CHAPTER (5)
RESULTS AND DISCUSSIONS

5-1 Introduction

This chapter contains the obtained experimental results, analysis and discussion of these results.

5-2 Results and Discussion

5-2-1 Potential Level

The daily records of the P/E potential for the three tested plates are shown in figure 5.1. This figure reveals the following:

a) Plate-X was always under-protected during the whole test period since its potential is less negative than the well established protection criterion of -0.85 V.

b) Plate-Y was protected from the front side during the whole test period. Potential at the back was slightly more positive but still more negative than protection criterion.

c) Plate-Z was protected from both sides during the whole test period. Potentials at back and front almost coincide and both were above protection criterion.

5-2-2 Anode Consumption

The measured metal losses of the three anodes used in the experiment are shown in Table 5.1. The total metal loss of Plate-Z anodes is 1427.1 g which is about 2.35 times that of Plate-Y anode. That is the loss of anode (1) is only 85.2 % of the average loss of anodes (2) and (3).

Table 5.1 Material loss of anodes

Plate	**Plate-Y**	**Plate-Z**	
Anode	Front anode (1)	Front anode (2)	Back anode (3)
Material loss, g	608	769.9	657.2
		1427.1	

5-2-3 Coupons Metal loss

The metal loss in one coupon was calculated as the difference between its initial and final weights after cleaning (as explained in the experimental set up). The calculated metal loss of the coupons fixed on the front and back of each plate are given in Table 5.2.

Table 5.2 The metal loss in the coupons of the three plates [mg]

Coupon No.	Position code*		Plate-X		Plate-Y		Plate-Z	
	Front code	Back code	Front, mg	Back, mg	Front, mg	Back, mg	Front, mg	Back, mg
1	FA1	BA1	122.4	143.2	28.7	28.0	37.6	28.3
2	FA2	BA2	156.1	147.5	23.5	23.0	31.8	26.8
3	FA3	BA3	111.9	139.0	24.7	20.6	36.2	23.3
4	FA4	BA4	102.8	100.4	26.9	4.6	30.4	28.4
5	FA5	BA5	113.0	205.5	27.9	111.8	24.0	31.7
6	FB1	BB1	124.4	108.2	75.8	58.6	33.1	31.2
7	FB2	BB2	143.9	101.0	25.7	26.4	32.4	29.1
8	FB3	BB3	150.0	146.6	27.7	45.2	30.8	57.0
9	FB4	BB4	152.2	139.4	55.2	99.0	29.2	34.6
10	FB5	BB5	157.4	98.6	36.5	134.8	30.8	4.2
11	FC1	BC1	125.7	98.5	25.9	29.9	38.9	35.4
12	FC2	BC2	85.6	72.6	30.3	53.6	32.2	41.3
13	FC3	BC3	137.4	131.0	20.9	25.8	30.5	31.9
14	FC4	BC4	111.8	83.4	53.9	90.9	26.6	27.9
15	FC5	BC5	86.3	95.1	29.0	97.0	28.3	27.9
16	FD1	BD1	60.0	63.5	50.6	85.4	41.9	27.6
17	FD2	BD2	52.1	70.7	34.8	50.4	29.3	25.9
18	FD3	BD3	49.0	48.6	25.0	7.8	29.3	28.5
19	FD4	BD4	64.7	58.0	27.5	85.9	27.8	29.6
20	FD5	BD5	94.2	76.2	67.8	52.4	28.2	31.9
21	FE1	BE1	81.2	80.2	25.0	23.5	32.3	33.6
22	FE2	BE2	77.7	66.6	20.6	22.5	34.3	27.3
23	FE3	BE3	75.3	73.2	21.5	26.3	37.9	52.4
24	FE4	BE4	69.0	65.2	21.8	27.5	29.1	10.3
25	FE5	BE5	84.0	70.6	26.4	25.7	28.2	34.0
Total loss in grams			2.588	2.483	0.834	1.257	0.791	0.760
			5.071		**2.090**		**1.551**	

* ***Position code:*** *F → Front surface, B → back surface;*
Letters A – E → row letters; numbers 1 – 5 → column numbers.

As shown from the above table, the total metal loss in coupons of unprotected Plate-X being 5.071 grams is the highest. Loss in back coupons is slightly less than that of the front side. It amounts to about 96%, which is practically acceptable due to the small initial masses of the coupons. Coupons of plate-Y showed the greatest metal loss differential

between the protected and unprotected sides. The metal loss in the unprotected side is about 1.5 times that of the protected side. However, the total metal loss from its coupons is only 41% of that of unprotected Plate-X. On the other hand, for Plate-Z the metal loss of the front side coupons is slightly higher (about 4%) than that of the back side coupons, being 0.791 and 0.760 grams, respectively. The difference is only 0.031 grams for the 50 coupons. In total, the coupons metal loss of Plate-Z is only about 74 % and 31 % of that of Plates Y and X, respectively. This indicates the importance of CP from the two sides in similar cases.

To explore the advantage of utilizing the coupons to monitor the metal loss over the two sides of each plate, a cylindrical 3-D bar diagrams are shown in figs 5.2 to 5.4.

Close examination of the metal loss patterns for the three plates reveals that:

- Corrosion in coupons of Plate-X (both sides) has in general little inconsistent irregularities.
- Losses in front coupons of Plate-Y (protected side) are much less than on back side with some irregularities. Plate-Y shows that the protected front side has low loss at the top and bottom edges of the plate as well as around plate center. On the other hand, unprotected back side shows corrosion patterns closely resembling that of Plate-X with more sharp expected irregularities due to the spread of local corrosion cells on its surfaces.
- The metal loss patterns of the front and back sides for the fully protected Plate-Z besides their low values they are nearly equal and uniformly distributed with comparatively very few exception points (BE1 & BE2).

5-2-4 Plate Metal Loss

Because of difficulty of measuring the initial weight of different parts of the three plates before testing as these plates had to be kept intact, a reference piece of the plates material is used to find out the material mass per unit area. The mass per unit area found to be 1.10266 g/cm^2 and used later to calculate the initial mass of each part after cutting these parts and finding their surface areas, accurately. The metal loss for the three plates was calculated from the weight data of the initial and final weight of each part.

Actual cut of each plate into equal area parts was practically difficult. For this reason the material loss of each part is calculated together with the loss rate in units of g/m^2 for the sake of comparison. The material loss and loss rate for each part of the three tested plates are given in Table 5.3. Moreover, the loss rate of different parts of the three plates is given in figures 5.5 to 5.7.

Examination of the results of the material losses of the three plates confirms the above finding given by the analysis of the material losses of the coupons. That is material loss in Plate-X is the largest and that of Plate-Z is the lowest. Obviously, the magnitudes of the material loss rate follow the same trend. The rate of loss in the fully protected Plate-Z amounted only to 38.0% and 18.9% of the one-side protected Plate-Y and the unprotected Plate-X, respectively. Comparison of the loss rate of Plate-X and Plate-Y shows that the rate of the latter is approximately 50% of the former. That means that protection of one side is not sufficient and corrosion inevitably attacks the metal.

5-3 Plate/Electrolyte Potential Difference

5-3-1 Potential Difference in the Parallel Planes

Referring to section § 4-3-3, the measured potential difference "PD" over the test period for Plate-Y is presented here in three forms:

The first form is a typical 3-D and contour sample plots for the PD measured at both sides of Plate-Y. the plots are, in fact, based on the coordinate data of the 16 measuring points and the values of the PD at these points, (figure 4.7). SURFER computer software is used to plot the 3-D and contours of the potential difference, figure 5.8 and 5.9.

The second form is a 2-D curves showing the change of the average PD measured at the 16-points/side during the test period, figure 5.10. a percentage change between the two sides is also shown on the figure, beside curve fits trends are moreover included.

The third form is a comparison of the PD contour plots for the protected and unprotected sides, figure 5.11. The aim of the last form is to find a link between the PD distributions and the distribution of the metal loss of Plate-Y.

The typical PD results presented in the 3-D form shown in figures 5.8 and 5.9 visualize the PD distribution on the protected and unprotected sides of Plate-Y, respectively. Detail examination of the differences between the two distributions would be mostly better using the contour plots.

Examination of results presented in figures 5.10, which show the average of accumulated readings over the test period for potential difference at both sides of Plate-Y reveals that; the plate/electrolyte potential difference shows an increasing trend with time up to a certain value where it remains almost constant. This is expected and a logic behaviour and is attributed to cathodic polarization effect. The observed scatter of some points on the curves is mostly explained by random

power supply failure (cut off), particularly over the week ends for external reasons.

