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The Effectiveness of SACP in Controlling Of Concrete Steel Reinforcement in Aggressive Environments

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By

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To my Parents,

My Wife,

My Sons and

daughters

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ABSTRACT

The Arabian Gulf is considered to be one of the world's most aggressive environments for reinforced concrete. Traditional methods of corrosion protection may not be enough to provide the required level of corrosion control for the design life of concrete structures in such environments.

Cathodic protection has been found as a viable technique of inhibiting chloride induced corrosion of steel in concrete structures. As an alternative to impressed current cathodic protection ICCP a remarkable developments recently have been made in the application of sacrificial anode cathodic protection as a means of enhancing the performance of patch repair.

The main objective of this thesis is to study the effectiveness of application of sacrificial anode cathodic protection (SACP) in preventing or reducing corrosion of steel reinforcement in the reinforced concrete in aggressive environments.

Various experimental settings are considered to account for the effectiveness of the sacrificial anodes (SA) locally and globally, immersed and atmospherically exposed, in relatively small and large patch repairs and in both old and new construction.

The experiment program was divided into two parts; in-situ and laboratory. In the in-situ program, three columns with significant corrosion were selected, evaluated, repaired and monitored for about one year. Local and global sacrificial anodes were used. In the laboratory part, six slabs were cast; they

were designed to simulate old repaired concrete with relatively small and large area of repairs, and new construction.

The results of in-situ program demonstrated that sacrificial anodes were working. Protection from corrosion in the columns that were treated by means of local SA was apparent relative to the control. The global SA effect was not equally apparent in such a short period. The results of SACP in new constructed slab showed positive effect in preventing steel from corrosion. Even though the average current density recorded in the slabs was appropriate for CP, the mean depolarsation potentials considerably short of the required level. It should be stated, however, that the intention was not to install sacrificial CP system but to study the performance of the sacrificial anodes in conditions where corrosion of steel reinforcement may be occurring nearby. This reflects the fact that electrochemical equilibration under polarizing conditions requires a considerable period of time to be established, particularly in the case of passive steel

The use of SACP in patch repairs has been proved to give cathodic protection to concrete. An electrochemical cell was formed in which SA was anode and surrounding steel was cathode as was seen from the potential results. This was clearer in the 20-year-old column than in newly cast laboratory slabs. Throughout the tests to date, the anodes have been found to be an effective method for controlling the problems associated with incipient anode generation and the premature failure of areas surrounding repairs in concrete, which are suffering from chloride, related corrosion.

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1 INTRODUCTION

1.1 Corrosion and Corrosion cost

Many countries (U.K., U.S.A, Australia, and others) have estimated the cost of corrosion and all have got same results. The annual corrosion cost estimates in the United States is in the range of $8 billion to $126 billion. National Beureau of Standards (NBS) and Battelle Memorial Institute carried out a study of annual cost of metallic corrosion, the results was $70 billion [1].

In Seoul, South Korea, October 1994, 32 persons were killed as a result of collapsing of a bridge into San River in rush hour time; the cause was breaking corroded extension hinges [2].

Crude oil spilled out from burst pipelines and contamination of underground water due to leakage of underground storage tanks could cause a big environmental problem. (3/8) of a ton of CO_2 - largely responsible for global warming - is released into air due to production of a ton of steel from ore iron to replace one lost to corrosion, this comes from the fact that 1 tonne of steel is transformed totally into rust every 90 seconds. Separately from metal wastage, the energy needed to produce one tonne of steel from iron ore is enough energy for 3 months provided to an average family home [3].

Now an emerging mid to long term solution to reinforcement corrosion is cathodic protection (CP) of reinforced concrete. It saves extensively in initial capital cost when compared with chloride contaminated concrete removal or reconstruction. It has showed high success and reliability in well designed and executed systems. Costs of applying cathodic protection in UK has been increased from £100,000 in 1986 to £20 million in 1991 for cost savings with confirmed performance [4]. Savings in capital cost by CP over the other long term alternatives will be almost a factor of 2; while this factor in highways structures will reach about a factor of 10 [4]. Savings of some £140 million can be obtained from spending about £615 million on using CP in highways structures in the next 10 years as estimated by the Department of Transport in the U.S [4].

1.2 Cathodic protection

More than 600 000 m^2 of corroding reinforced concrete structures in North America have been protected by CP [5]. CP has been applied to 500 bridges, in Europe (mainly in UK, Norway and Italy), in Asia (Middle East, Korea, and Japan) and Australia [5]. In Italy CP has been applied to almost all prestressed concrete structures and about 150,000 m^2 of new concrete structures in the early 1990s [5].

There are two types of CP: sacrificial CP, which is considered a passive method, and impressed current CP, which is an active method of protection. Sacrificial CP is based on the principle of dissimilar metal corrosion and the relative position of specific metals in the galvanic series. Sacrificial CP systems have the advantage of no auxiliary power supply; however, the anode is soluble and is therefore consumed.

CP by impressed current uses a power supply and rectifier with an inert anode to protect the metal structure as a cathode. A low-voltage direct current is driven from the anode through the concrete to the surface of the steel. The system has the advantage of controlling the amount of current being received at the reinforcing steel through adjustment of the power supply.

1.3 Local experiences in cathodic protection

In the United Arab Emirates, cathodic prevention has been applied to the reinforced concrete frame of the Juma Bin Usayan Al-Mansouri building in Abu Dhabi (3,700 m^2), and the replacement coping to the quayside of Port Rashid in Dubai (10,800 m^2) [6]. Also it was used in mina zayed in Abu Dhabi as titanium mesh anode overlaid by sprayed concrete applied to 11,000 m^2 of beam sides and soffits. A total of less than 10 m^2 of delamination were located and repaired at a 100% inspection 3 months after placement. Further 100 % inspections 12-18 months after placement confirmed no new delaminations and no growth of those, which had been repaired [6].

Cathodic protection (CP) systems of 15 fixed offshore platforms were monitored by measuring anode and platform potentials and sacrificial anode depletion, these steel template structures off the coast of the United Arab Emirates, are in water depths between 125 and 185 ft (115 and 170 m).

Measured steel potentials < -900 m V show that all structures were very well polarized and functional providing protective potentials [7].

1.4 Objectives of the thesis

The main objective of this thesis is to study the effectiveness of application of sacrificial anode cathodic protection in preventing or reducing corrosion of steel reinforcement in the reinforced concrete in aggressive environments. This research will investigate the effectiveness of electrochemical repairs of reinforced concrete structures in terms of durability, lifetime cost and the ability to extend concrete protection beyond the boundaries of localized patch repair. In addition to developing an effective repair strategy and specification of a deteriorating reinforced structure, which take into account the cause of deterioration and the risk of unsuitable materials and techniques being specified. To fulfill this objective, the following items are considered:

- Compare the sacrificial anodes used in atmospherically exposed concrete and the ones immersed in soil in underground concrete.
- Evaluate the performance of sacrificial anodes located in the patch repair in conjunction with ones located globally in the structure,
- Study the effect of relative size of repair and the cathode anode ratio between the repair area and the surrounding concrete,
- Study the performance of sacrificial anodes used in new constructions as a prevention measure to corrosion in concrete.

1.5 Thesis outline

This thesis is divided into five chapters. Definition of the problem with the suggested solution and the objective of this thesis are introduced in chapter 1. The following chapters are ordered as follows:

Chapter 2 illustrates the basic principles of corrosion process and cathodic protection. This review details some technical advances in the use of galvanic technology for protecting reinforced concrete structures, with examples of actual installations and supporting data obtained.

Chapter 3 describes the investigation stage of the columns including the visual examination of site and the established repair procedures to achieve the required goals that implemented in this study, supported by photographic documentation for the work steps. The set-up procedures of the slabs are discussed in this chapter. In addition, this chapter describes the monitoring procedure for potential and current output of the sacrificial anodes.

Chapter 4 discusses the obtained results from the half-cell potential measurements and the potential and current output by making comparisons between the samples under the study with the corresponding control samples. Chapter 5 addresses some of comparison and appraisal of electrochemical techniques with general conclusions and requirements for future developments.

Chapter Two

Literature Review

2 LITERATURE REVIEW

2.1 Introduction

Although concrete/steel composite is inherently inhomogeneous, the most of reinforced concrete structures do not exhibit rebar corrosion. The high alkalinity of concrete results in the formation of a passive oxide layer on the surface of the reinforcing steel that reduces corrosion to extremely low levels. However, the ingress of chemical agents lead to a breakdown in the protective passive layer and subsequent corrosion of reinforcing steel can occurs, this is because of the finite permeability of concrete.

The two most commonly causes of rebar corrosion are (a) carbonation in which carbon dioxide causes a pH reduction in the concrete pore solution and (b) chloride attack. These processes lead to breakdown of the passive oxide layer and subsequent formation of expansive corrosion products, which can lead to cracking and spalling of the concrete surface [8].

Several solutions to the problem of reinforcement corrosion are available and can be used to treat structures in the initiation/propagation phases or following failure. Recently, improved understanding of the corrosion process has permitted development of electrochemical techniques, which try to modify the involving chemistry. "These types of repairs are thus considered by a number of experts to be the 'next generation' of concrete repair techniques".

In the 19th century a technique called cathodic protection was developed and used extensively for protecting pipelines and more recently offshore structures. In the 1970's, impressed current cathodic protection (ICCP) was applied to reinforced concrete structures and has since been applied to a number of structures suffering from chloride induced corrosion problems, in USA and Europe. An alternative to ICCP uses a galvanic anode to supply the protection current to the steel and this technique has been used in pipeline projects where the absence of an external power source is required. Until recently, only reinforced concrete structures in marine environments have been protected using sacrificial anodes. This review details some technical advances in the use of galvanic technology for protecting reinforced concrete structures, with examples of actual installations and supporting data obtained.

2.2 Corrosion of steel in concrete

Why does steel corrode in concrete? A more sensible question is why steel does not corrode in concrete. It is known that mild steel and high strength reinforcing steel bars corrode (rust) with the presence of air and water. As concrete is porous and contains moisture why does steel in concrete not usually corrode? The answer is that concrete is alkaline. In other words it is not acid. Acids lead to metals corrosion, but alkalis often protect them. This means that it contains microscopic pores with high concentrations of soluble calcium, sodium and potassium oxides. These oxides form hydroxides, which are very alkaline, when water is added. This creates a very alkaline condition (pH 12-13). The alkaline condition leads to a formation of a 'passive' layer on the steel surface. Because the passive layer is a dense, impenetrable film it prevents further corrosion of the steel. Part of the layer formed on steel in concrete is metal oxide/ hydroxide and part mineral from the cement [9].

2.2.1 The Corrosion Process

As a result of the passive layer break down areas of rust will start appearing on the steel surface. The chemical reactions are similar between chloride attack and carbonation. Corrosion of steel in concrete results in steel ions dissolving in the pore water and giving up electrons [10]:

The anodic reaction: $Fe \rightarrow Fe^{2+} + 2e^-$

The two electrons ($2e^-$) generated in the anodic reaction must be taken elsewhere on the steel surface to keep electrical neutrality. This means that another chemical reaction must take place consuming the electrons. This is a reaction that consumes water and oxygen [10]:

The cathodic reaction: $2e^- + H_2O + \frac{1}{2}O_2 \rightarrow 2OH^-$

You will notice the generation of hydroxyl ions ($2OH^-$) in the cathodic reaction. These ions increase the local alkalinity and will therefore strengthen the passive layer, preventing the effects of carbonation and chloride ions at the cathode. Water and oxygen are needed at the cathode for corrosion to occur. Several more stages are required for 'rust' to form. As shown below where ferrous hydroxide becomes ferric hydroxide and then hydrated ferric oxide or rust [10]:

$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$ Ferrous hydroxide

$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$ Ferric hydroxide

$2Fe(OH)_3 \rightarrow Fe_2O_3.H_2O$ Hydrated ferric oxide (rust) + $2H_2O$

The volume of unhydrated ferric oxide Fe_2O_3 is about twice that of the steel it replaces when fully dense. Thydrated ferric oxide is even bigger in volume and porous. In other words the volume increase at the steel/concrete interface two to ten times. Consequently the cracking and spalling occurs and the red/brown brittle, flaky rust on the bar and the rust stains observed at cracks in the concrete.

2.2.2 The Chloride Ion

Chloride attack is the major mechanism of deterioration of concrete structures in aggressive environments. These ions migrate through the concrete mix until they reach the steel reinforcement. The rate of penetrating is dependent on several factors, including the concrete cover and permeability, drainage, wetting and drying cycles, temperature, degree of cracking, and effectiveness of other protection methods. Chlorides also can be introduced by the use of contaminated aggregates, the addition of chlorides as set accelerators, and the use of seawater in the mix or for curing. In aggressive environments, it is not unusual for chloride ion levels to exceed 0.3 wt % of concrete at a depth of 75 mm (3 in.) below the concrete surface after only 10 years. Visible signs of deterioration have been reported to develop in <7 years. The levels of chloride needed for corrosion initiation are very low [11].

There have been many recommendations for maximum chloride concentrations. The American Concrete Institute (ACI) Committee 222 recommends the following chloride limits in concrete for new construction, expressed as a wt% of cement (acid-soluble test method):

. Prestressed concrete- 0.08%

. Reinforced concrete in wet conditions-0.10%

. Reinforced concrete in dry conditions-0.20%

A chloride threshold for corrosion also can be expressed in terms of the chloride/hydroxyl ratio. The $[Cl^-]/[OH^-]$ ratio is directly proportional to corrosion rate. Corrosion is observed when the chloride concentration exceeds 0.6 of the hydroxyl concentration. This approximates to a concentration of 0.4% chloride by weight of cement if chlorides are cast into the concrete and 0.2% if they diffuse into the hardened matrix [4].

2.3 Passive Methods of Protection

Traditionally, corrosion protection systems for new reinforced concrete structures have used passive methods of protection. The effective period before initiation of corrosion for each of the following methods is dependent on various factors (i.e., exposure conditions, system effectiveness, and degree of maintenance). No one system is typically used, and more commonly a combination of systems is required. The method(s) of corrosion protection are generally selected on the basis of cost effectiveness, the most common being as indicated by [12]:

2.3.1 Low Permeability Concrete and Increased Cover

For durable concrete we have to take these factors into account, because adequate cover and low water/cement ratios increase the time needed for chlorides to reach reinforcing steel. ACI provides nominal cover requirements for different environments and concrete grades. However, high cover can lead to shrinkage cracking, which may need to be controlled by the addition of fiber additives. Concrete additives and cement replacement materials, such as fly ash, slag, silica fume, and other materials can enhance durability by reducing the pore size and blocking pores. However, it is very necessary to make proper curing to get required performance from these materials. Fly ash, slag, and silica fume additives are generally compatible with CP. However, if silica fume concentration exceeds 10 wt % of cement, the resistivity of concrete may become high [12].

