes sensor (Fig.2). A sine tri-angular wave voltage was applied accompanied with 13 kinds of frequencies in a range of 10~0.01Hz. The currents between Counter Electrode (CE) and Working electrode (WE) were collected corresponding to each frequency. Guard-ring electrode was used here for restricting the current direction of CE. Cole-Cole plot was also drawn out in the computer connected to the corrosion meter. And it was changed into Bode plot for fitting afterwards.

3. RESULTS AND DISCUSSIONS

3.1 HALF-CELL POTENTIALS

It has been known that active and passive areas of the sheath show a difference in electrochemical potentials provoking current flow in concrete. The electric field coupled with this corrosion current can be measured with a suitable reference electrode (half-cell) concrete surface. The obtained corrosion potential E_{corr} of sheath is the voltage difference between the reference electrode (RE) and the un-corroded part (cathode) of sheath. Similarly, E_{corr} of PC bar is the voltage difference between RE and the un-corroded part (cathode) of sheath. In case of specimens S1-S5, the above principle is the same although tap water is taken as an electrolyte instead of concrete. The measured E_{corr} of sheath and PC bar is plotted in Fig.3.

The electric field of SGT element is a composite one because it is coupled with the corrosion currents both in sheath and PC tendon. But, due to the shielding effect of surrounding galvanized steel sheath, the electric field of inner PC tendon may not be detected by RE at water surface.

As what we imagined, The anatomy of SGT specimen verified that no corrosion happened in PC bar even though all of E_{corr} were around –500mV. The real HCP values of PC bar are not obtained. A random potential difference between sheath and PC bar represents the existence of resistances between them resulting from the change of water-content in the pore of grout material and/or corrosion products and the moisture in the void.

3.2 MODELLING AND FITTING OF EIS SPECTRA

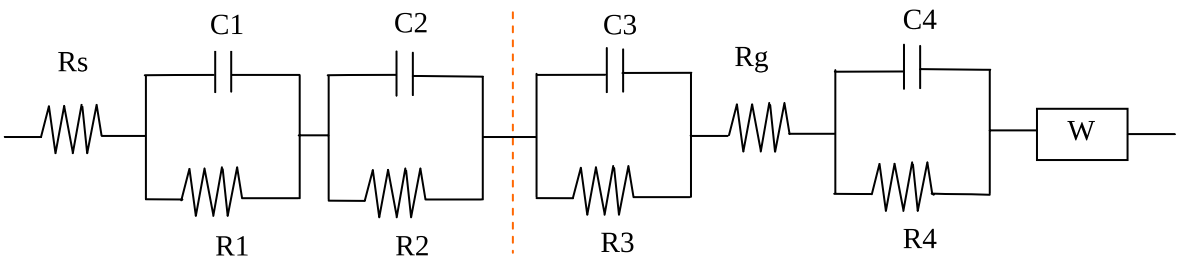

Fig. 4 Equivalent circuit for sheath and PC bar

EIS is a powerful analytical technique for providing information on the corrosion reactions, including the mass transport and the electrical charge transfer characteristics of the cell. While a huge amount of information can be collected by EIS method, these data need to be carefully examined and interpreted. This is usually done using an equivalent circuit (EC) which compromises assemblies of electrical circuit elements that model the electrochemical characteristics of the electrode/solution interface. In spite of the continuous development in the interpretation of the EIS spectra, sometimes they reveal the special features difficult to be explained. The constant phase element (CPE) and the finite Warburg diffusion element (WDE) are usually introduced into the ECs considering the non-standard capacitance behavior and mass diffusion in the interface.

The ECs of galvanized steel sheath and PC bar of specimens S1~S5 are constructed (Fig.4) based on the obtained Cole-Cole plots. Three interfaces are considered in the circuit including water-sheath interface, sheath-paste interface and paste-bar interface. The circuit on the left side of the dash line contains two time constants to represent oxide layer and ongoing anodizing process in the first interface when lead wire is connected to the sheath. The total circuit describes the current path when lead wire is connected to PC bar. In some circumstances, the constant Phase Element (CPE) is adopted instead of standard capacitance and Warburg Diffusion Element (WDE) is added according to the style of Cole-Cole plots.