Figure 5.11 presents the PD contours for the above same case, which is examined in view of the results in coupons metal loss distribution presented in figure 5.4. Analysis of the above mentioned figures shows and reveals the following important facts.

1) Pattern of PD contour on front surface is nearly symmetric around plate center whereas on the back surface tend to be dense near one corner (lower left corner).

   This means potential gradient id not the same on both sides.

2) Taking into consideration that potential drop in plate itself is negligible; it can be easily understood that the indicated difference in potential is due to change in electrolyte potential. This means that more negative value indicate cathodic area and vice versa.

This distortion in potential field undoubtedly shall lead to induce of corrosion circuits on the unprotected side, which is strongly clear on the plate mass loss rate, figure 4.6 and 4.7.

Comparison between figures 4.5 and 4.6 shows heavier corrosion loss in Plate-Y at the anodic area than the unprotected Plate-X. In other words, corrosion damage due to induced corrosion circuit is exceedingly higher than that in the corresponding case of no protection. To shed more light of the rate of mass loss distribution over the three plates (X, Y and Z), such expected distributions as would be very difficult to obtain in practice, the SURFER computer software is used to produce the 3-D and contour plots shown in figures 4.12, 4.13 and 4.14 for plate X, Y and Z, respectively.

5-3-2 Potential Difference in the Perpendicular Plane

The electrolyte/Plate-Y potential difference was measured in a vertical plane perpendicular to the plate middle surface at 18 points/side (as indicated diagrammatically in figure 4.6). The average reading of each point over the test period was obtained. The PD for three levels under water surface (500, 700 and 900 mm) are drawn as shown in figure 4.16 which indicate slight decreasing trend in the PD at the points nearer to the plate surface or deeper in the electrolyte. Moreover, the PD at the plate protected side (front) is slightly lower than the corresponding values at the unprotected side (back). This results confirms and agrees with the previous findings for both the parallel PD results and rate of plate corrosion pattern.

5-4 Plates Sample Analysis

Close examination of the X-ray electronic photography of the samples taken from the three plates at the end of test period reveals an intersecting behaviour which agrees with the previous findings. The surface of Plate-X has shown pitting, gelatinization and heavy corrosion, Photo 5.1. This can be attributed to the hydrolysis of iron metal and its transformation to iron oxy-hydroxides. The unprotected surface of Plate-Y behaved similar to the surfaces of the unprotected Plate-X, Photo 5.2. On the other hand the surfaces of the fully protected Plate-Z have found clear of any pitting or gelatinization which support the low metal loss of Plate-Z, Photo 5.3. Finally, it would be worth mentioning here again that cathodic protection of large steel structures from one side only is not better if not worse than no protection at all because of the shielding effect and induced accelerated corrosion of the unprotected side.

Table 5.3 Material loss and loss rate in different parts of the three plates

Part No.	Plate-X		Plate-Y		Plate-Z	
	Mass loss, g	Mass loss rate, g/m^2	Mass loss, g	Mass loss rate, g/m^2	Mass loss, g	Mass loss rate, g/m^2
1	27.996	134.213	3.916	48.959	10.428	132.690
2	21.040	96.971	8.067	100.154	0.782	9.991
3	76.372	384.762	4.487	56.781	-0.504	-6.444
4	43.702	212.005	4.761	58.998	1.218	15.528
5	80.954	381.363	5.022	63.621	9.351	120.099
6	28.639	139.311	5.016	63.198	0.575	7.201
7			4.081	51.091	-0.441	-5.458
8			3.957	49.120	-1.023	-12.390
9			5.486	70.916	11.193	141.403
10			6.555	83.117	2.654	33.821
11			6.433	80.457	1.709	21.809
12			4.554	57.539	2.189	27.769
13			16.147	206.515	11.259	140.415
14			15.918	202.727	2.204	27.667
15			21.208	263.630	0.411	5.184
16			26.689	333.719	1.726	21.491
Total	**278.703**	**Average 224.771**	**142.297**	**Average 111.909**	**53.731**	**Average 42.549**

Lay out of the cut parts of the three plates at the end of testing

Part position

Column / row	1	2	3
A	P1	P2	P3
B	P4	P5	P6

Column / row	1	2	3	4
A	P1	P 2	P 3	P 4
B	P 5	P 6	P 7	P 8
C	P 9	P 10	P 11	P 12
D	P 13	P 14	P 15	P 16