2.3.2 Penetrating Sealers

Penetrating sealers such as silane resist the ingress of water that contain chlorides. They are relatively inexpensive. But they cannot elongate to bridge cracks. And it is difficult to insure adequate application. Sealers are typically reapplied every 2 to 5 years. Applying CP through penetrating sealers is possible [12].

2.3.3 Waterproof Membranes

Waterproof membranes are available in many formulations. They comprise combinations of up to four constituents: a binder (i.e., chlorinated rubber, epoxy resins, and polyurethane resins), inert fillers, or pigments, liquid solvents/ dispersants, and additives to enhance particular properties. Membranes must be applied without defects. Careful detailing is required to avoid water and chlorides getting under the edges. It is difficult to locate the location of leakage if membranes fail, because it can occur in many areas. Waterproofing membranes must be replaced after service life of ~15 years. Membranes can be applied with CP [12].

2.3.4 Epoxy Coated Rebar

The first application to fusion bonded epoxy coated reinforcement (FBECR) in bridge in 1973, since that date it has been used on more than 100,000 structures in the U.S. and Canada. However, serious corrosion problems have been noticed in the substructure of bridges in the Florida Keys, built in the late 1970s with FBECR. Also in Saudi Arabia a seawater intake structure constructed using FBECR was deteriorated prematurely (after 4 years). Loss of adhesion is one of concerns with coated steel. Because of the insulating properties associated with the coating, the application of CP to existing FBECR structures is expensive [12].

2.3.5 Galvanized Rebar

Galvanizing is considered by North American research as an inferior option to epoxy coated rebar. However, galvanized bar will accept damage in handling, since the zinc will sacrifice itself and defects are not as important as with FBECR. Galvanized bars will consume rabidly if they are mixed with bare steel. Its estimated design life is 15-year in good-quality concrete. It works with CP, despite levels of protection should be higher [12].

2.3.6 Corrosion inhibitors

Compound groups of corrosion inhibitors such as chromates, phosphates, hypophosphates, alkalies, nitrites, and fluorides have been investigated. Many have been concluded that they are effective. Recently, calcium nitrite has been used in concrete structures as a corrosion inhibitor. The dosage of calcium nitrate depends on anticipated chloride ion content of the concrete during the design life of the structure. The recommended range is from 10 L/ m^3 to 30 L/m^3 (2 gal/yd^3 to 6 gal/yd^3) of concrete and the level of protection increases in proportion to the dosage. The long-term effectiveness calcium nitrate is still not fully understood. No great effect for calcium nitrite on concrete resistivity. So it can be used with CP [12].

2.4 General considerations and definitions

Before describing the general aspect of CP it is convenient to give a few general considerations and definitions on corrosion and protection of metals particularly to steel in concrete.

2.4.1 Immunity, activity and passivity conditions

Metal cannot corrode (i.e. 'immunity' condition) if the potential of the metal in the electrolyte contacting its surface (E) is lower than the equilibrium potential for the oxidation process (E_{eq}) which given by Nernst's law. Corrosion can take place only if $E>E_{eq}$. In most of situations (e.g. steel in soil or in sea water but also in carbonated concrete) the corrosion rate (i_a) exhibits the behavior called 'active' in which it increases with the potential (Figure 2-1a). In some cases (e.g. steel in concrete and, more generally, in alkaline environments but also stainless steels in neutral media), the behavior, called 'active-passive', and i_a increases above E_{eq} in the (activity zone), then decreases to very small values in the (passivity zone) because of film formation on the metal surface, and finally when this film is destroyed, it increases again at high potentials (Figure 2-1b)[13].

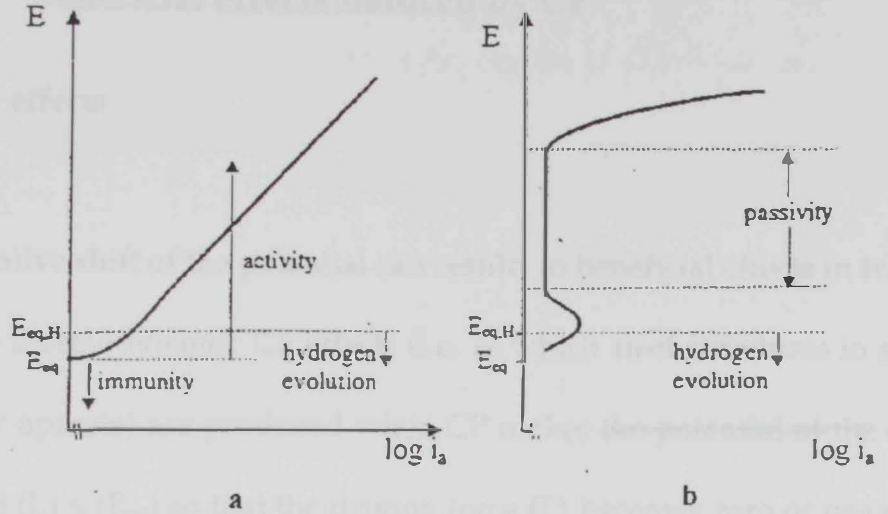


Figure 2-1 a) active b) active-passive anodic behavior of metals

2.4.2 Hydrogen evolution

When the potential of the metal (E) becomes lower than the equilibrium potential of the hydrogen evolution (E_{eq},H), hydrogen evolution can take place [13].

2.4.3 Corrosion potential, driving force, reaction resistance and corrosion rate

Corrosion potential, E_{cor} for metals in aggressive environments is higher than their equilibrium potential, The driving force (L) of the anodic reaction is given by the difference between (E_{cor}) and (E_{eq}): $L = E_{cor} - E_{eq}$' The oxidation reaction is resisted by an anodic resistance (R), generally called anodic overvoltages, which can be very high in passive conditions. Thus corrosion rate (i_a) equal the ratio of L to R: $i_a = L/R$ [13].

2.4.4 Beneficial effects induced by CP

Primary effects

The negative shift of the potential can results in beneficial effects in two ways: First the thermodynamic CP effects (i.e. in which steel structures in soil or in seawater operate) are produced when CP makes the potential of the cathodic structure (E) ≤ (E_{eq}) so that the driving force (L) becomes zero or negative (i.e. immunity); or near to E_{eq} to make L and thus the corrosion rate (i_a) very small (i.e. quasi-immunity) (Figure 2-2a). Second the kinetic CP effects which utilized by CP in concrete - increase or maintain the resistance of anodic process R high – which occur because of a passivity condition setting up or maintaining it in a wider environmental aggressiveness range (e.g. at higher chloride content) caused by the reduction of the driving force L. Figure 2-2 [13].

Secondary effects

The cathodic processes (usually oxygen reduction, and also hydrogen evolution) consume oxygen and produce alkalinity on the reinforcement surface. These effects are beneficial because they widen the passive region (Figure 2-3a) and depolarize the cathodic process (Figure 2-3b) to stop or prevent corrosion. In corroding steel, they stop local acidification and also prevent pitting initiation ('buffer effect'). On the other hand, in chloride contaminated concrete, due to the current circulation chlorides move from the cathode to the anode, which results in a reduction of the chloride content on the rebar surface or in a reduction of the ingress of chlorides into concrete and make it impervious -increase with the current itself- ('chloride barrier effect') [13].

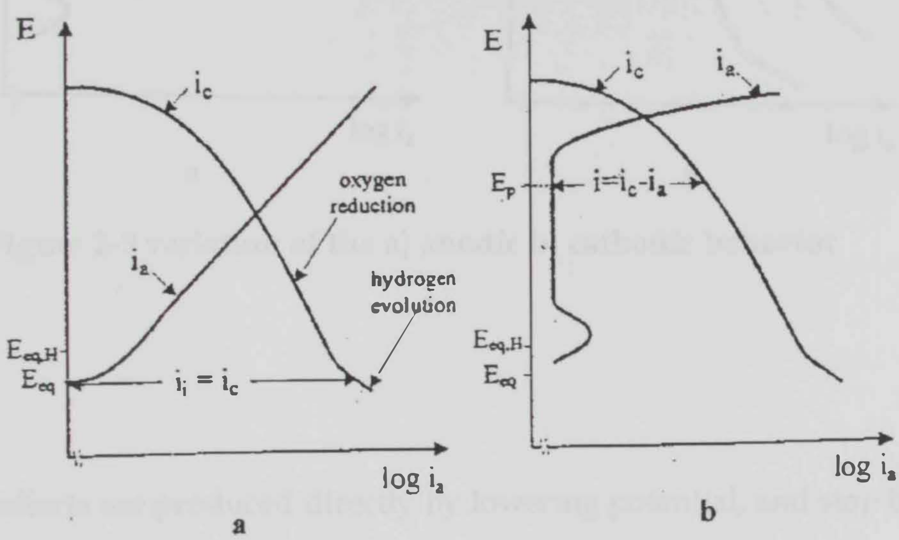


Figure 2-2 Cp in the case of a) active b) active-passive behavior

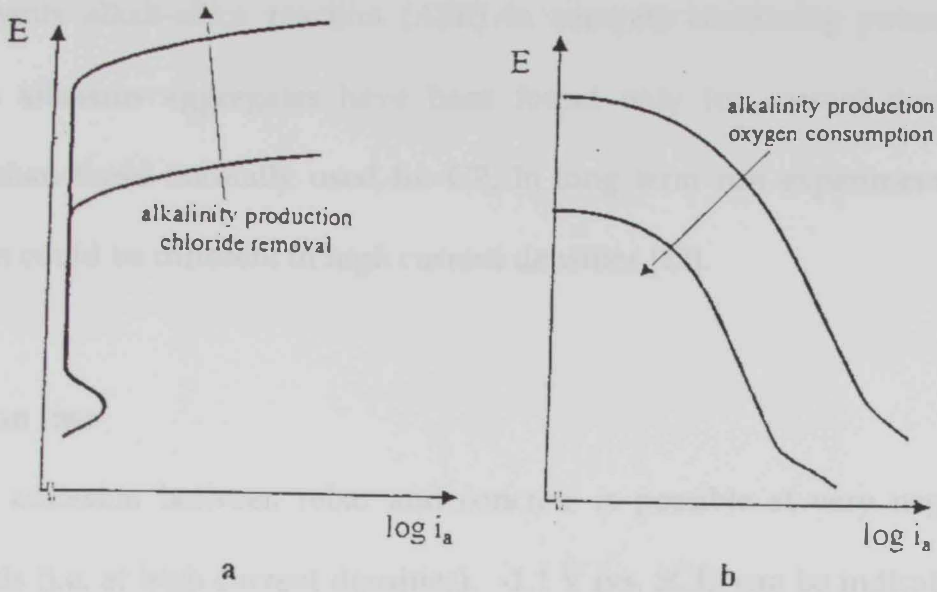


Figure 2-3 variation of the a) anodic b) cathodic behavior

Beneficial effects are produced directly by lowering potential, and stop by the current interruption, while the last two effects may not have so immediate results but they may provide more persistent protection. (The techniques known as electrochemical realkalization and chloride removal are based on these last two effects.)

2.4.5 Negative effects induced by CP

Concrete degradation

In theory concrete that contains alkali-reactive aggregates are subjected to damage if alkalinity around the reinforcement is increased. In short run experiments alkali-silica reaction (ASR) in concrete containing potentially reactive siliceous aggregates have been found only for current densities higher than those normally used for CP. In long term run experiments the situation could be different in high current densities [13].

Adhesion loss

Loss of adhesion between rebar and concrete is possible at very negative potentials (i.e. at high current densities). -1.1 V (vs. SCE) can be indicated as the lower limiting potential for long-term polarization (like in the case of CP)[13].

Hydrogen embrittlement

High strength steels used in prestressed constructions (but not the ordinary steels for reinforced concrete constructions) can be subjected to hydrogen embrittlement if their potential is brought to values at which hydrogen evolution can take place [13].

2.4.6 Criteria for prevention and protection

The criteria for obtaining protection in chloride-contaminated structures to control corrosion and prevention to non-corroding ones are different.

Initiation of corrosion and its prevention

Cathodic prevention of steel reinforcement corrosion is based on the influence of the active-passive behavior of steel in concrete, which is greatly affected by the chlorides presence. As is shown in Figure 2-4. The highest chloride content compatible with passive conditions for each potential is the critical chloride content at that potential [5].

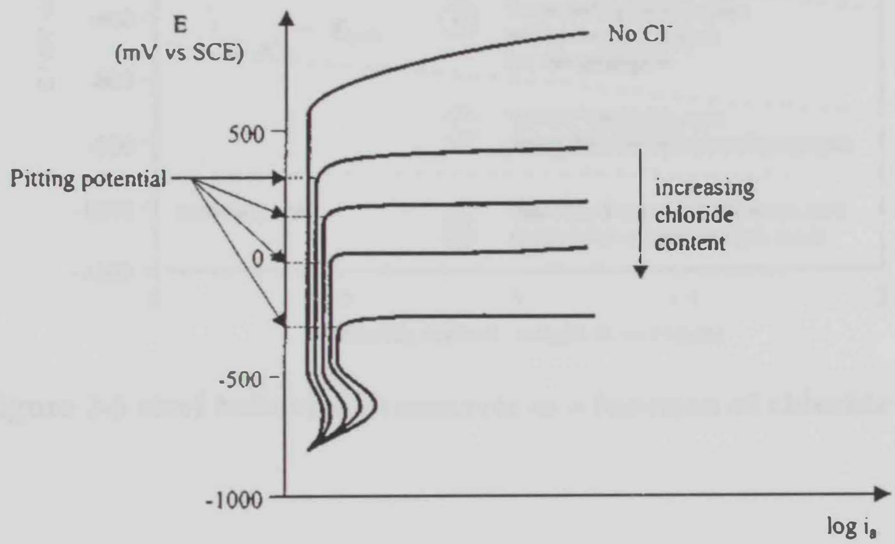


Figure 2-4 anodic behavior of steel in presence of chlorides

Propagation of corrosion and its control

If, for a given chloride content, the rebar potential (E) becomes more positive than E_{pit} or, for a given potential, the chloride content is higher than the critical value, the protective film can be locally destroyed and consequently a localized attack can take place. Once the attack is initiated, it can also propagate at potentials more negative than E_{pit}. To stop it, it is necessary to reach a lower potential (E_{pro}) below which steel repassivates [5].