The CPE is a non-intuitive element that was discovered while looking at the response of real-world systems where the Cole-Cole plot was a depressed semicircle with the center some distance below the x-axis. A possible explanation for this phenomenon may be varying thickness or composition of a coating. Mathematically, a CPE's impedance is given by

$$1/Z = Y = Q^0 (j\omega)^n \qquad (1)$$

where Q^0 is the admittance $(1/|Z|)$ at $\omega = 1rad/s$. A consequence of this simple equation is that the phase angle of CPE impedance is independent of frequency and has a value of $-(90\times n)$ degrees. This gives CPE its name. When $n=1$, this is the same equation as that for the impedance of a standard capacitor, where $Q^0 = C$.

$$1/Z = Y = j\omega Q^0 = j\omega C \qquad (2)$$

The WDE is used to simulate the phenomenon of the slow diffusion of oxygen through a coating or a passive film. It is characterized by two parameters, an "admittance" parameter, Y_0, and a "time constant" parameter, B (unit: $\sec^{1/2}$). The equation for the complex impedance is given by

$$\vec{z}(\omega) = \left\{\frac{1}{Y_0\sqrt{j\omega}}\right\}\tanh[B\sqrt{j\omega}] \qquad (3)$$

By use of Eqs.1-3 and complex nonlinear least squares method, parameters of EC for specimens S1-S5 are obtained and listed in table 3. Fig. 5 shows the experimental and evaluated Bode plots of Impedance and Phase for specimens S1-5. Specifically, the resistance between sheath and PC bar, Rg, is extracted and it accurately reflects the grout degree of specimens S1-S5. The maximum and minimum resistances are in S1 and S5 respectively, corresponding to two boundary situations, i.e., without grouting and perfect grouting. S2 has almost the same low resistance as that of S5 while those of S3 and S4 has higher ones. Test location has more influence on specimen S4 than S3. These are resulted from the fact that current flows along the shortest way.

Table 3 Calculated parameters of EC for specimens S1-S5

	Rs	C1 (C) or CPE(Q^0/n)	R1	C2(C) or CPE(Q^0/n)	R2	C3 (C) or CPE(Q^0/n)	R3	**Rg**	C4（C） or CPE(Q^0/n)	R4	WDE （Y_0/B）
S1	0.46	8.8/0.66	0.42	2.05/0.95	0.03	0.68/0.64	18.3	**3.47**	0	0	0
S2-G	0.3	4.9/0.6	0.13	9.2	0.39	8.48	3.4	**0.07**	0	0	2.2/4.3
S2-V	0.32	12.1/0.3	0.86	39.2	0.17	7.72	1.8	**0.07**	0	0	2.4/12.9
S3-G1	0.53	12.5/0.4	0.82	41.3	0.24	1.44/0.75	10.7	**0.36**	0.36/0.7	0.85	0
S3-V	0.34	6.65/0.6	0.35	15.3	0.13	0.85/0.62	7.69	**0.49**	0.42/0.9	0.41	0
S3-G2	0.38	10.8/0.4	0.52	31.6	0.2	1.11/0.72	9.12	**0.39**	0.37/0.8	0.68	0
S4-G	0.32	20.5/0.77	0.3	1.96	0.21	3.3/0.45	2.27	**0.17**	0.33	0.18	0
S4-V	0.36	8.8/0.57	0.48	25.9	0.13	0.8/0.5	9.3	**0.31**	0.21	0.34	0
S5	0.36	23.9/0.68	0.31	4.11/0.81	0.03	2.16/0.62	1.7	**0.04**	16.4	0.33	0

Units of parameters : Rs, Rg – kΩ; Q^0, Y_0 , C - $(\times 10^3)\mu Fa$; B- $\sec^{1/2}$

4. CONCLUSION

The electrochemical properties of sheath-grout-tendon element are investigated in tap water by the measurement of HCP and EIS method. It is concluded that the real HCP values of PC bar inside galvanized steel sheath cannot be tested due to the shielding effect of surrounding sheath. The difference of HCP values for sheath and PC bar is only resulted from the existing resistance between them. Based on the measured EIS data, the ECs of SGT element can be constructed and parameters are evaluated. Resistance Rg, representing the grouting degree, is extracted and agrees well with the real grouting situation in specimens S1-S5.