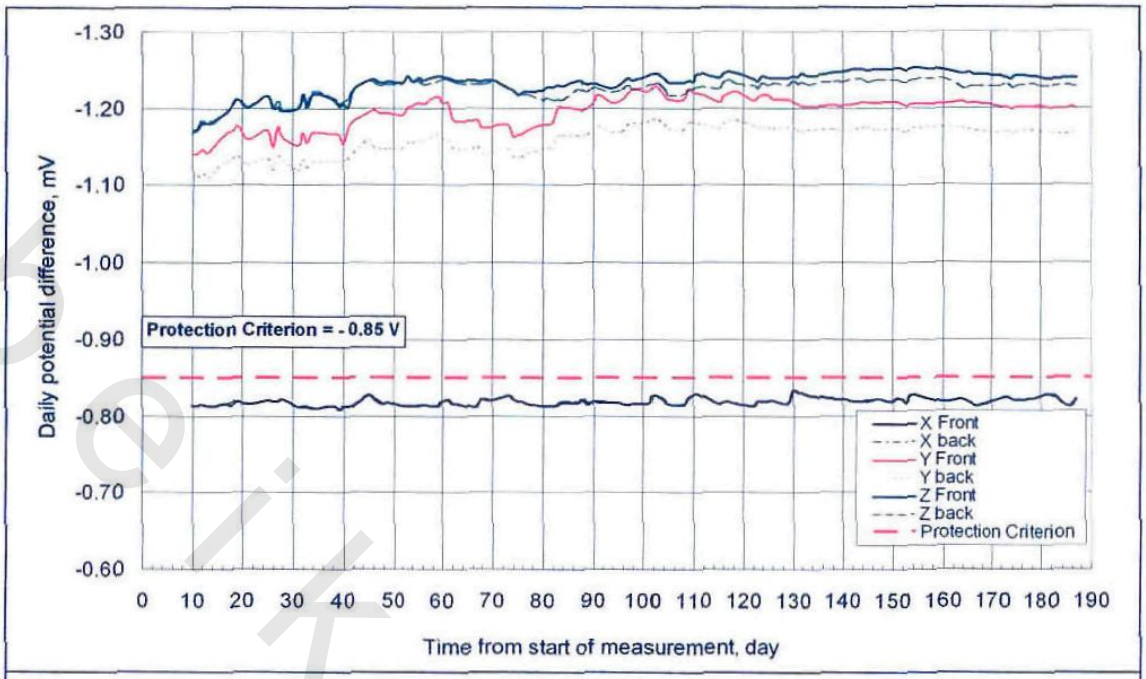

Figure 5.1 Daily potential difference measurement for the three plates, mV

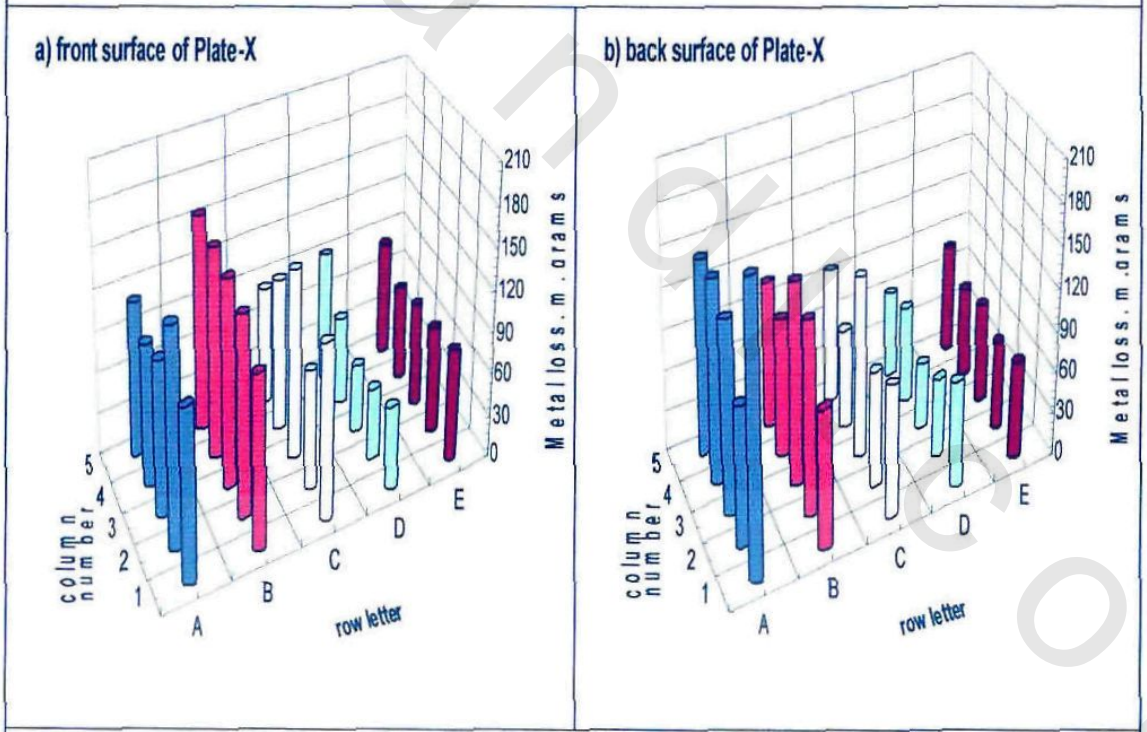

Figure 5.2 Metal loss distribution patterns in coupons over unprotected Plate-X

a) front, b) back

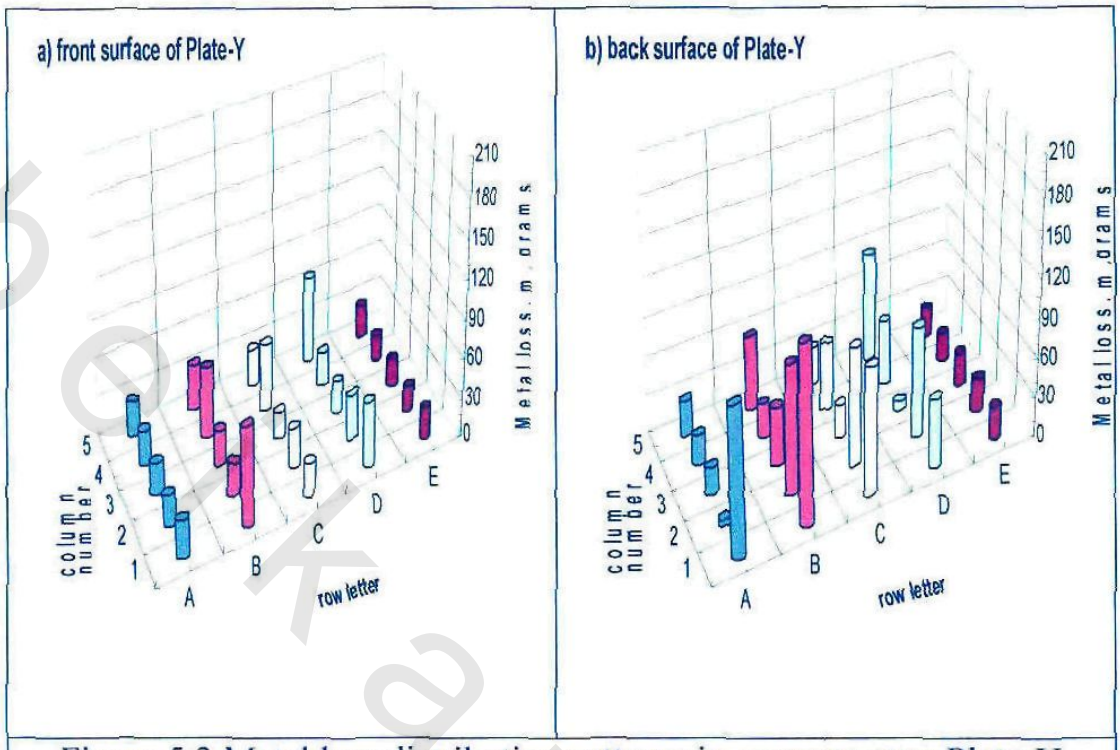

Figure 5.3 Metal loss distribution patterns in coupons over Plate-Y protected from front side

a) front, b) back

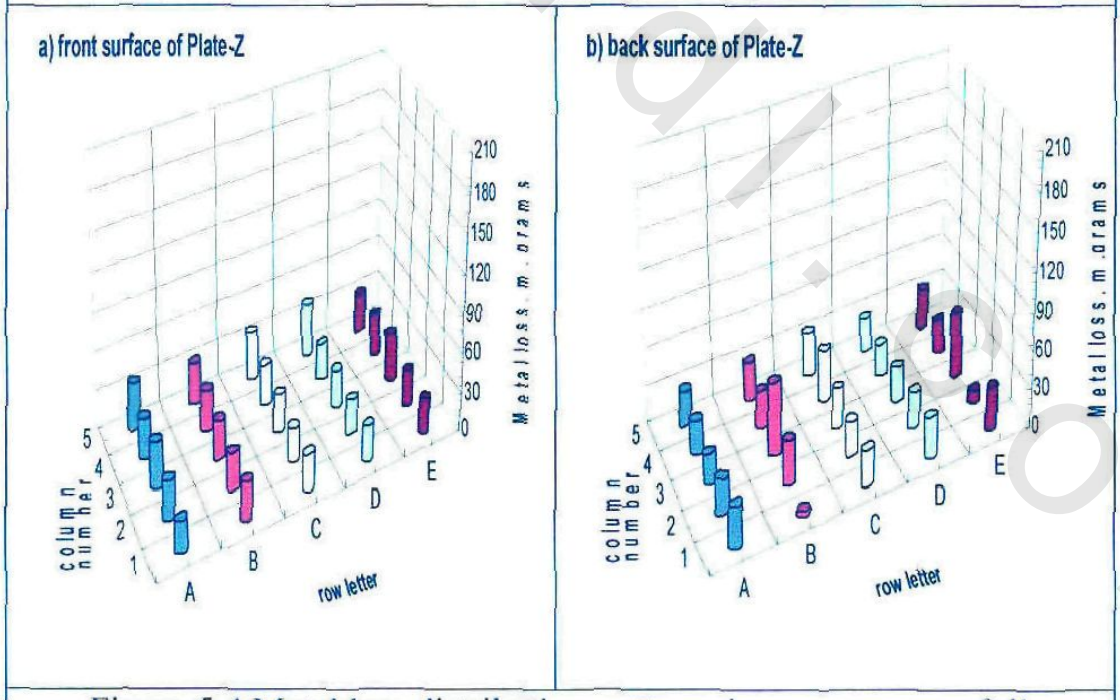

Figure 5.4 Metal loss distribution patterns in coupons over full protected Plate-Z