2.4.7 Operating conditions on the cathodic side

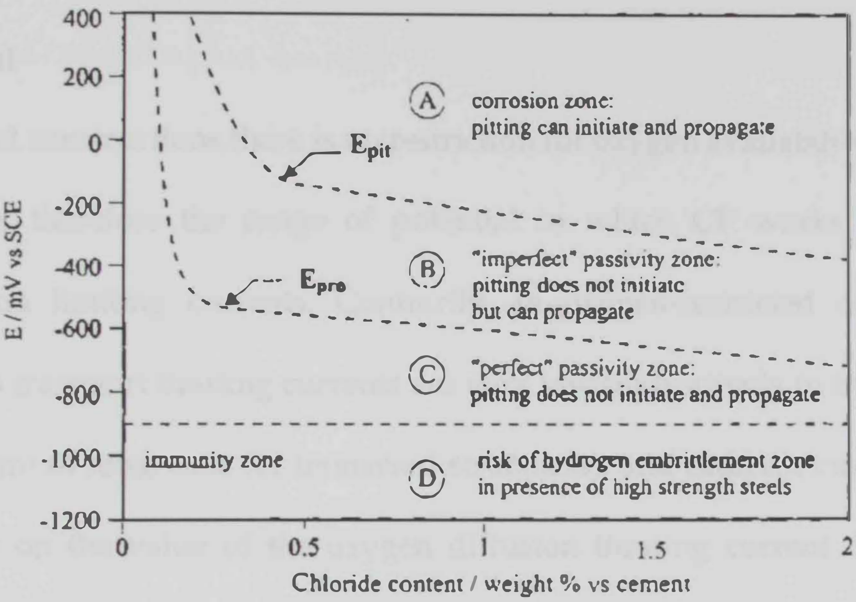


Figure 2-5 steel behavior in concrete as a function of chloride content

Potential

Figure 2-5 shows the behavior of steel in a range of potentials and chloride contents at a 20°C. Different zones can be described: A (corrosion zone) where corrosion can initiate and propagate; B (imperfect passivity zone) where corrosion does not initiate but can propagate at a lower rate as the potential moves from E_{pit} to E_{pro}; lower part of zone B (imperfect passivity zone) where the corrosion rate of active zones becomes greatly reduced; C (perfect passivity zone) where corrosion does not initiate or propagate; D and E (hydrogen evolution zone) where hydrogen embrittlement of the reinforcement in the presence of high strength steel can take place; E zone where loss of adhesion between concrete and the reinforcement can occur. On aerial structures rebar potentials in zone C and in the lower part of zone B are compatible with the 100 mV depolarization criterion [5].

Current

In aerial constructions there is no restriction for oxygen availability at the steel surface, therefore the range of potential in which CP works is far from diffusion limiting currents. Contrarily, in oxygen-restricted concrete, the oxygen transport limiting currents are very low (indicatively in the range 0.2-2 mA/m^2 of rebar area for immersed structures), and cathodic curve depends mainly on the value of the oxygen diffusion limiting current density. The current densities needed to prevent (i.e. to increase the critical chloride content by at least of one order of magnitude) corrosion in aerial constructions can be between 0.5 and 2 mA/m^2 (with respect to reinforcement area), up to 15 mA/m^2 to reduce the corrosion rate so that the 100 mV criterion is verified (the highest values for high chloride contents); up to 20 mA/m^2 or even more to repassivate a corroding rebars (the requested current density increases with the chloride content) [5].

2.5 Sacrificial Anodes Cathodic Protection

2.5.1 Laboratory evaluation experiments

Sacrificial anode materials evaluation

Laboratory experiments were conducted on a group of anode materials (i.e. including Al, Mg, and Zn alloys) that could be used in sacrificial cathodic protection of reinforced concrete. Anodes were prepared in a coupon form and coupled to short steel bars. Then they placed in simulated concrete environments consisting of sealed containers filled with silica sand which dried to get resistivities of 23 Ω-m, 100 Ω-m, 260 Ω-m with a mixed alkali solution containing 6 kg/m^3 of chloride ion (Cl^-) by volume of sand. Measurements of current flow, circuit resistance, potential, and depolarization were taken over 18 months period. Current between anode and steel is inversely proportional to environment resistivity. For resistivties similar to concrete exposed to atmosphere (≥ 100Ω-m) measured current flows < 10 mA/ft^2. Currents outputs from Al alloy anodes were the biggest. Mg anodes worked badly near 100Ω-m resistivities. NACE 100 criterion was verified by 4 h depolarisation measured after interruption of current. Largest values of driving force were obtained for Al anodes group and smallest for both penny scrap Zn and Mg anodes. This means that penny scrap Zn and Mg anodes may not give enough potential to protect steel in high resistivities [14].

Investigation of magnesium anodes was conducted by measuring electrochemical impedance as specified by ASTM Test Method G 97-89 and

NOM K 109- 77. It was found that, between the two standards of magnesium anodes testing, the presence of $Mg(OH)_2$ film can be proved only under conditions of the ASTM method (an aerated 5 g/l $CaSO_4$ + 0.1 g/l $Mg(OH)_2$ solution) throughout the test [15].

Using Al for sacrificial cathodic protection of reinforced concrete was evaluated in laboratory. The Al-steel couples were placed in simulated concrete environments consisted of sealed containers filled with silica sand which dried to get resistivities of 1600, 4190 and 7500 Ω-cm and treated with a chloride solution. Every day and for two weeks current flow, potential and EIS were measured. It could be concluded from the results obtained that Al could be used as galvanic anode in reinforced concrete in a wide range of resistivities [16].

Effect of oxidation products

The effect of oxidation products of aluminum sacrificial anodes has been studied using different mortar designs and anode geometries, to evaluate the effectiveness of different mortars designs in preventing cracking of concrete by oxidation products of aluminum sacrificial anodes. T. de Rincón et al. found that we cannot use either magnesium or zinc as sacrificial anodes embedded in concrete. Concrete cracks due to the volume of oxidation products of magnesium shortly, and in case of zinc, steel does not polarize adequately, but with aluminum and good design, oxidation products have much smaller volume and better diffusion properties than those of magnesium thus concrete does not crack and reinforcing steel is protected. The results showed that it is feasible to use aluminum sacrificial anodes embedded in mortar to control the corrosion of reinforcing bars in concrete, but it is not recommended to use impressed current to accelerate the corrosion rate of aluminum in evaluating the effect of the aluminum corrosion products on cathodic protection in mortar. Also it was observed that the corrosion rate of aluminum anodes increases with increasing chloride concentration and porosity of the mortar. Mortars with porosity of 16.5 to 23.5% and 0.1% Cl^- did not crack, while cracking was observed in the laboratory with higher chloride contents [17].

Sprayed zinc sacrificial anodes

Laboratories experiments were conducted on sprayed zinc sacrificial anodes, it is observed that in marine substructure conditions, after 2 years of testing the active anodes in the laboratory delivered current density in the order of 1.1μA/cm^2. Steel polarization decay exceeded 100 mV within 4 h in high expected corrosion area. Decrease in current density was observed in medium (near 60%) and low (near 25%) RH environments during time and the dryer the environment, more pronounced the decrease. However potential decay reached to significant values may be because not much corrosion rate in dry concrete. A significant decrease in current delivery with time was shown by 85 % RH laboratory slabs specimens and a corresponding reduction in steel protection indicated by polarization decay findings concrete resistivity was not an essential limiting factor in galvanic anodes performance [18].

New and previously aged thermal-sprayed Zn anodes on steel-reinforced concrete were treated with aqueous solutions of the humectants (i.e. substances promote the retention of moisture) lithium nitrate (LiNO) and lithium bromide (LiBr). LiBr was the most beneficial humectant, increasing the average galvanic current density of new thermal-sprayed Zn anodes by as much as a factor of six improving the performance of galvanic cathodic protection systems [19].

Patch sacrificial anodes

The performance of the sacrificial zinc anode has been evaluated in laboratory specimens, which comprise two regions of concrete containing 0.8% and 4% w/c chloride, within which steel bars are encased. Prior to repair, the specimens were stored within an environment of 80% RH at room temperature for 350 days, in which time corrosion was visibly observed and detected electrochemically. A control specimen was repaired with standard repair mortar and a test sample repaired incorporating a sacrificial zinc anode. Two months after repair the control shows clear evidence for the formation of incipient anodes at the periphery of the repair (see Figure 2-6). The test sample, however, clearly demonstrates the presence of the sacrificial anode unit as shown in Figure 2-7. Disconnection of the anode for 24 hours confirmed that the steel had been cathodically polarized by the zinc anode as the potential of the steel exhibited substantial depolarization shifts, after 18 months of operation. The sacrificial anode is offering a level of cathodic protection to the whole of the steel within the test specimen [20].

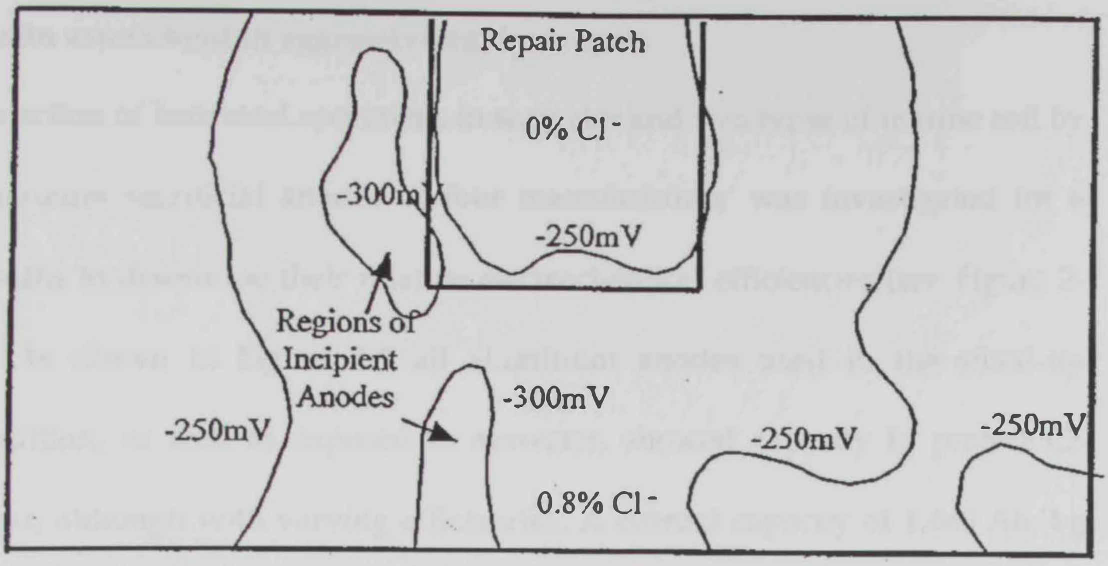


Figure 2-6 1 month after application of SA

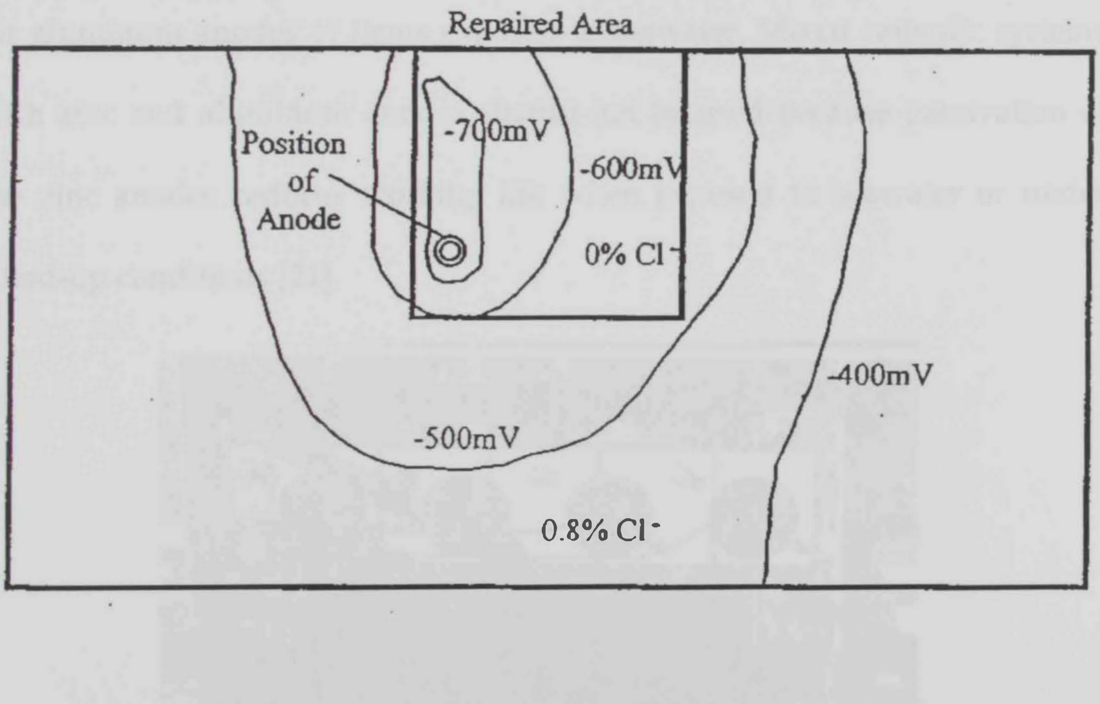


Figure 2-7 control slab 2 months after repair

2.5.2 Long Term Performance field tests

In situ assessment in aggressive environments

Protection of bare steel specimens in seawater and two types of marine soil by aluminum sacrificial anodes of four manufacturers' was investigated for 6 months to determine their relative electrochemical efficiencies (see Figure 2-8). As shown in Figure 2-9 all aluminum anodes used in the silted-up condition, as well as exposed to seawater, showed capacity to protect CS items, although with varying efficiencies. A current capacity of 1,440 Ah/kg with average current density 60 mA/m^2 for aluminum anodes, and 740 Ah/kg with 88 mA/m^2 for zinc anodes may be considered as a reference value for CP in sites silted lip with argillaceous marine soil, and 1,850 Ah/kg for aluminum anodes of items exposed to seawater. Mixed cathodic systems with zinc and aluminum anodes should not be used because passivation of the zinc anodes reduces working life when exposed to seawater or under silted-up conditions [21].