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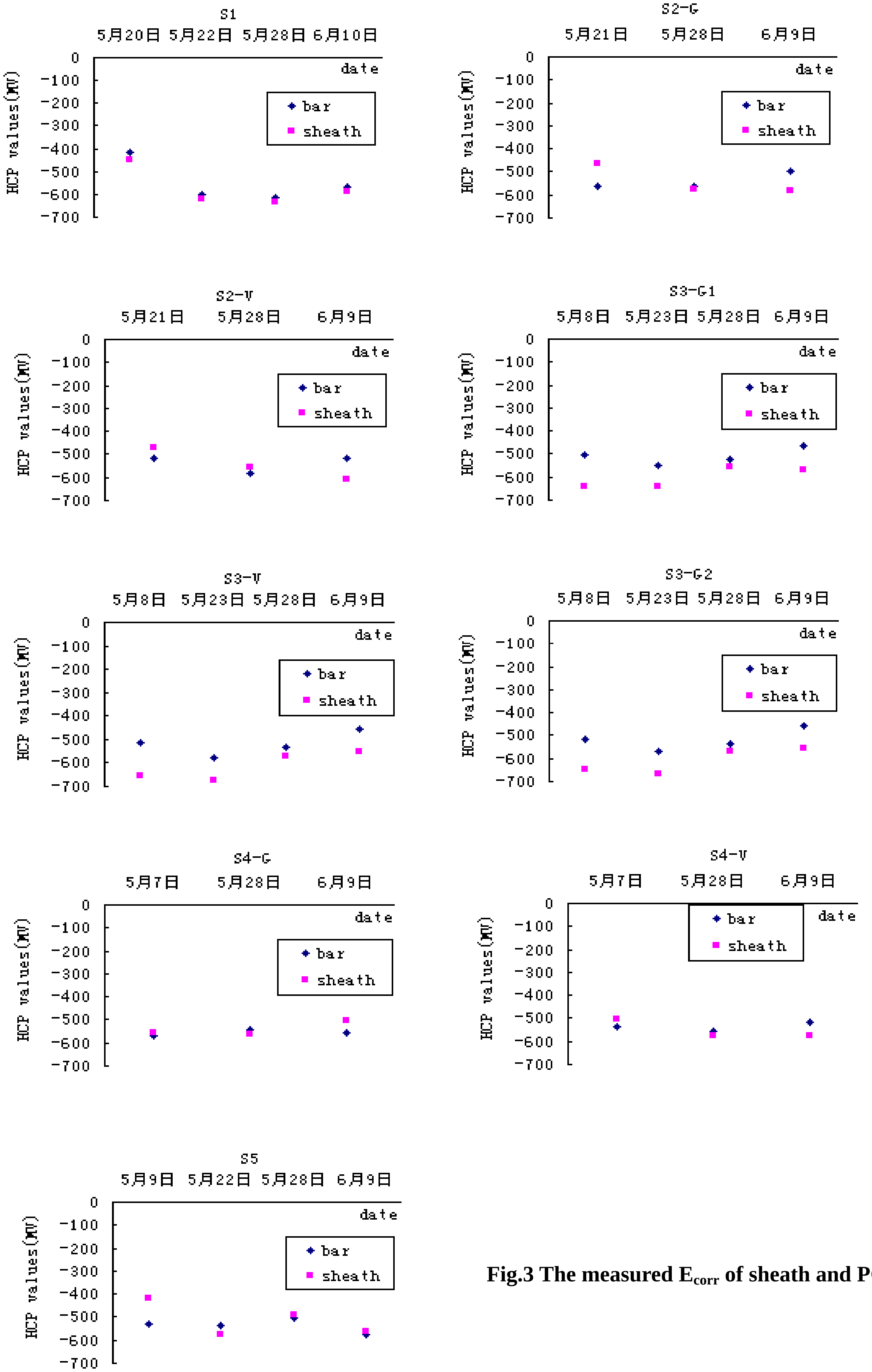
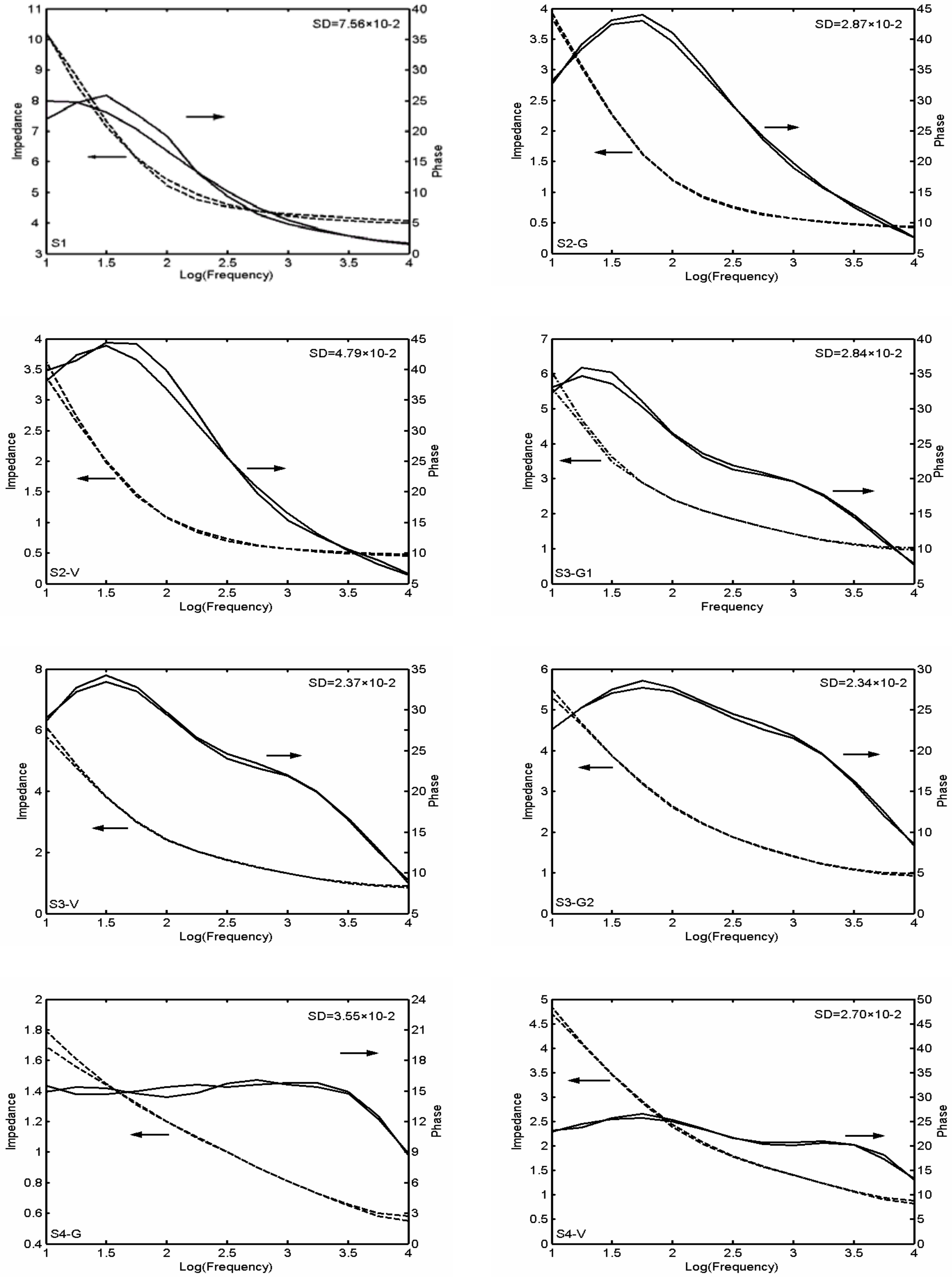


Fig.3 The measured E_{corr} of sheath and PC bar



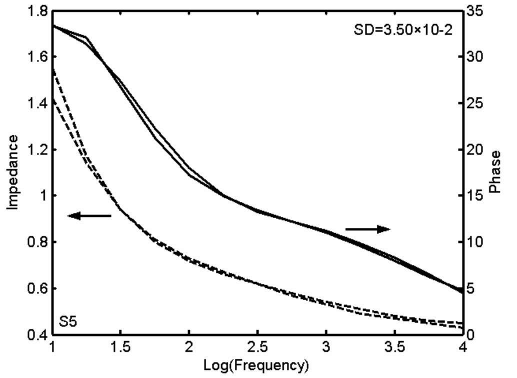


Fig.5 Experimental and evaluated Bode plots of Impedance and Phase for specimens S1-S5.

Note:

(1) SD in each figure means standard deviation.

(2) Two dash lines in each figure mean experimental and evaluated values for impedances and two solid ones for phases.