a) front, b) back

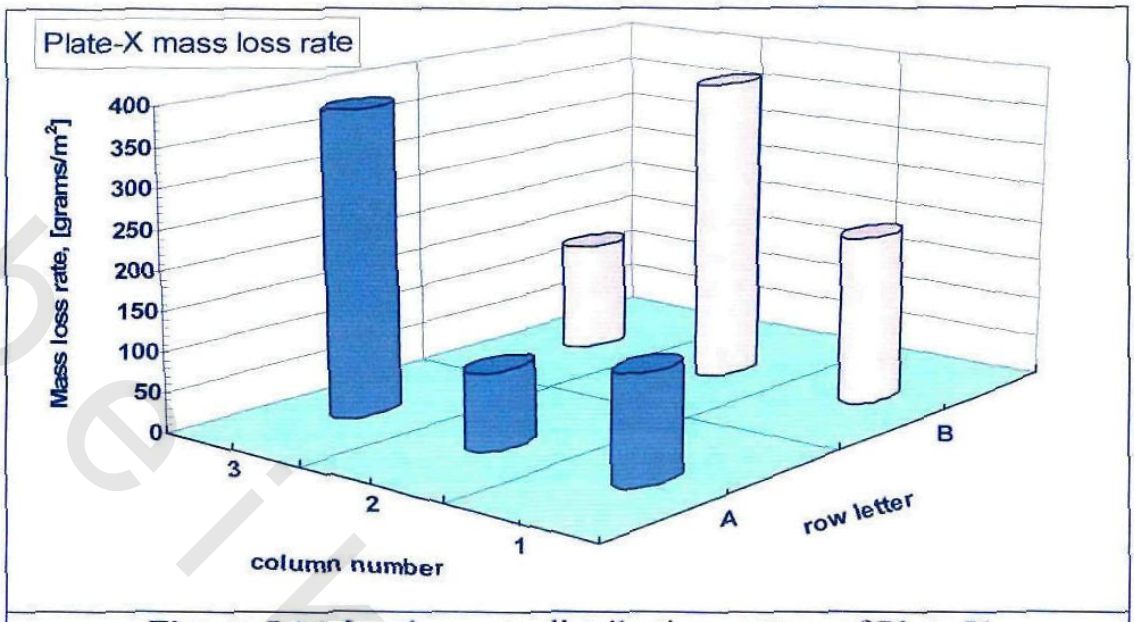

Figure 5.5 Mass loss rate distribution pattern of Plate-X

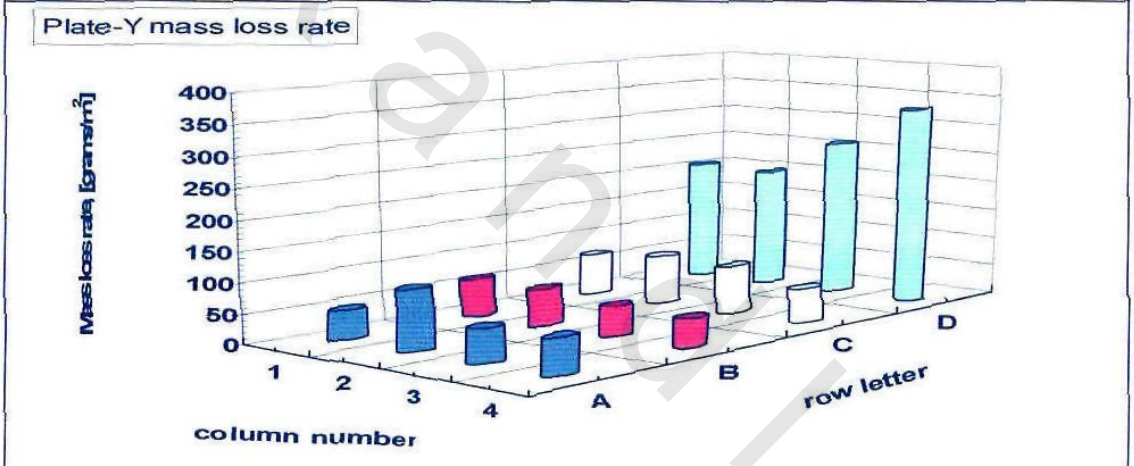

Figure 5.6 Mass loss rate distribution pattern of Plate-Y

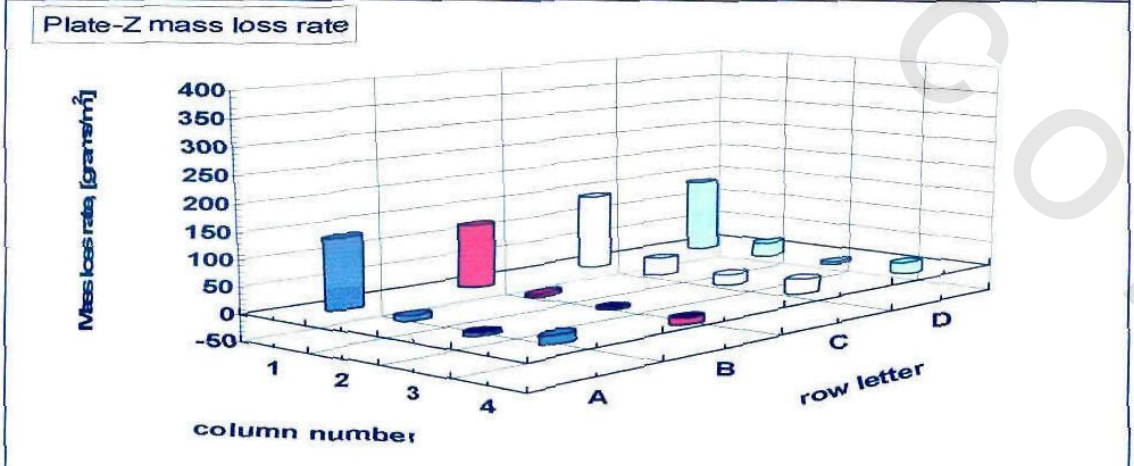

Figure 5.7 Mass loss rate distribution pattern of Plate-Z

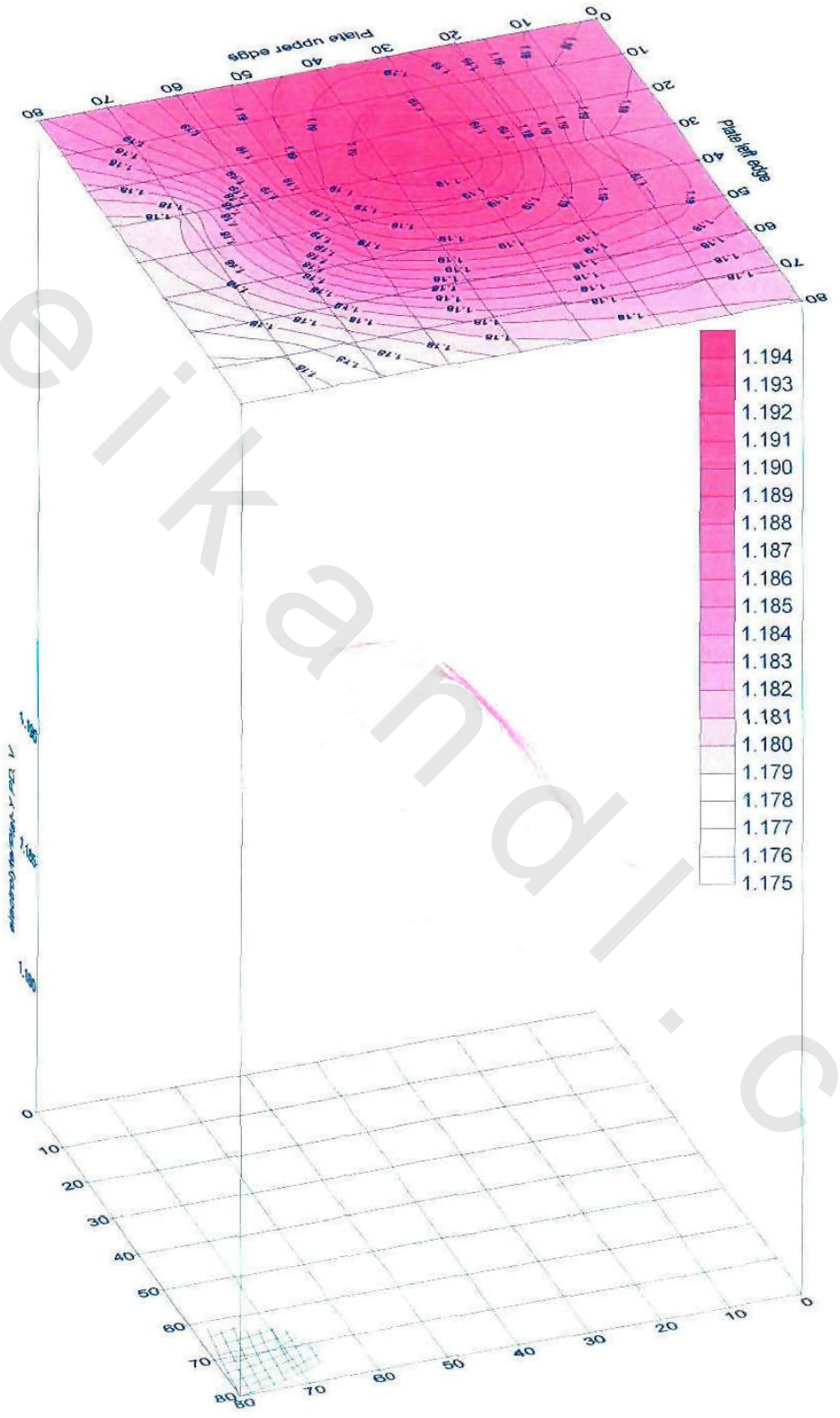

Figure 5.8 electrolyte/Plate-Y 3-D and contour Potential difference in a plane parallel to the protected side of Plate-Y at a distance 25 mm.