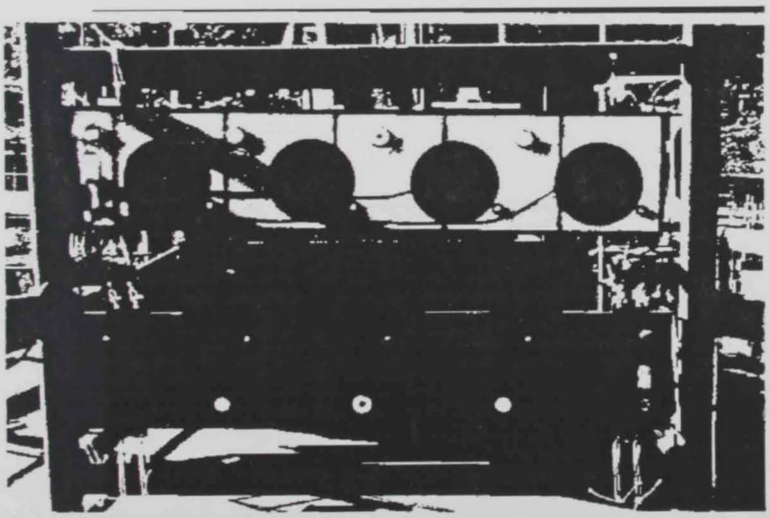


Figure 2-8 test plates installed at a square-based device

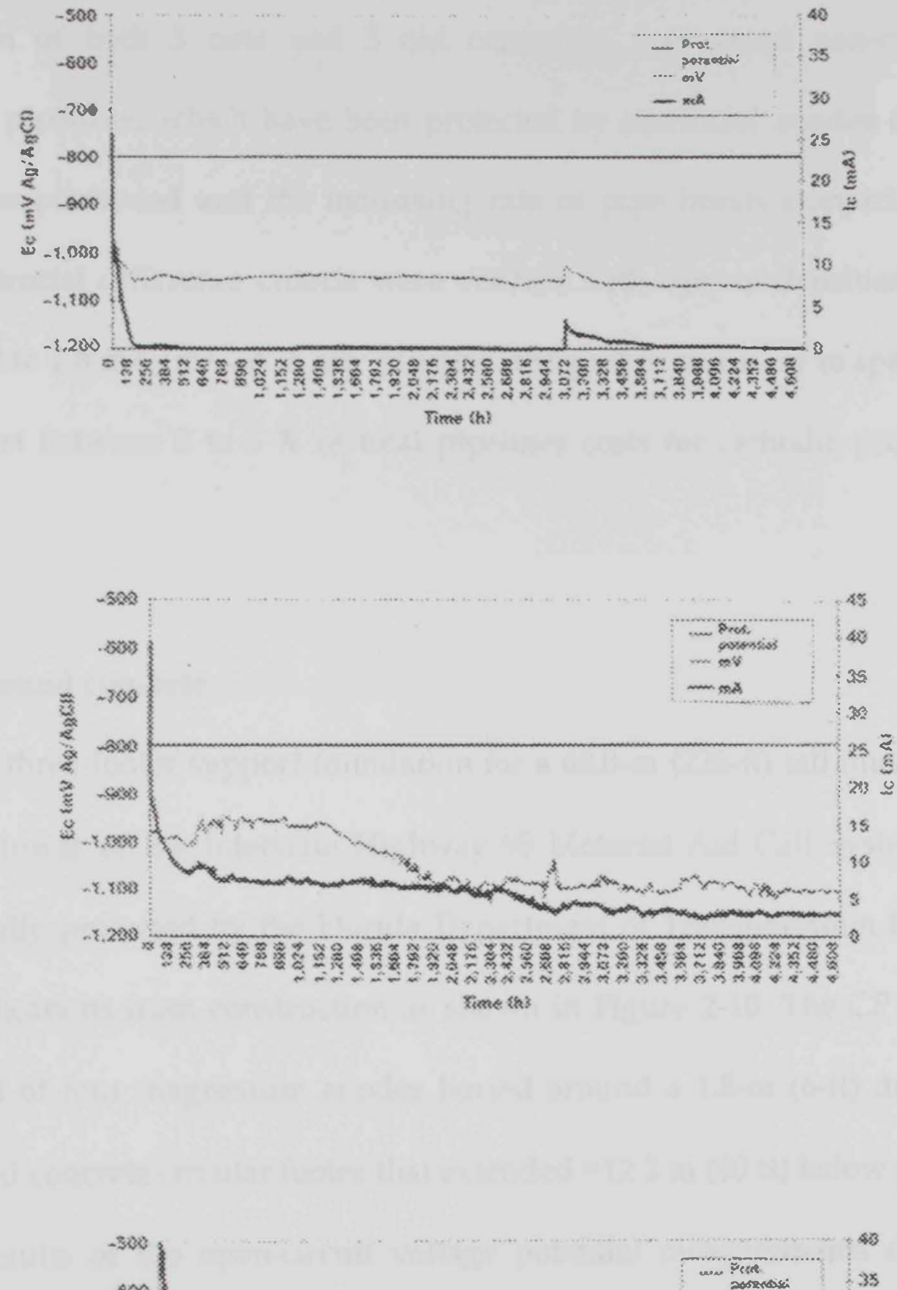


Figure 2-9 potential and current vs. time for protection with SA

Prestressed concrete pipelines

Corrosion of both 5 new and 3 old corroding prestressed non-cylinder concrete pipelines, which have been protected by sacrificial anodes over 18 years was prevented and the increasing rate of pipe bursts stopped. In all cases potential difference criteria were verified with current densities in the range 0.2 to 1.8 mA/m^2. So in any pipeline design it is necessary to specify an initial cost between 2 to 5 % of total pipelines costs for cathodic protection [22].

Underground concrete

Part of a three-footer support foundation for a 68.8-m (226-ft) tall microwave antenna tower of the Interstate Highway 95 Motorist Aid Call System was cathodically protected by the Florida Department of Transportation because of complications from construction as shown in Figure 2-10. The CP system consisted of four magnesium anodes buried around a 1.8-m (6-ft) diameter reinforced concrete circular footer that extended =12.2 m (40 ft) below ground level. Results of the open-circuit voltage potential measurements and the polarization decay test showed that the system meets established CP criteria [23].

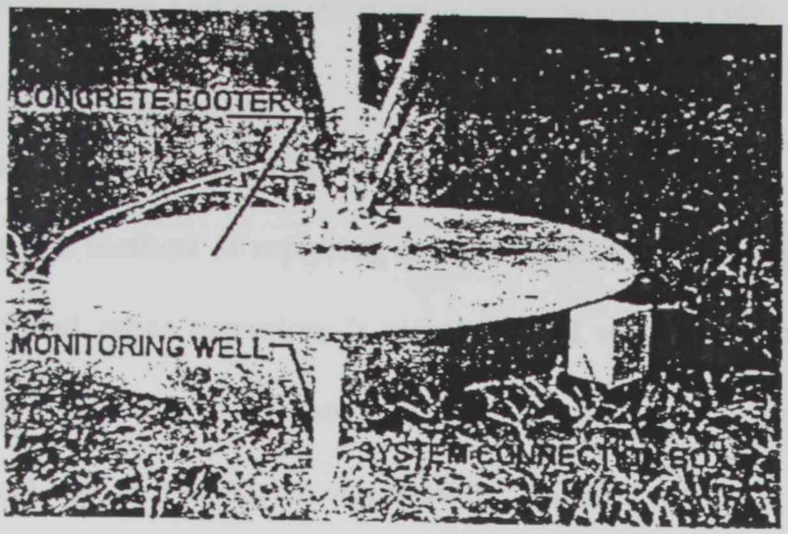


Figure 2-10 cathodically protected footer

Lifejcketing

Zinc Mesh Systems which consist of encapsulating internally placed zinc mesh anodes within a stay-in-place fiberglass form filled with a sand-cement mortar first introduced in 1994 by The Florida Department of Transportation (FDOT), on two substructure pilings of the 1949 Broward River Bridge on SR 105 in Jacksonville, Florida. Since this more than 1,500 jackets have been installed at more than 75 locations in the U.S. and worldwide. The 100 mV polarization criterion (NACE Standard RPO290-90) was verified. Accelerated tests were conducted by FDOT at the Corrosion Research Laboratory (Gainesville, Florida) to evaluate the long-term effect of zinc consumption (self-corrosion by-products) on the surrounding concrete, which is largely unknown. Results obtained have showed that there are not any harmful consequences on the zinc activity or adhesion loss of the concrete in and around the anode surface caused by diffusion of the zinc corrosion products into the concrete pores and onto the nearby concrete surface [24].

Discrete Galvanic Anodes (DGA)

A very common method of repairing concrete spalling on structures due to chloride induced rebar corrosion, is reinstatement with a low permeability repair- mortar. This involves removal of loose concrete and further breakout to clean steel, prior to mortar application. As the corrosion previously occurring in the repair patch has been eliminated, its influence in effectively cathodically protecting the surrounding steel is also lost. However, this repair technique does not guarantee removal of chloride bearing concrete, which may remain in areas adjacent to the repair. Thus, new electrochemical corrosion cells may be set up between steel in the fresh repair (0% chloride) and the adjacent chloride contaminated concrete, which can ultimately lead to failure at the periphery of a repair. This is commonly referred to as the 'incipient anode effect '(or 'ring anode') (see Figure 2-11).

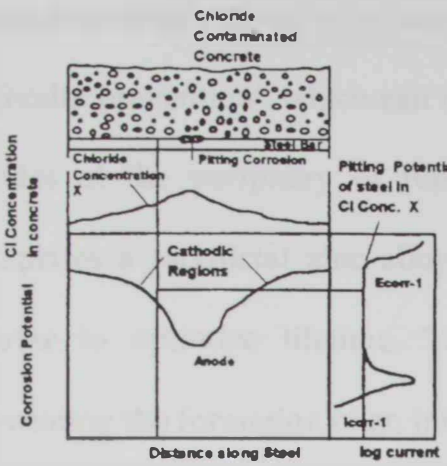


Fig 1. prior to patch repair

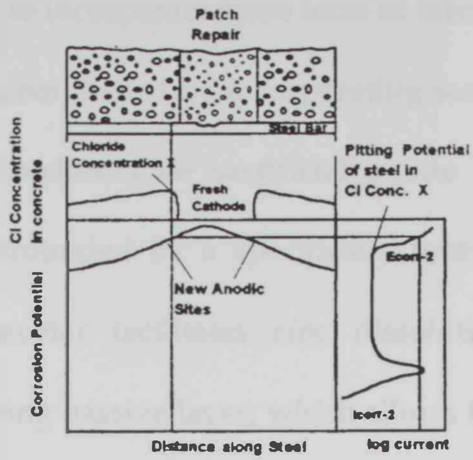


Fig. 2. after patch repair

Figure 2-11 a) localized corrosion b) incipient anode

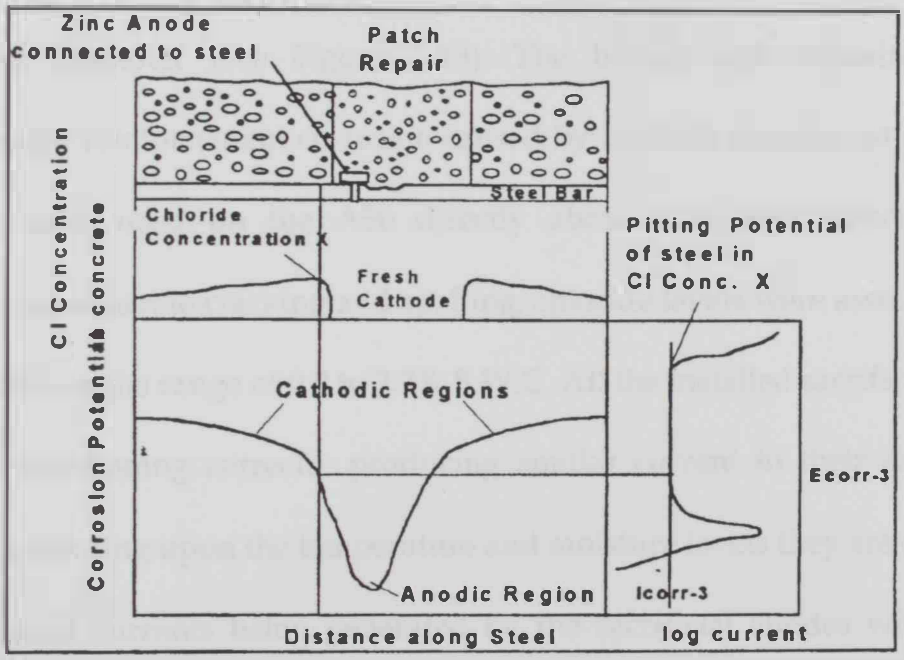


Figure 2-12 protection of steel in patch repair from SA

In order to avoid triggering this problem of 'incipient anode' formation around the repair zones, it is desirable to incorporate some form of intentional 'cathodic prevention', which can be accomplished by incorporating sacrificial anodes at the periphery of repair patches. One sacrificial anode design comprises a sacrificial zinc alloy, surrounded by a specifically formulated mortar to optimize lifetime. The mortar facilitates zinc dissolution by preventing the formation of an interfering passive layer, which allows the less noble zinc to corrode and sacrificially protect reinforcing steel to which it is attached, thus countering the formation of anodic sites outside the periphery of the patch repair (see Figure 2-12). This evaluation was carried out on a reinforced concrete structural crossbeam on a bridge supporting the A50 at Groby in Leicester (see Figure 2-13). The bridge was suffering from considerable reinforcement corrosion caused by chloride contamination from de-icing salts used on the A50 directly above. The area selected had experienced concrete cracking and spalling, chloride levels were assessed and found to be in the range of 0.8 to 2.2% B.W.C. All the installed sacrificial units are still functioning correctly producing similar current to their early age values depending upon the temperature and moisture levels they are exposed to. The total currents being generated by the sacrificial anodes within the repair provide a current density compatible with levels reported for cathodic prevention in the repaired area including a sphere of influence of around the perimeter of the trial area [25].

As an extension of the discrete anode discussed previously, further developments based on similar galvanic technology allow protection of structures prior to the requirement for patch repairs. In this case, the sacrificial anode core/active mortar composite is formed into a geometry, which facilitates installation onto a reinforced steel concrete structure, to allow galvanic protection outside the region of patch repairs. This system has been installed on a number of structures, suffering from chloride-induced reinforced concrete. A global sacrificial anode system consisting of Twenty sacrificial units along with six embedded Ag/AgCl reference electrodes was used on the deck of a reinforced concrete multi story car park, which had been suffering from spalling as a result of chloride-induced corrosion in conjunction with the previously discussed patch repair system (see Figure 2-14). This is because of the chlorides found globally throughout the deck, which require more than just patch repair to extend its working life. Averaged results indicate that these units provide significantly higher currents than the sacrificial units used in patch repairs. As shown in Figure 2-15 current densities achieved using this global system also fall well within values reported for cathodic prevention levels as indicated in. All 4-hour depolarization results are positive (more noble) showing that the steel is polarized by the sacrificial anodes to a significant level which is also ties in with seasonal temperature changes as it along with current outputs increase with rises in temperature when a greater level of protection is required [26].

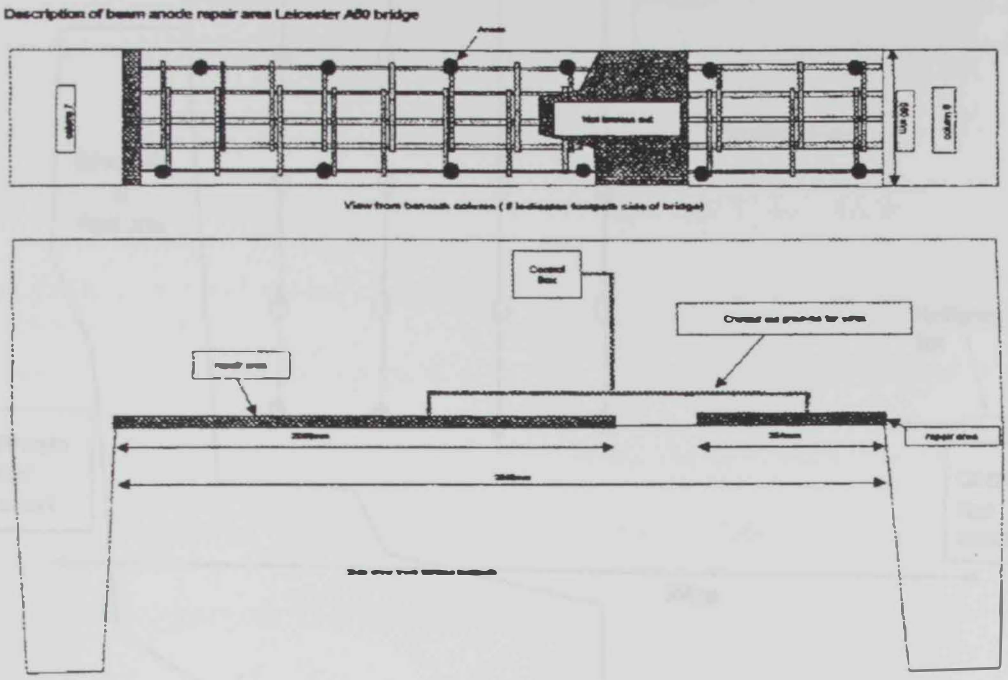


Figure 2-13 A50 crossbeam details and trial layout

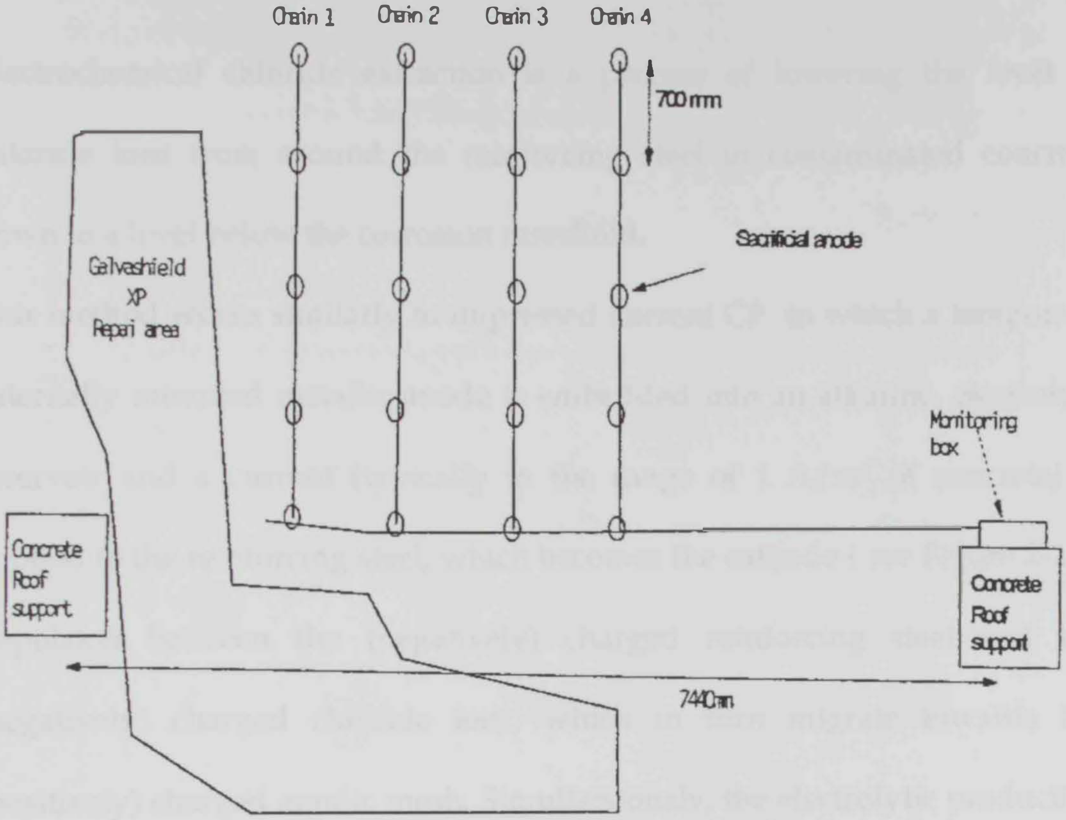


Figure 2-14 plan of car park site trial

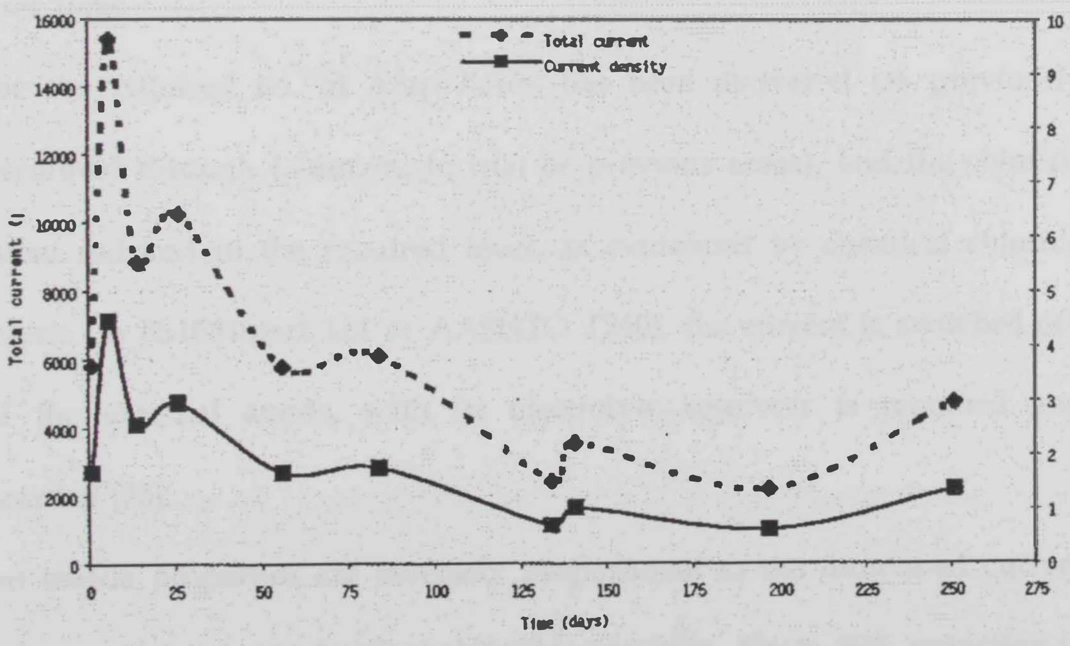


Figure 2-15 total current and current density results from car park

2.6 Electrochemical chloride extraction (ECE)

Electrochemical chloride extraction is a process of lowering the level of chloride ions from around the reinforcing steel in contaminated concrete down to a level below the corrosion threshold.

This method works similarly to impressed current CP, in which a temporary externally mounted metallic anode is embedded into an alkaline, electrolyte reservoir and a current (typically in the range of 1 A/m^2 of concrete) is applied to the reinforcing steel, which becomes the cathode (see Figure 2-16). Repulsion between the (negatively) charged reinforcing steel and the (negatively) charged chloride ions, which in turn migrate towards the (positively) charged anodic mesh. Simultaneously, the electrolytic production of hydroxyl ions at the steel surface results also in the displacement of chloride ions and subsequent re-passivasion of the steel with an effective buffer zone.

Once the required no. of Amp/hours has been delivered (as previously determined through treatment to trial or previous areas), and the chloride content reduced to the required level, as evidenced by chemical chloride analysis (to BS1881:part 124 or AASHTO T260), the current is switched off, and the external anode, with its electrolyte reservoir is removed and discarded [28].

Steel tensile properties are inversely proportional to the impressed current density used in electrochemical chloride extraction. Up to 50% reduction in the tensile parameters tested is associated with changes in impressed cathodic current densities. Consequently a high risk of hydrogen absorption by the steel during the process makes the feasibility of an ECE application to prestressed concrete structures dangerous [29].

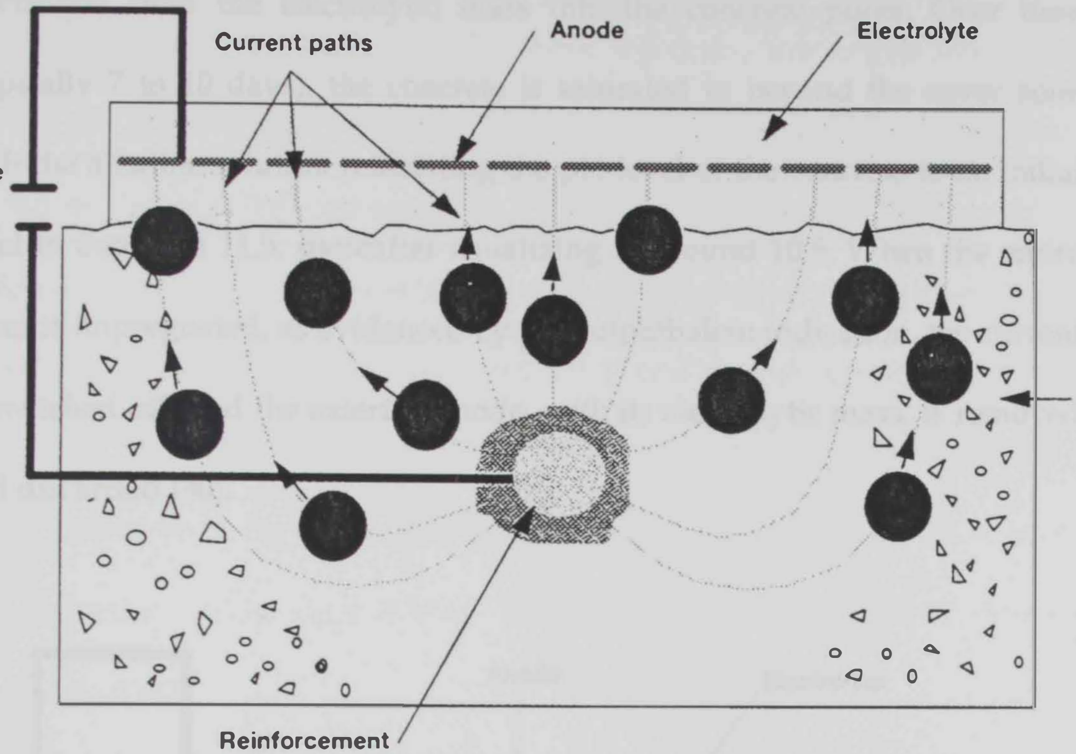


Figure 2-16 schematic illustration of chloride extraction process

2.7 Electrochemical Realkalisation (ERA)

Although not relevant in the context of structures affected by chloride attack, it is useful to understand the principle of this treatment when looking at electrochemical solutions for other forms of reinforced concrete deterioration. ERA (see Figure 2-17) works on the basis of electro-osmosis and is used to realkalise carbonated concrete by creating the existing reinforcement as the negative electrode, or cathode. As with ECE, a temporary external metallic anode mesh is installed and embedded in a disposable electrolytic mass containing a molar Potassium carbonate based solution. On applying a voltage between these electrodes, the electrolyte is drawn towards the reinforcement. The movement results in ionic migration under the influence of the applied current and electro- osmosis. This action pulls the ERA electrolyte from the electrolytic mass into the concrete pores. Over time (typically 7 to 10 days), the concrete is saturated to beyond the cover zone with the alkaline solution reinstating the pH level of the concrete to an initial level in excess of 11.5, thereafter equalizing to around 10.5. When the entire cover is impregnated, as evidenced by phenolphthalein indication, the current is switched off, and the external anode, with its electrolytic mass, is removed and discarded [30].

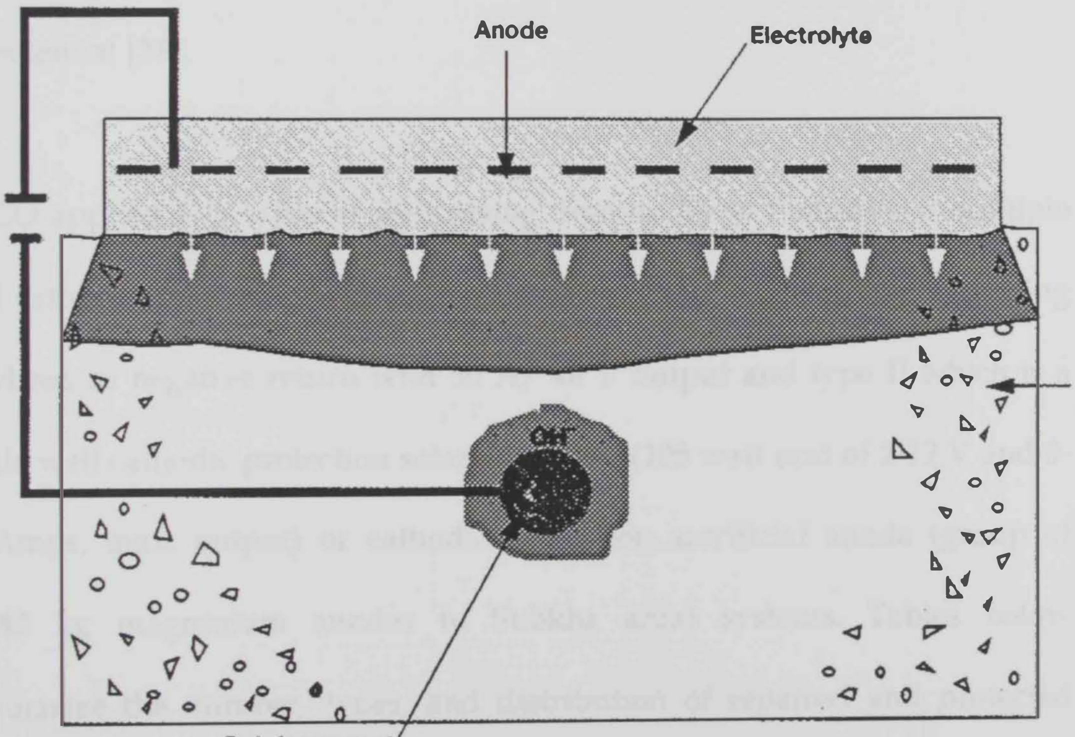


Figure 2-17 schematic illustration of realkalisation process

2.8 ADCO experience in well casing cathodic protection

Serious casing external corrosion problems associated with several failures have been experienced since 1980's: 3 wells abandoned from 1982 to 1986, 2 wellheads collapsed in 1982 & 1997, 2 wells top casing cracks and rupture in 1989 & 1992, 1 well had a gas leak at wellhead in 1987, and 2 wells showed severe surface casing corrosion in 1997. ADCO operates 1300 wells of different types. 425 wells are provided with well casing cathodic protection. In house development and implementation of well casing cathodic protection was taken as a remedial action. The well casing current demand was 5-15 Amps (based on E log I test results), with system design life of 15-20 years. The protection criteria were -950 mV close off potential and -1000 mV remote off potential [31].