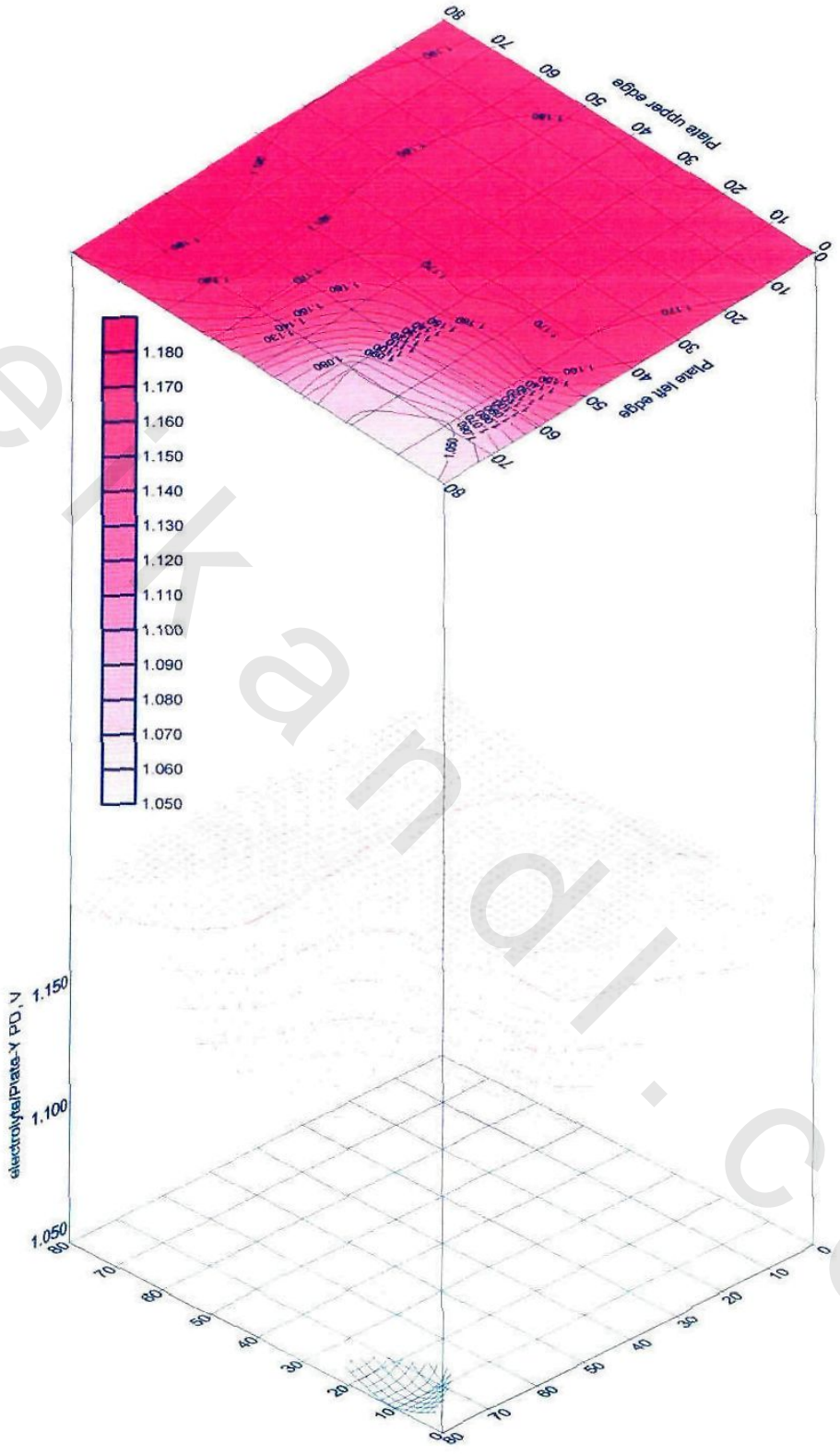

Figure 5.9 electrolyte/Plate-Y 3-D and contour Potential difference in a plane parallel to the unprotected side of Plate-Y at a distance 25 mm.

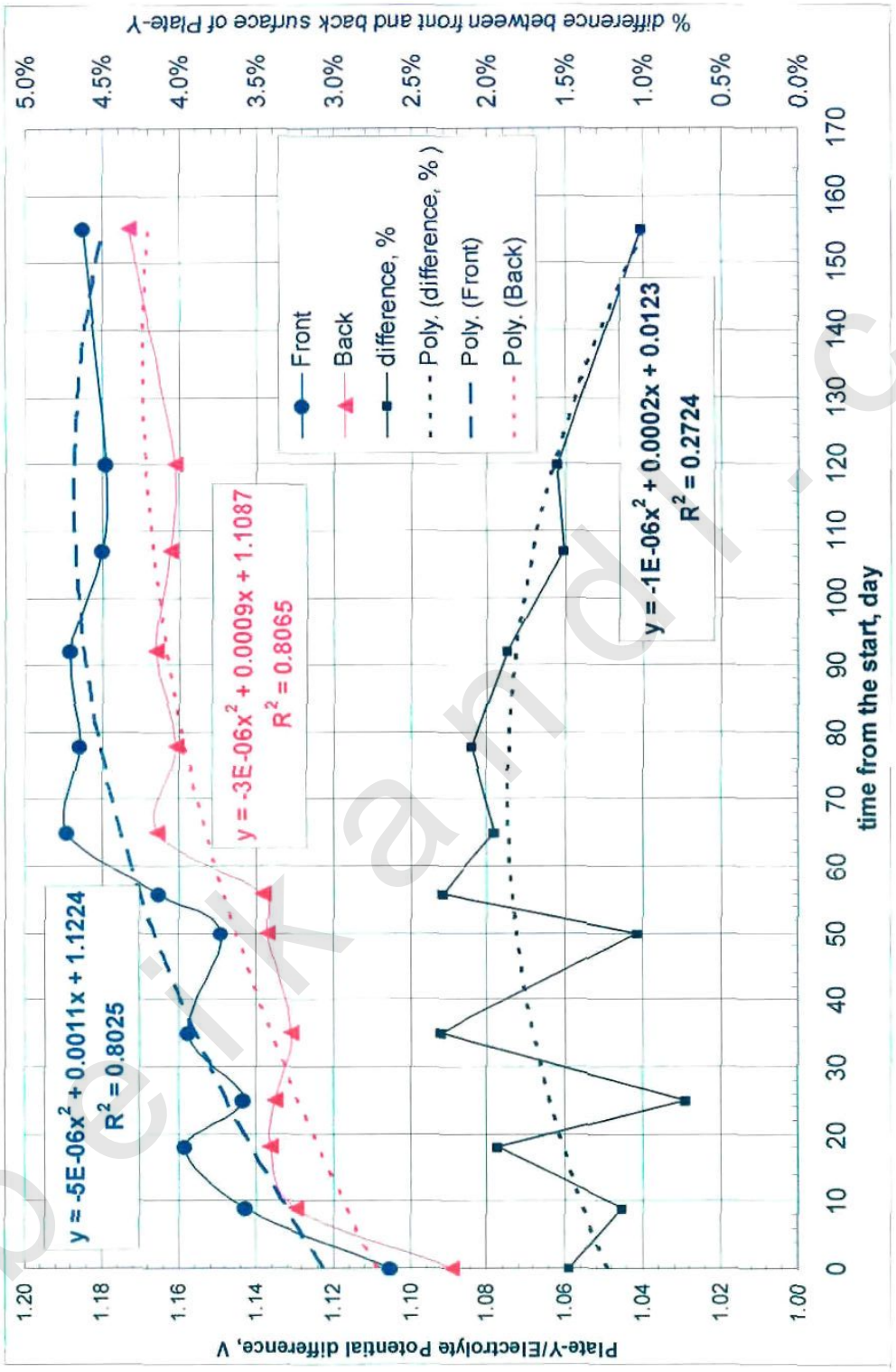

Figure 5.10 Comparison of electrolyte/Plate-Y PD from the protected and unprotected sides and the percentage difference between the two sides.