ADCO applied two types of well casing designs. Type I which is a multiple well cathodic protection with a transformer rectifier 2-3 wells system using flowlines as negative return with 50 A/ 48 V output and type II which is a single well cathodic protection solar energized (105 watt unit of 2-12 V and 0-20 Amps. max. output) or cathodic protection sacrificial anode (group of 20X42 kg magnesium anodes in Subkha area) systems. Tables below summarize the number, types, and distribution of repaired and protected wells [31].

Table 2-1: applied well casing CP designs and costs

CP System	Number of protected wells	Design life (Year)	Estimated Costs, $	
			Per System	Per Well/Year
Transformer rectifier Multiple well protection	2-4	20	40,000	1000
Solar energized (single well protection)	1	20	50,000	2500
Sacrificial anode (SA) (single well protection)	1	5	5000	1000

Table 2-2: current performance of impressed current W/C CP system

Field						No. of Protected Wells, Remote On (-mV)		
	Type	Number	Drain Amps.	No. %	A %	> 950	> 1000	> 1050
Asab	TR	23	858	100	75	52	39	35
Bu hasa	TR	45	1253	100	56	112	82	62
Bab tham 'C'	SE	30	357	100	60	30	29*	24
Bab tham 'f'	SE	60	907	100	80	56	48**	35

Number of Wells above – 1000 mV Off:
* 25 (83%); 12 Amps in average ** 40 (71%); 16 Amps in average

Table 2-3: well casing CP – end 1997

Field	Type and number of CP stations				Well covered by CP				
	CPTR	CPSE	CPSA	Total	Oil	Gas	Water	Other	Total
Asab	42	14	0	56	0	14	125	1	140
Sahil	4	4	0	8	0	4	8	0	12
Shah	6	0	0	6	19	0	0	1	20
Bu hasa	45	0	0	45	0	0	84	0	84
Bab	13	90	64	167	20	93	40	4	157
a. Dh. N. East	3	0	9	12	12	0	0		12
Total	113	108	73	294*	51	111	257	6	425

CPTR: Transformer Rectifier; CPSE: Solar Energized; CPSA: Sacrificial Mg Anodes
* Including 51 Nos. Being Installed/ Modified.

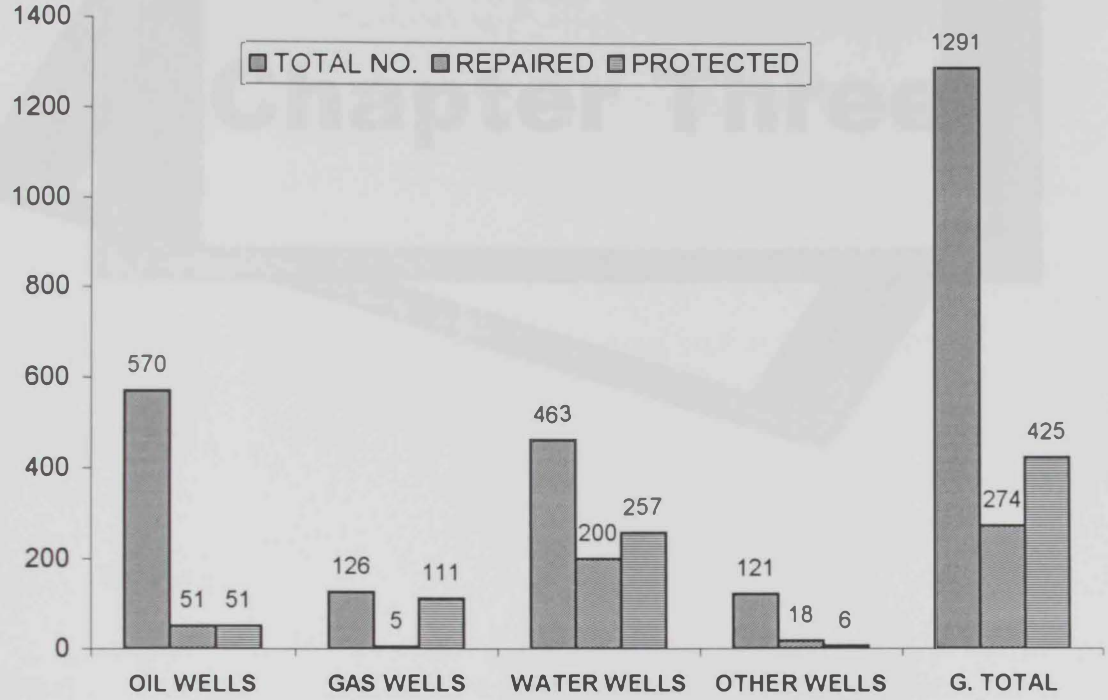


Figure 2-18 well inventory casing repairs and cathodically protected wells

Chapter Three

Methodology and Experimental Setting

3 METHODOLOGY AND EXPERIMENTAL SETTING

The experimental part of this work is divided into two parts; in-situ testing as well as laboratory testing. In the in-situ program, a structure with some degree of deterioration shall be evaluated, repaired using sacrificial anode, and monitored for 1 year to check the efficiency of the system. The laboratory part shall consist of laboratory controlled mixing, curing and testing.

3.1 Materials

3.1.1 Cement

Ordinary Portland Cement (OPC) manufactured in Al-Ain Cement Factory was used. This type of cement is mostly used in construction in the UAE. The cement used has the characteristics shown in the below tables (3-1 and 3-2):

Table 3-1: Type of Cement: OPC, Al-Ain. Test Method: BS 4550

No.	Aspects of Testing	Unit	Result	Specified Standard Limits / BS12-OPC
1	Standard Consist	%	27.0	--
2	Initial Setting Time	Minute	145	≥45
3	Final Setting Time	Minute	195	≤600
4	Soundness (as-received)	mm	2	≤10
5	Fineness (constant vol.)	m^2/kg	372	≥275
6	Mortar Strength (3day)	N/mm^2	39.0	≥25

Table 3-2: Chemical composition of the OPC used in this work as tested according to ASTM C114

No.	constituents	(% by weight)
1	Silicon Dioxide (SiO_2)	23.70
2	Aluminium Oxide (AL_2O_3)	5.10
3	Ferric Oxide (Fe_2O_3)	4.61
4	Calcium Oxide (CaO)	66.00
5	Magnesium Oxide (NgO)	1.41
6	Sulphur Trioxide (SO_3)	2.56
7	Sodium Oxide (Na_2O)	0.10
8	Potassium Oxide (K_2O)	0.22
9	Alkalies (Na_2O+0.658 K_2O)	0.24
10	Insoluble Residue	0.07
11	Loss on Ignition	1.03
12	Tricalcium Aluminate (C_3A)	5.71
13	(C_4AF+2C_3A)	25.44

3.1.2 Aggregates:

The coarse aggregate used in our experiments was crushed Lime Stone from Ras Alkhaima. The fine aggregate is also from Ras Alkhaima.

The following properties of the aggregates were determined. Tables (3-3 and 3-4):

Table 3-3: Coarse Aggregate: Crushed.Test Method: BS 812

No.	Aspects of Testing	Unit	Value
A	Shape Properties:		
A1	Material finer than 0.075mm BS 412 Test Sieve	%	0.4
A2	Flakiness Index	--	15
A3	Elongation Index	--	18
B	Physical Properties:		
B1	Particle Density - Oven Dry	Kg/m^3	2.68
B2	Particle Density - Saturated Surface Dry	Kg/m^3	2.70
B3	Particle Density - Apparent	Kg/m^3	2.72
B4	Water Absorption - Percentage of Dry Mass	%	0.5
C	Mechanical Properties:		
C1	Aggregate Crushing Value (14-10mm Fraction)	%	22
C2	Aggregate Impact Value (14-10mm Faction)	%	22
D	Particle Size Distribution	Size	Value
	Sieve Analysis	mm	%
D1	Material Passing BS Test Sieve	37.5	100
D2	Material Passing BS Test Sieve	20.0	98
D3	Material Passing BS Test Sieve	14.0	35
D4	Material Passing BS Test Sieve	10.0	2
D5	Material Passing BS Test Sieve	5.0	0.3
D6	Material Passing BS Test Sieve	2.36	--
D7	Material Passing BS Test Sieve	1.18	--
D8	Material Passing BS Test Sieve	0.60	--
D9	Material Passing BS Test Sieve	0.30	--
D10	Material Passing BS Test Sieve	0.15	--
D11	Material Passing BS Test Sieve	0.075	--

Table 3-4: Fine Aggregate: Crushed.Test Method: BS 812

No.	Aspects of Testing	Unit	Value
A	Shape Properties:		
A1	Material finer than 0.075mm BS 412 Test Sieve	%	0.6
A2	Flakiness Index	--	35
A3	Elongation Index	--	27
B	Physical Properties:		
B1	Particle Density - Oven Dry	Kg/m³	2.68
B2	Particle Density - Saturated Surface Dry	Kg/m³	2.70
B3	Particle Density - Apparent	Kg/m³	2.74
B4	Water Absorption - Percentage of Dry Mass	%	0.8
C	Mechanical Properties:		
C1	Aggregate Crushing Value (10-6.3mm Fraction)	%	22
C2	Aggregate Impact Value (10-6.3mm Faction)	%	19
D	Particle Size Distribution	Size	Value
	Sieve Analysis	mm	%
D1	Material Passing BS Test Sieve	37.5	--
D2	Material Passing BS Test Sieve	20.0	--
D3	Material Passing BS Test Sieve	14.0	100
D4	Material Passing BS Test Sieve	10.0	95
D5	Material Passing BS Test Sieve	5.0	6
D6	Material Passing BS Test Sieve	2.36	0.3
D7	Material Passing BS Test Sieve	1.18	--
D8	Material Passing BS Test Sieve	0.60	--
D9	Material Passing BS Test Sieve	0.30	--
D10	Material Passing BS Test Sieve	0.15	--
D11	Material Passing BS Test Sieve	0.075	--

3.1.3 Repair mixture

The cementitious free flowing micro concrete used for the purposes of structural repair of the columns in the test is Renderoc LAXtra supplied by Fosroc. It has the following characteristics:

1. Shrinkage-compensated in both liquid and cured states.
2. Contains no metallic expansion system.
3. Pre-packed and factory quality controlled to ISO 9002 accredition.

4. Maximum equivalent sodium oxide content of 3 kg/m³ (UK Department of Transport Specification for Highway Works 1986, Clause 1704.6),
5. Free flowing cementitious material that has a coefficient of thermal expansion fully compatible with the host concrete and which complies with the following requirements Table (3-5):

Table 3-5: Properties of repair mixture

Property	Test method	Results
Drying shrinkage	ASTM C157-93	< 300 microstrains @ 7days <500 microstrains @ 28days
Permeability	DIN 1048 Part 5	< 10 mm
Flextural strength	BS 6319 Pt. 3	>9 N/mm2 @ 28 days
Typical Compressive strength - N/mm²	BS 1881 Pt.116	39 @ 3 days 45 @ 7 days 60 @ 28 days
Tensile strength	BS 6319 Pt. 7	> 5 N/mm2 @ 28 days
Water absorption	BS 1881 Pt. 121	< 2 %
Resistivity	DRAM system	8200-16000 ohms-cm

The micro-concrete was mixed and placed in accordance with the manufacturer's recommendations, particularly with regard to water content, mixing equipment and placing time.

3.1.4 Sacrificial embedded anode:

Two types of sacrificial embedded anodes shall be used as follows:

1. The galvanic anode unit used to prevent the 'incipient anode' effect and provide galvanic corrosion prevention within & adjacent to the repair zone is called Galvashield XP, see Figure (3-1a). It may be described as follows: -

a) An amphoteric zinc based anode encapsulated by a highly alkaline mortar surrounding block, and provided with fixing wires to permit direct attachment to exposed steel reinforcing within the repair zone.

b) The mortar surround has a pore solution pH, which is sufficiently high for corrosion of the anode to occur and for passive film formation on the anode to be avoided as described in patent number PCT/GB94/01224.

c) The complete anode unit is so designed that no expansive stresses are exerted onto the repair mortar or concrete within which the units are placed.

The Galvashield XP units are designed for application in repairs performed in chloride contaminated steel reinforced concrete structures. To prevent the onset of corrosion, each Galvashield XP anode unit will provide galvanic protection within its sphere of influence subject to continuity of steel reinforcement.

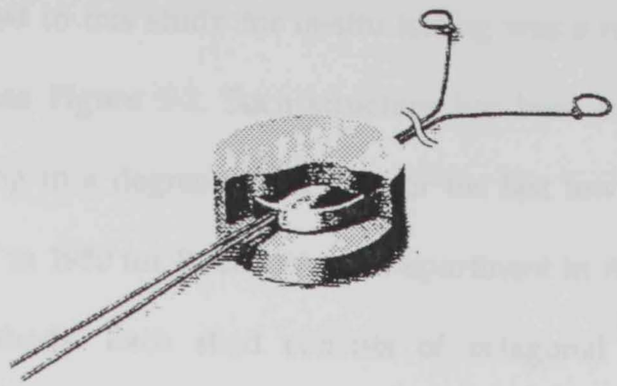
2. The 'Drill & Fix' discrete galvanic anode unit used to provide galvanic corrosion prevention in areas not requiring breakout of concrete is Galvashield CC, see Figure (3-2b). It may be described as follows: -

a) An amphoteric zinc based anode encapsulated by a highly alkaline mortar surrounding cylinder, designed to be inserted into predrilled holes located in a grid pattern of spacing determined by rebar configuration.

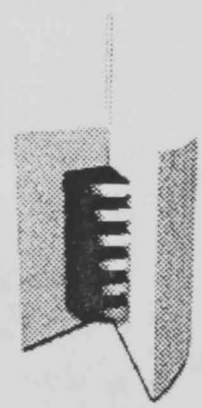
b) The mortar surround has a pore solution pH, which is sufficiently high for corrosion of the anode to occur and for passive film formation on the anode to be avoided as described in patent number PCT/GB94/01224.

c) The complete anode unit is so designed that no expansive stresses are exerted onto the concrete within which the units are placed.

The Galvashield CC units are designed for application in chloride contaminated steel reinforced concrete structures, in situations where delamination has not yet occurred. To prevent the onset of corrosion, each Galvashield CC anode unit will provide galvanic protection within its sphere of influence subject to continuity of steel reinforcement.



(a)



(b)

Figure 3-1 sacrificial anodes types a) local patch repair b) global

3.2 In-situ field testing (Car park sheds)

The structure used in this study for in-situ testing was a reinforced concrete car park shed, see Figure 3-2. Such structure has been exhibiting signs of corrosion resulting in a degree of spalling for the last few years. The sheds were constructed in 1980 for Public Works Department in Abu Dhabi, U.A.E. There are 200 sheds. Each shed consists of octagonal column and six cantilever beams covered by a slab. Because of inadequate repair system carried out in the past in these sheds, corrosion of the reinforcement keeps appearing.

Figure 3-2: Works department car park sheds

3.2.1 Visual inspection

A visual inspection of the sheds was carried out to explore the extent of the damage. The survey indicated that the damage was seen at the lower part of the columns extending upwards. The damage was concentrated in areas adjacent to ground level Figure 3-3. Heavy deposits of salts, rust stains, cracks, and spalls in concrete cover were observed, see Figure 3-4. The extent of corrosion of the columns varied from negligible at a distance of 1.5 m from the ground surface to very severe at ground level.

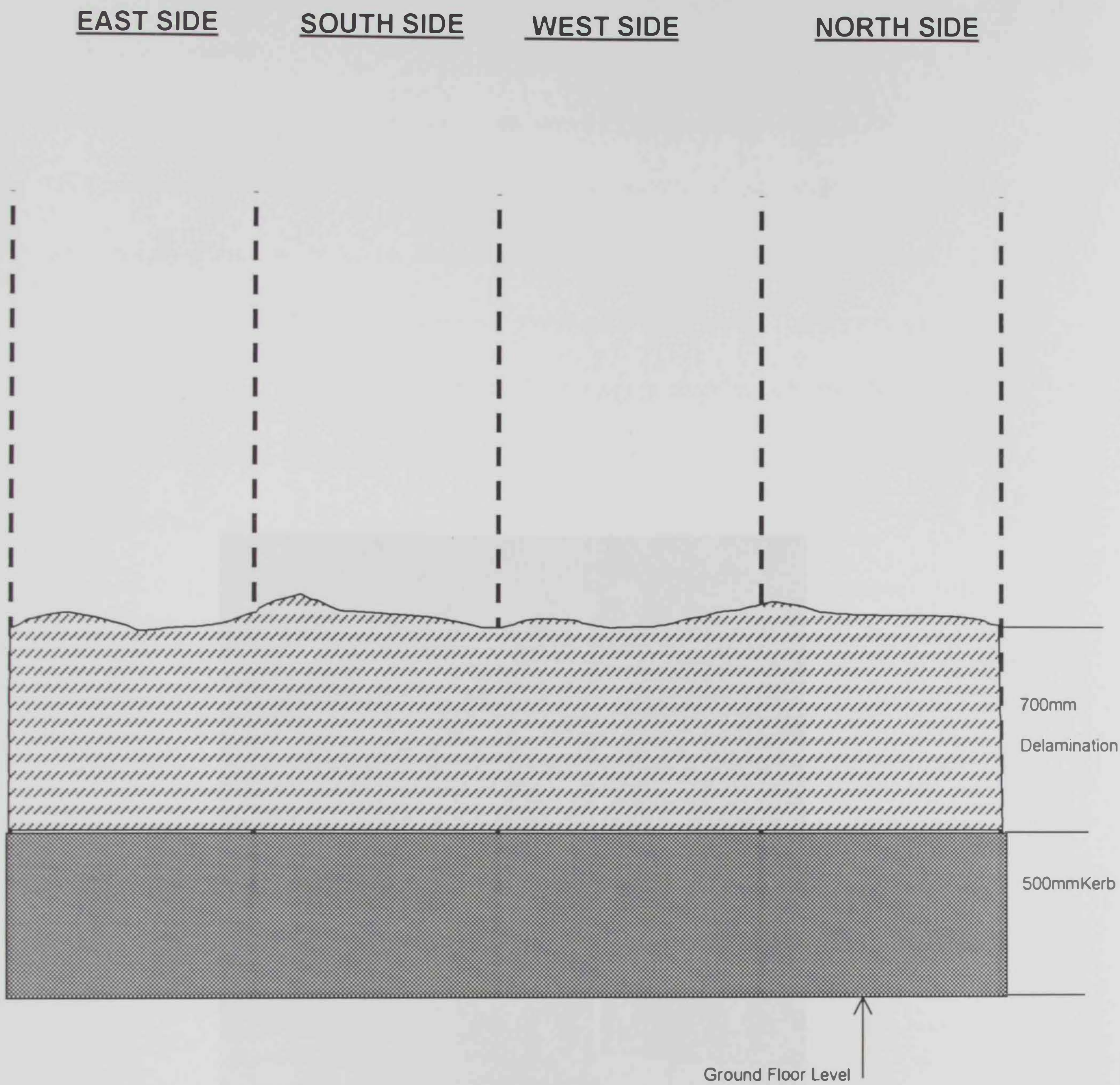


Figure 3-3 Delamination survey of C1

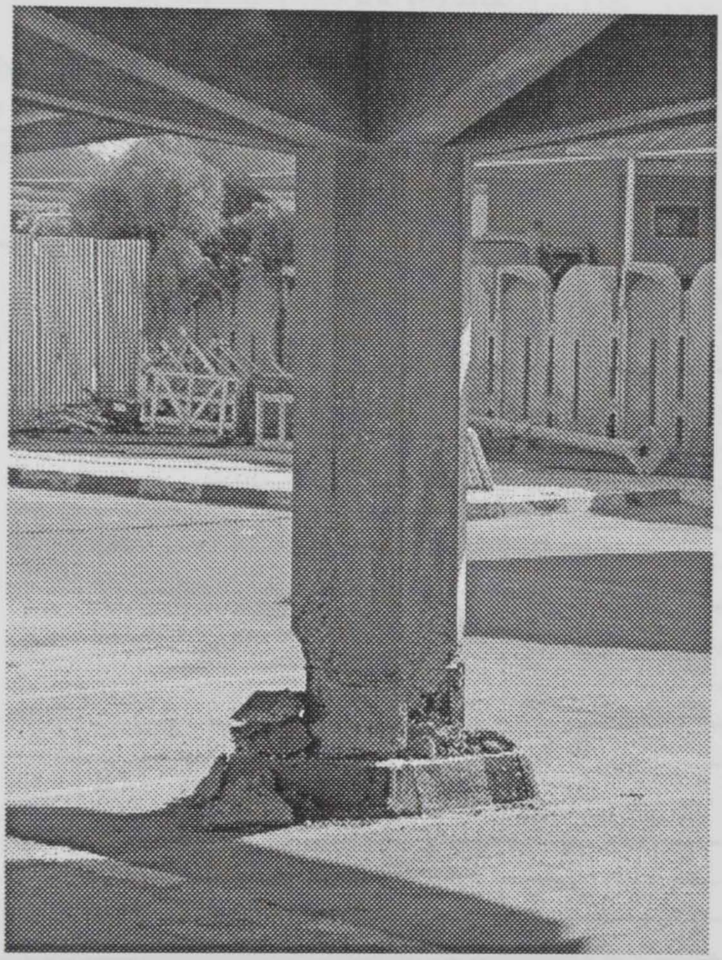


Figure 3-4 Initial state of column C1 before repair

3.2.2 Investigation & testing

Chloride content

Testing for chloride content was carried out by independent laboratory as per BS specification BS1881 Part124. Samples over depth ranges 0 -20 mm, 25-40 mm and 40-60mm were taken from different locations as indicated in Figs. 3-3 and 3-4. The results recorded were the average of two tests. The concentration of acid-soluble Cl^- at the level of steel bars varied from 0.06% (by weight of concrete) in areas of moderate deterioration to 0.28% in areas of severe deterioration. Table (3-6) summarizes the results.

Table 3-6: Chloride Content (% by weight of oven dried concrete) Test Specification: BS 1881 Part 124

Column	Location	Dust Sample No.	Level Location	Depth mm	Chloride as Cl By Wt %
Column A1	North Side	D1	800mm From the Ground Level	0 - 20	0.26
				20 - 40	0.25
				40 - 60	0.19
		D2	1000mm From the Ground Level	0 - 20	0.05
				20 - 40	0.06
				40 - 60	0.08
Column A2	North Side	D1	650mm From the Ground Level	0 - 20	0.28
				20 - 40	0.24
				40 - 60	0.16
		D2	850mm From the Ground Level	0 - 20	0.06
				20 - 40	0.07
				40 - 60	0.07
Column A3	North Side	D1	750mm From the Ground Level	0 - 20	0.14
				20 - 40	0.11
				40 - 60	0.11
		D2	950mm From the Ground Level	0 - 20	0.07
				20 - 40	0.09
				40 - 60	0.07

Concrete cover

Thickness of concrete cover was determined using electronically sensored device. The results obtained showed that cover varied from 15 mm to 36 mm. The specified concrete cover was 30mm. The depth of carbonation was nil. The mean compressive strength of concrete was 36 MPa as hammer test indicated. The results also showed that the amount of sulphates in the concrete mass was not significant.

Electrical Potentials

Measurements of electrical potential in the study areas were taken according to ASTM C - 876 in a grid pattern at spacing of 250 mm by 120 mm, see Figure 3-5. Figure 3-6 shows the percent of potentials more negative than -0.35 V varied from 35% to 50% and concentrated in the lower part of the column (within 1 meter above the ground level) as evidenced also by delimination test results Figure 3-3.

EAST SIDE		WEST SIDE		NORTH SIDE		SOUTH SIDE	
-219	-232	-249	-222	-199	-222	-179	-196
-257	-267	-264	-237	-214	-246	-197	-219
-289	-299	-277	-265	-222	-290	-234	-227
-312	-316	-297	-288	-246	-322	-262	-276
-319	-346	-344	-304	-309	-366	-290	-312
-362	-397	-390	-334	-390	-425	-322	-354
-414	-441	-446	-417	-487	-490	-390	-422
-472	-490	-504	-490	-554	-532	-422	-490
-524	-535	-584	-556	-656	-620	-490	-525
-597	-622	-637	-621	-729	-717	-454	-566

Ground Floor Level   120mm   25

Figure 3-5 Half-cell potential survey of column C1

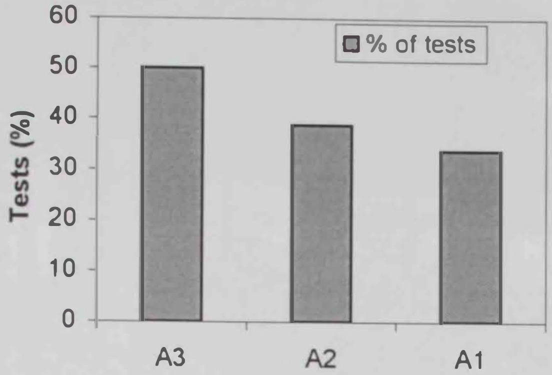


Figure 3-6 Cumulative frequency curve-more negative than -350 mV

3.2.3 Repair procedure

Three columns were chosen for testing Figure 3-7. The first column was labeled (C1) and was repaired using conventional repair system. This column shall be considered the control. The second column which was labeled (C2) was repaired using conventional patch repair with sacrificial embedded anodes to investigate the effect of sacrificial anode in preventing the incipient anode phenomenon. The third column which was labeled (C3) was repaired in the same manner as column C2 with the additional of global sacrificial anode system. The effects of sacrificial embedded anodes as well as the combination of both sacrificial embedded anodes and global sacrificial anode shall be compared to the control (C1).

Figure 3-7 the columns were chosen for testing

All deteriorated concrete and corroded steel was removed using light pneumatic hammer till sound concrete and non-corroded steel was reached. The Deteriorated concrete that was removed, reached 3cm beyond the reinforcement, and was measured to be 10cm thick. This deterioration appeared in the region between 50cm above the ground level and 50cm under the ground level. The areas was marked out in the works and adjusted as work proceeds according to the condition found. Figure 3-8.

Figure 3-8 Breaking out deteriorated concrete using penumatic hammer

Special care was exercised to ensure that any reinforcement exposed was not cut or damaged. The depth of breakout on the edge of any repair area shall be a minimum of 10 mm and feather edges were not be accepted. To achieve this the perimeter of the area to be repaired shall first be cut to a depth of 10mm using a suitable tool. The preparation was such as to leave a sound exposed concrete surface free from dust, loose particles and any deleterious matter. The following points were observed: -

- Heavily corroded reinforcement bars which have significant loss of section (more than ~25%) were replaced.
- Reinforcement bars were cleaned by successive sandblasting and air blasting performed with the shotcreting equipment. Figure 3-9.

Figure 3-9 Concrete sandblasting with shotcreting equipment

- 5 sacrificial anodes units were installed in the repaired patch in both columns (C2 and C3). They were distributed around the perimeter of the column. Details of the distribution of the sacrificial anodes are presented in Fig 3-10. Individual wires were fed into an external junction box where they were connected to the reinforcement via additional wires to facilitate current monitoring.

Figure 3-10 Sacrificial anodes installation

- In column C3 an extra 5 global sacrificial anodes were inserted with wires fed into a junction box to allow for current and steel potential measurements to be taken. For the purpose of this evaluation an area of the column C3 was selected that had not shown any signs of spalling but had significant levels of chloride contamination (between 1.7 and 2.8 % chloride-by weight of cement-) and according to half cell potential reading was likely to be corroding.
- 3 embedded Ag/AgCl reference electrodes were installed in each of the three columns, and all the wiring was connected to a junction box to measure the potential difference.

- Formworks were erected prior to placing the patch repair materials. Materials were mixed for 5 minutes as per manufacturer instructions. Figure 3-11.
- Repair materials are placed within the formwork and was consolidated by conventional vibration.
- All the repaired columns were cured for 3 days by covering them with a wet fabric.

Figure 3-11 Formworks erecting prior repair material placing

3.3 Laboratory trials

To evaluate the performance of sacrificial anodes of the type illustrated previously, a number of 6 reinforced concrete slabs were cast. The following parameters were considered:

The size of the slabs was 0.5X1.0X0.2 m. They were reinforced using steel bars # 10 placed 15cm c/c. Transverse steel was of # 10 was placed 15cm c/c. The slabs were cast to represent different schemes as follows:

- The slab should be of dimensions that allowed ease of handling in the laboratory and at the same time be large enough to withstand chiseling areas of repair.
- It is necessary to have depth of concrete cover to steel reinforcement as realistic as possible.
- Moulds were relatively simple in order to incorporate steel bars and to make slabs either for repair or to be used as controls.