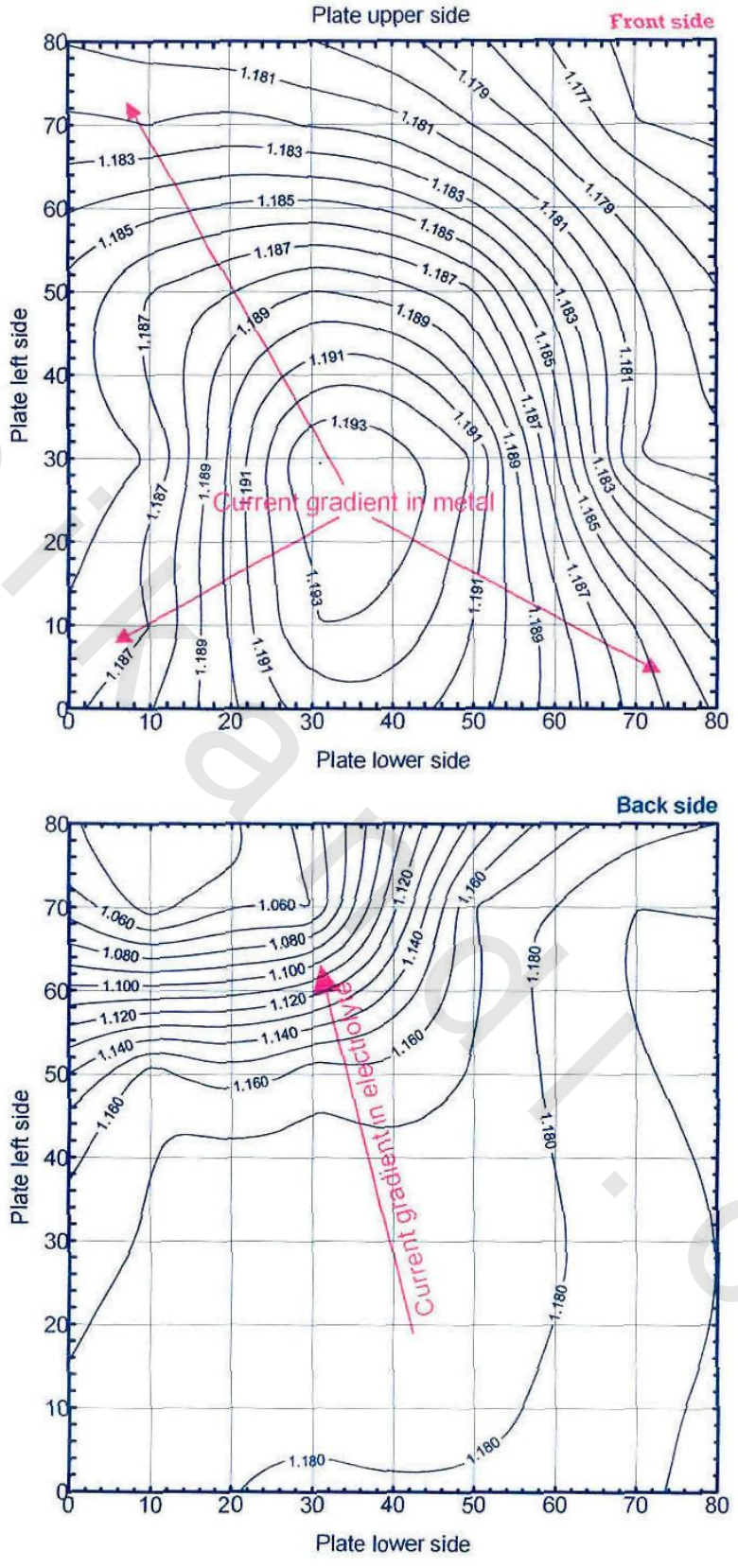

Figure 5.11 A typical electrolyte/Plate-Y potential difference measured in planes parallel to the plate 25 mm from the corresponding front and back sides, V

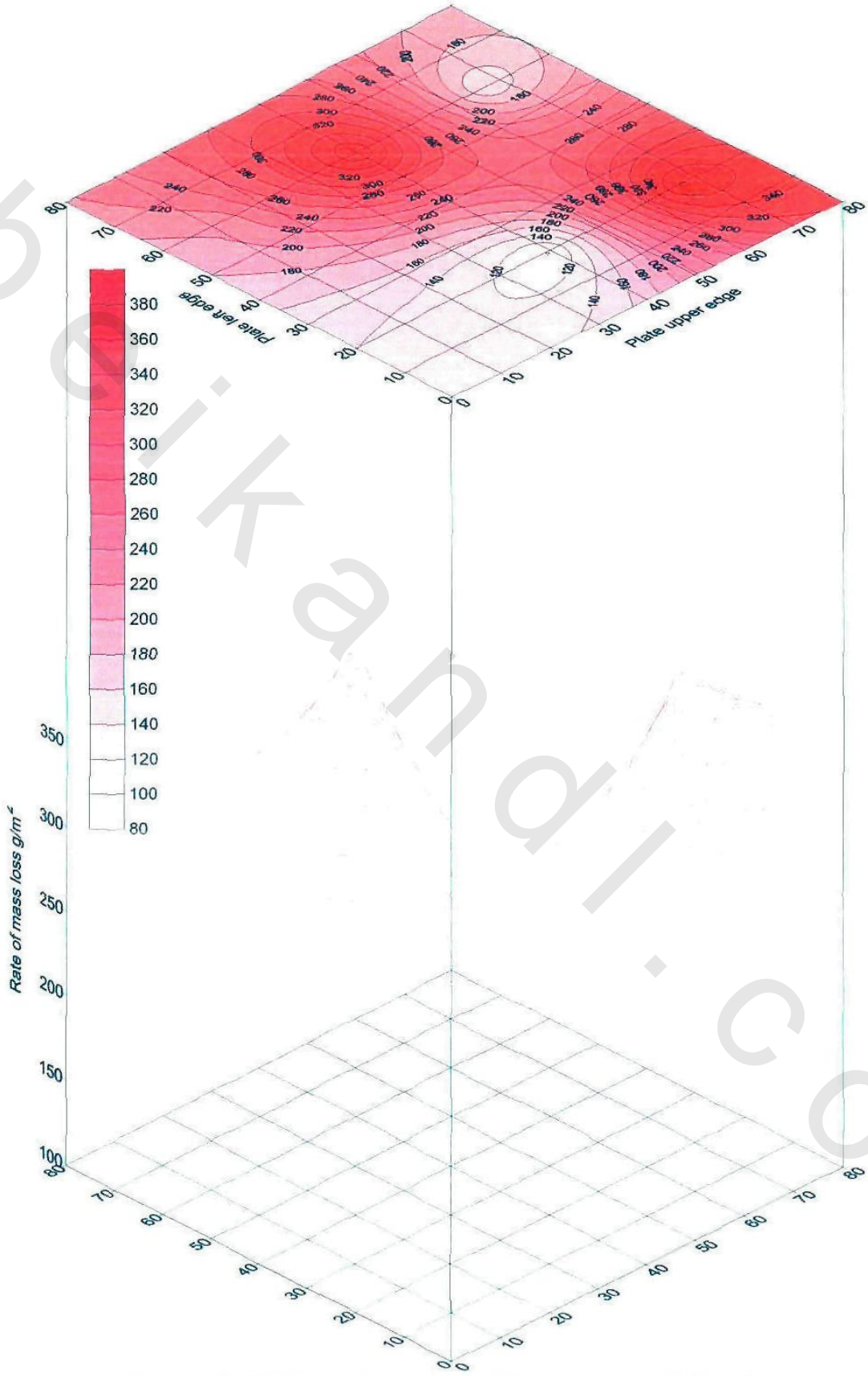

Figure 5.12 Rate of mass loss distribution of Plate-X

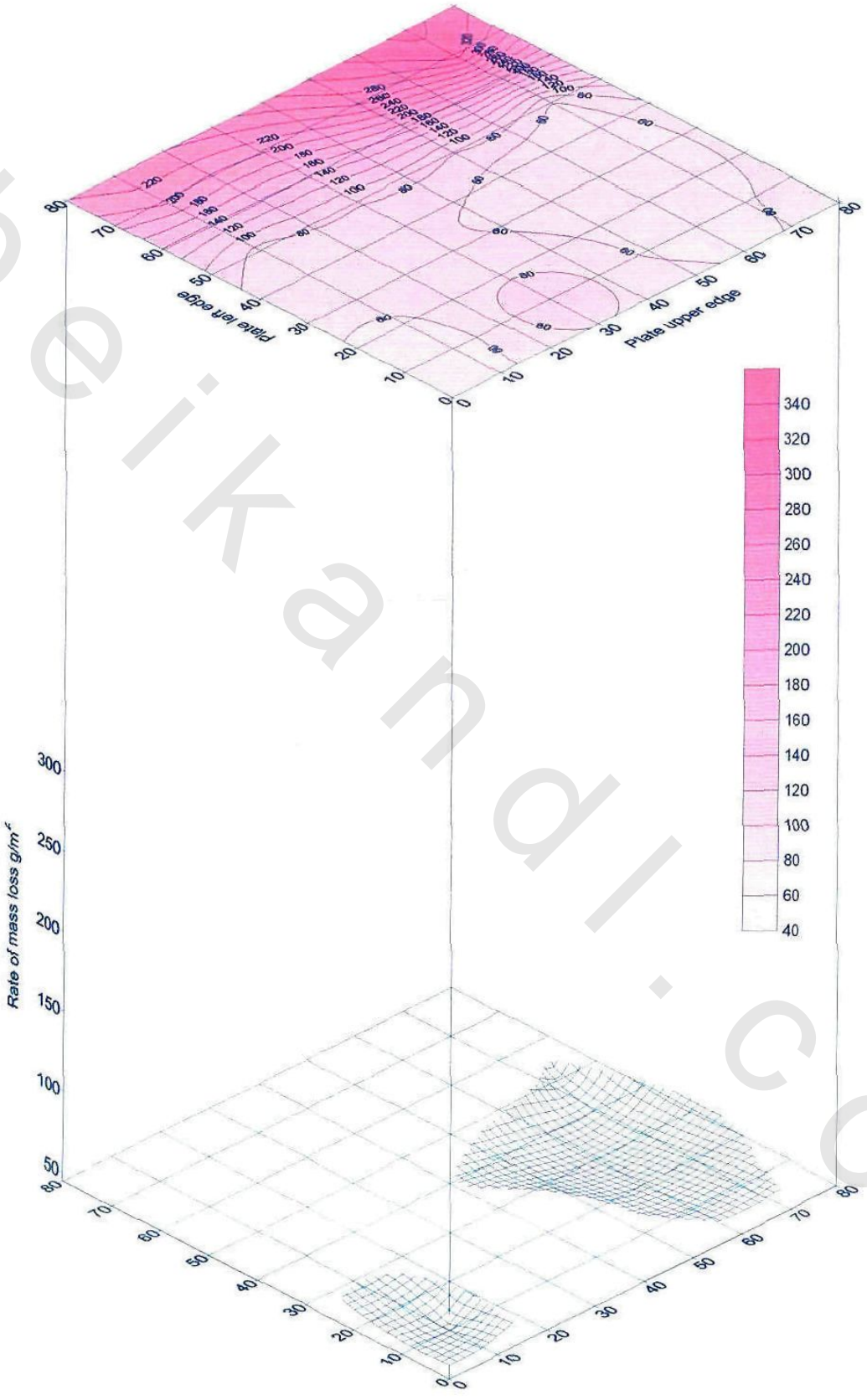

Figure 5.13 Rate of mass loss distribution of Plate-Y

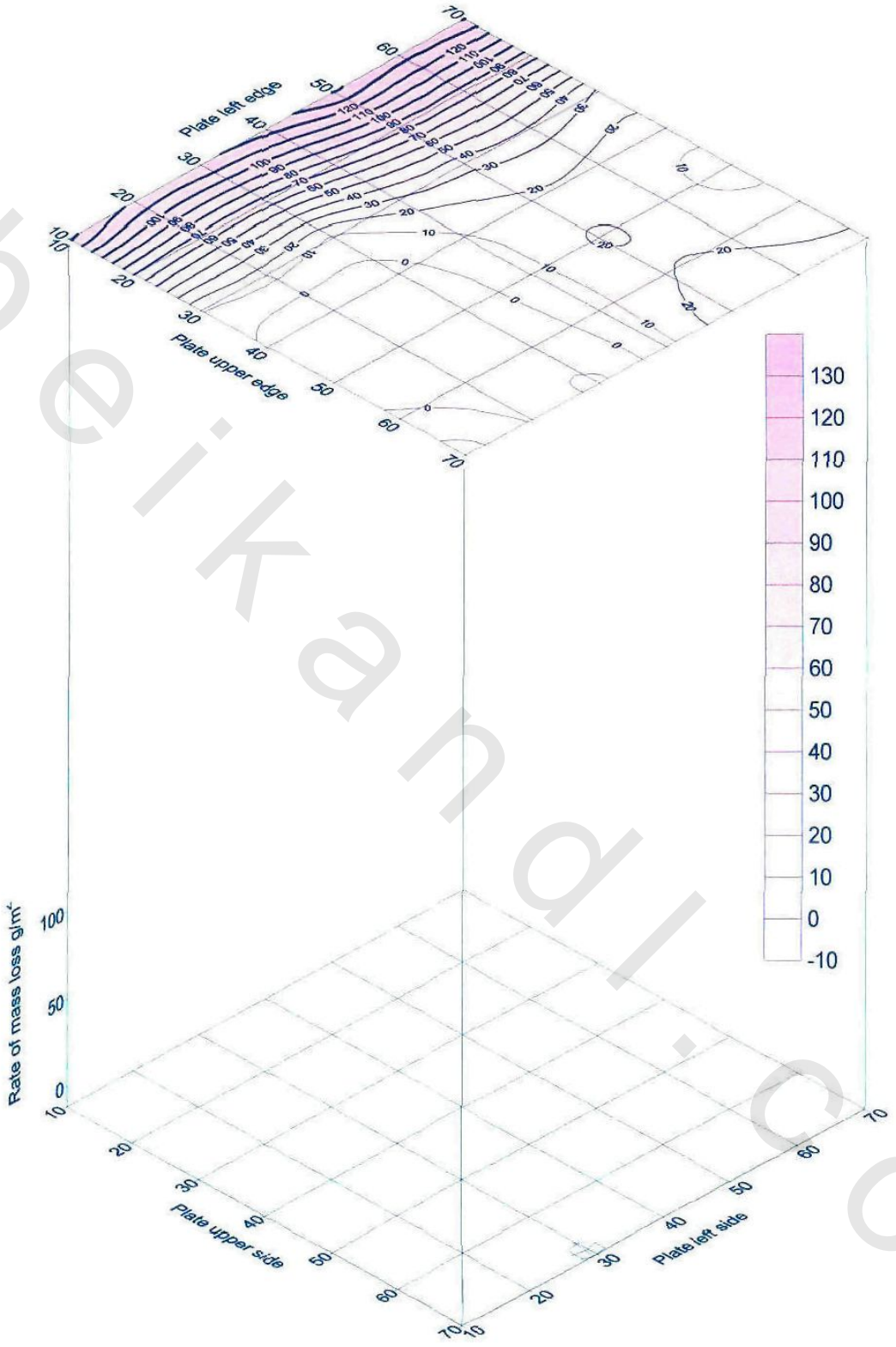

Figure 5.14 Rate of mass loss distribution of Plate-Z

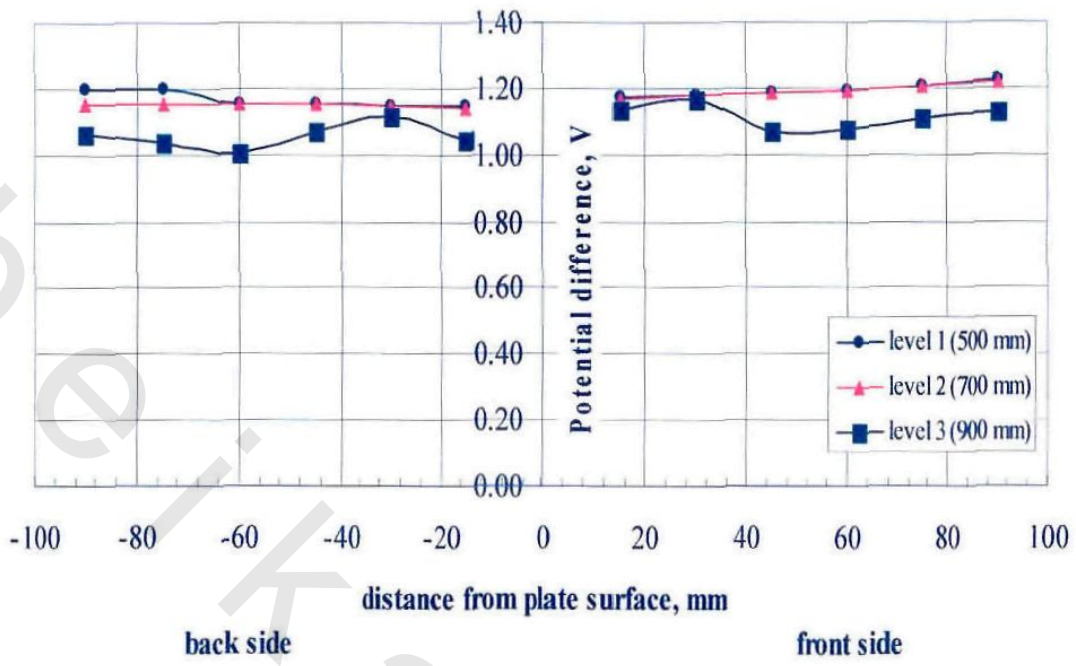

Figure 5.15 electrolyte/Plate-Y potential differences at both sides in a plane perpendicular the middle of the plate.

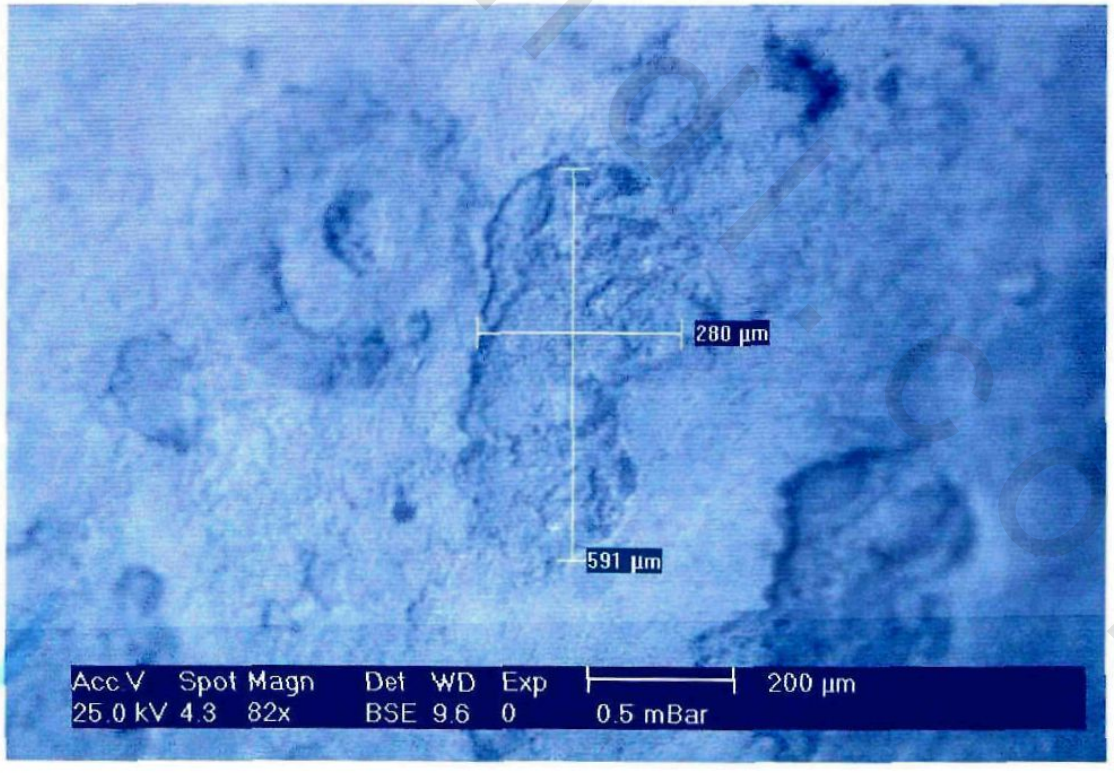

Photo 5.1 Plate-X electronic microscopic photographic

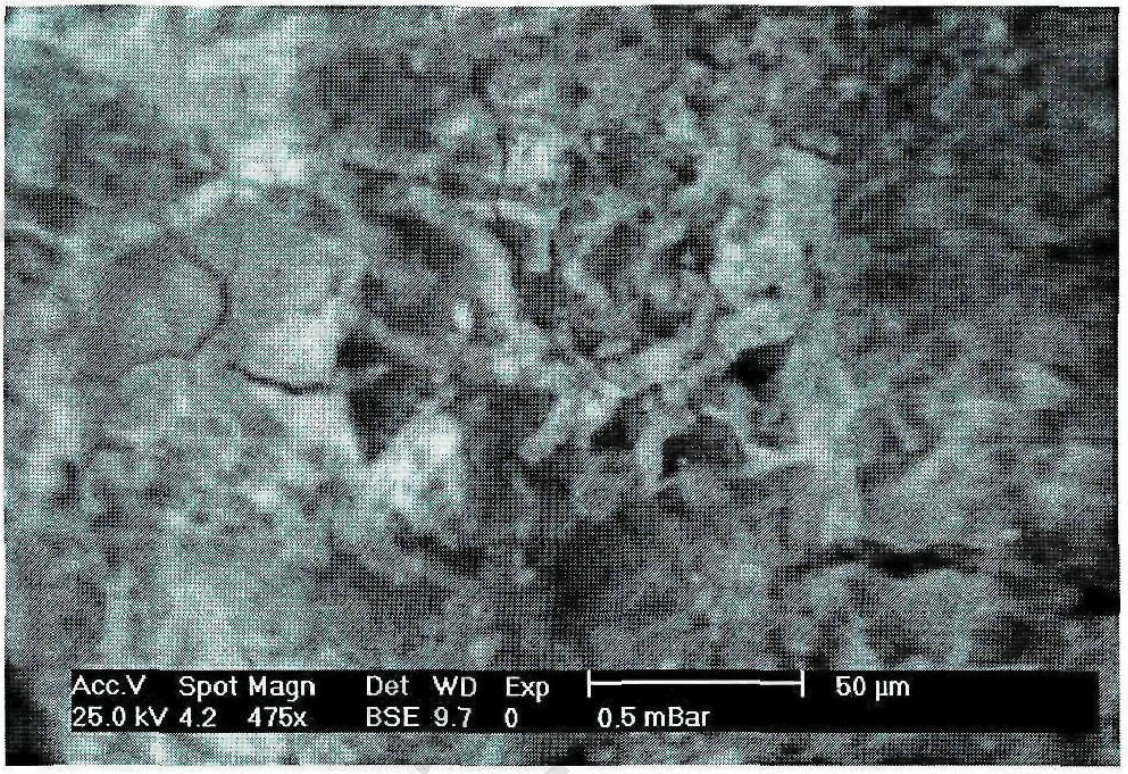

Photo 5.2 Plate-Y electronic microscopic photographic

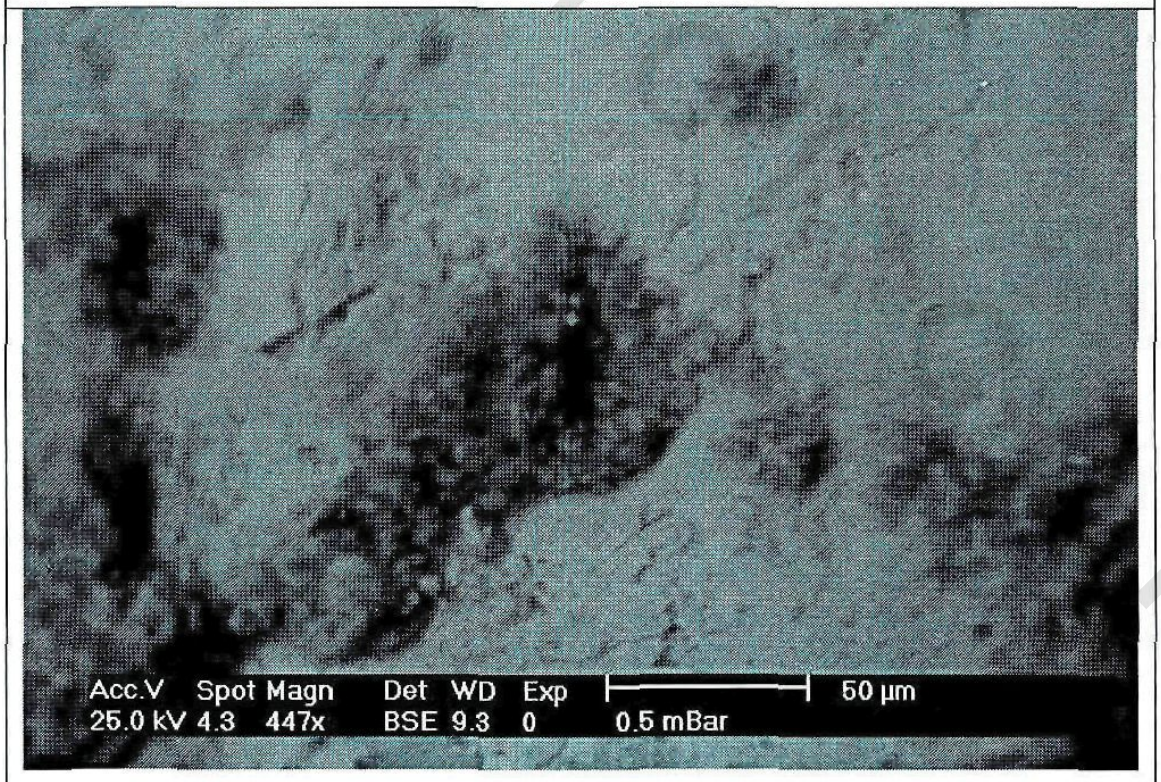

Photo 5.3 Plate-Z electronic microscopic photographic