Slab # 1, see Figure 3-12 (showing locations of SA in small repaired area)

Slab # 3, see Figure 3-13 (showing locations SA in large repaired area)

Slab # 2, see Figure 3-14 (showing locations SA in new concrete)

Slab # 4, see Figure 3-15 (showing location of small repaired area)

Slab # 6, see Figure 3-16 (showing location of large repaired area)

Slab # 5, see Figure 3-17 (showing new slab before casting)

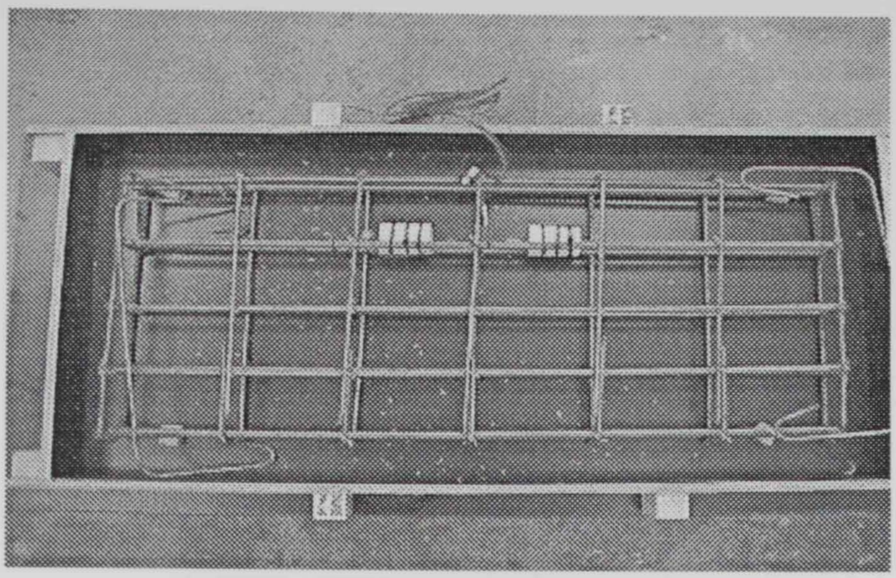


Figure 3-12 Locations SA in small repaired area

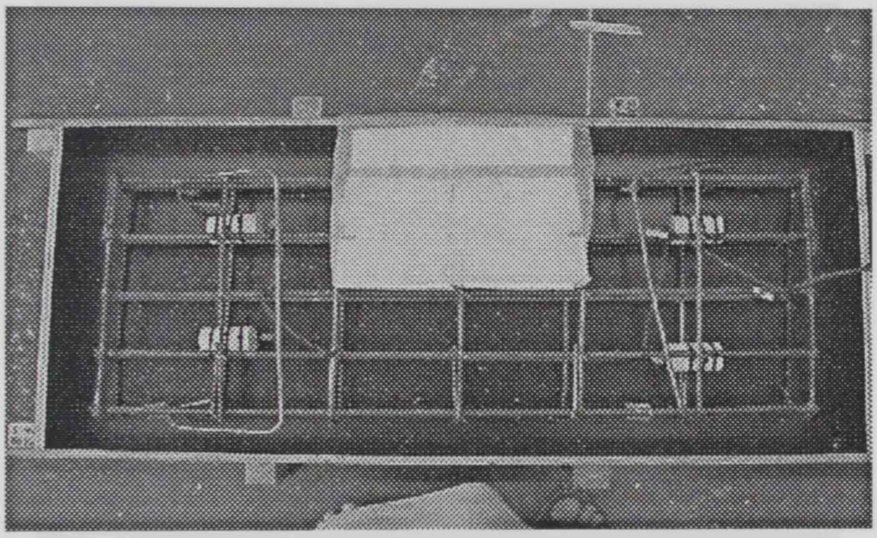


Figure 3-13 Locations of SA in large repaired area

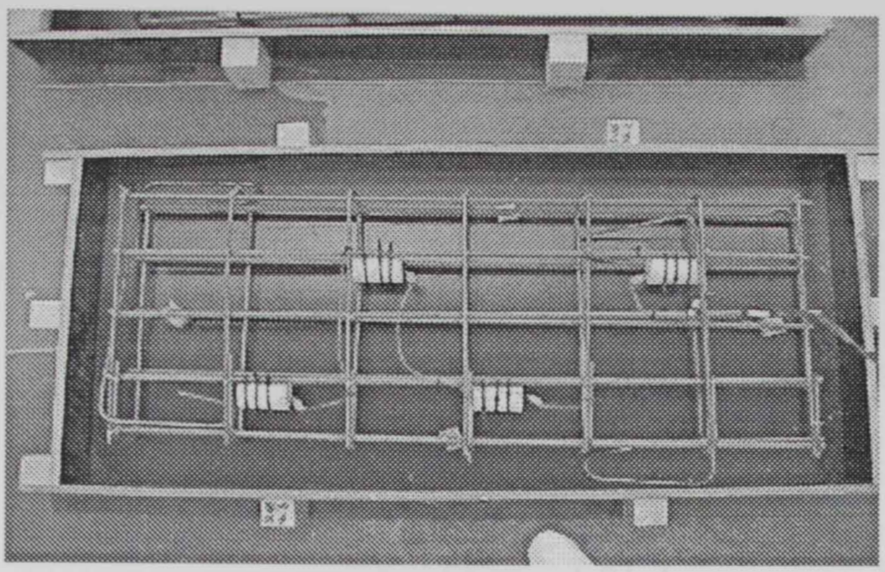


Figure 3-14 Locations of SA in new concrete

Figure 3-15 Location of small repaired area

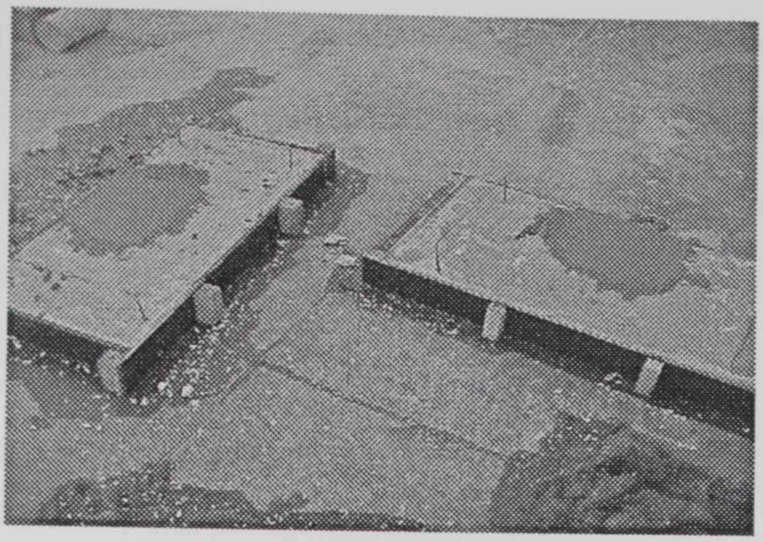


Figure 3-16 Location of large repaired area

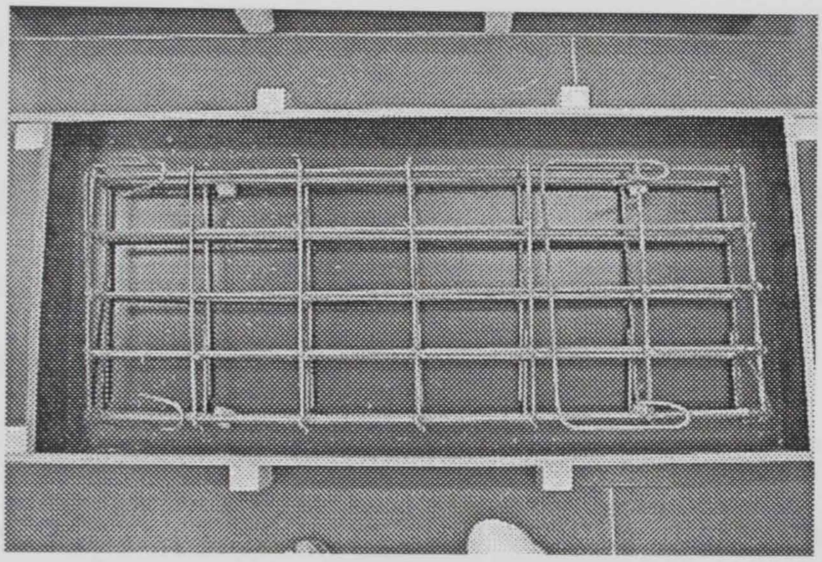


Figure 3-17 New slab before casting

In slab 1 the notched area simulates area from which concrete has spalled and are large enough to provide a realistic area for repair whereas in slab 2 this area simulates area, which is not repaired but adjacent to the repair to investigate the cathode/ anode ratio effect on the system. In slab 3 this area did not exist because slab 3 simulates the new construction concrete. It is formed by placing piece of polyesterene sheet in the upper middle of the mould. The slabs were reinforced by means of eight steel bars 10 mm diameter in two layers at equal distances along the whole length of each slab and joined together by welding through 6 mm diameter stirrups, see Figure 3-17.

3.3.1 Set-up procedure

To evaluate the performance of sacrificial anodes of the type illustrated above, a number of 6 reinforced concrete slabs 1000X500X100 were made as the following:

1) 4 units of sacrificial anodes were installed in slab 1 and 4 units were installed in slab 2 in large area of repair and 2 units were installed in the small area of repair in slab 3.

2) The pre-packed concrete was mixed with the specified water quantity for 1 minute and placed in large part in slab 1 and 1C.

3) Mixing the gradients of the host concrete for 5 minutes in the mixer starting firstly with fine aggregate. Afterward the coarse aggregate was deposited. Half of the specified quantity of salt water was laid into the mix first, then the cement bags were dumped into the mixer followed by the rest amount of the salt water. Finally the whole mix was placed in the small area of slab l and 1C and the large area of slab 2 and 2C.

4) Pre-packed concrete was mixed in the same way as the previous and placed in small area in slab 2 and 2C. Curing of all the slabs was achieved by covering them with wet sheets. Figure 3-18.

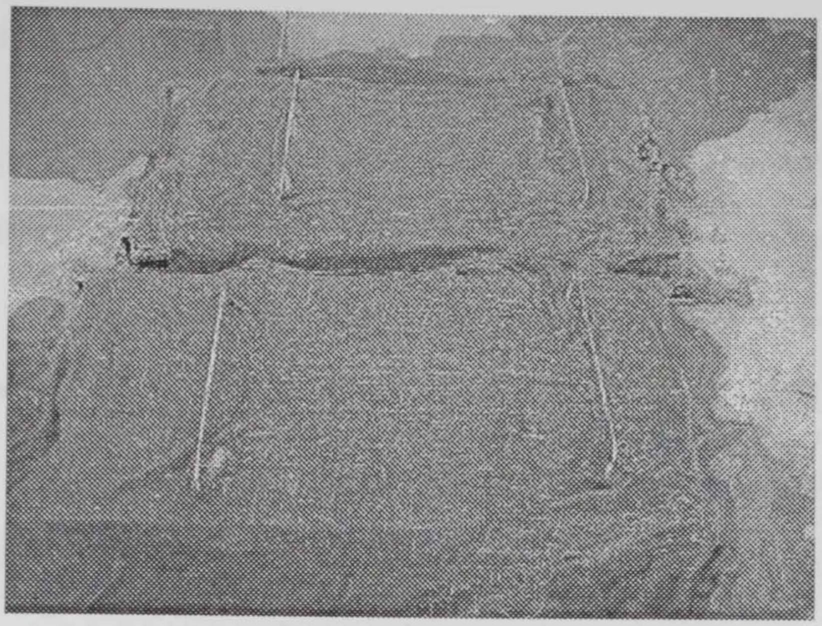


Figure 3-18 Slabs curing with wet sheets

In slab 1 the small area of repaired concrete had 0 % of chloride content and the large area was contaminated with 0.4 % of chloride content. Two units of sacrificial anodes were installed into the repaired area, all the wiring was then chased back to a junction box to allow for current and steel potential measurements to be taken.

To the opposite of slab 1, in slab 2 the small area of concrete was contaminated with 0.4 % of chloride content and repair material was placed in the large area. Four units of sacrificial anodes were installed in the repair area. Slab 3 represents the new construction concrete with normal chloride content applying sacrificial anodes as a prevention measure. Each slab had equivalent slab as a control for the purpose of comparison between them.

3.4 Monitoring procedure

Potentials of the steel taken at pre-marked locations on the surface of the concrete using a copper/copper sulphate reference electrode were mapped [32]. The wetting procedure prior to the measurement of potentials was standardized in order to remove errors in the values of potential related to variability in internal moisture of the concrete. This involved wetting of the reference electrode prior to the measurements. An initial potential mapping survey was carried out for all the columns a few days before any concrete removal was undertaken. This initial survey was necessary for providing benchmark readings that could determine the early effect of the embedded sacrificial anodes. Soon after the installation of the sacrificial anodes, the discrete anode cathodic protection system was switched on.

In each subsequent visit potential mapping was carried out after which the potential difference and current between anode and the steel reinforcement were recorded as table 3-7 below. A delay of five seconds after the initial connection to the steel was allowed prior to the recording of the values. This delay was necessary because of the difficulty in reading the instant-on current owing to its rapid early drop. Five seconds were sufficient to allow a degree of stabilization of the readings and at the same time ensure a standardized procedure for comparison of results.

Table 3-7 Half-cell potential and output measurements schedule

DATE	Half cell potential		Potential & current measurements		DATE	Half cell potential		Potential & current measurements	
	Col.	Slab				Col.	Slab	Col.	Slab
25/03/02					19/05/02				
02/04/02					27/05/02				
06/04/02					28/05/02				
09/04/02					11/06/02				
14/04/02					16/06/02				
16/04/02					23/06/02				
20/04/02					04/07/02				
23/04/02					27/08/02				
27/04/02					16/09/02				
30/04/02					03/10/02				
04/05/02					08/10/02				
07/05/02					18/10/02				
14/05/02					04/11/02				
					13/11/02				

Chapter Four

Results and Discussion

4 RESULTS AND DISCUSSION

4.1 Introduction

The primary objective of this work is to evaluate the effectiveness of the sacrificial anode cathodic protection (SACP) in preventing the incipient anode phenomena. The results of the field and laboratory testing are being presented and discussed in this chapter. The conclusion on the sacrificial anodes performance can be made by studying the potential and current output measurements. Comparison of the half-cell potential values of the control specimens with those protected using sacrificial anodes will be used to assess the ability of these anodes to prevent the formation of "incipient anode" problem around repair zone. This chapter is divided into four sections. Section 4.2 summarizes all the in-situ tests results in graphical forms. Section 4.3 summarizes all the laboratory tests results in graphical forms. The effect of SACP in protecting reinforced concrete from corrosion and preventing incipient anode phenomenon is discussed in section 4.4. Section 4.2 focuses on the effect of using global anodes in conjunction with local ones as in in-situ test of column 3. The effect of relative size of repair is addressed in section 4.3 as in slab 1 and 3 in laboratory trials. Section 4.3 discusses the effect of SACP in new construction as in laboratory test of slab 2.

4.2 In-situ results

4.2.1 Half-cell potential survey

Column 1

This column is considered to be the control column that could be used to assess the effectiveness of the sacrificial anodes in protecting reinforced concrete. It is clear from Figure 3-1 that the degree of the deterioration in column 1 before repair due to corrosion of steel is significant. The results of half-cell potential survey for this column carried out just before repair process are shown in Figure 4-1. The results indicated that maximum corrosion was concentrated at that part of the column adjacent to ground level. Corrosion decreased upwards which was confirmed by visual inspection in Figure 3-1 and delamination test in Figure 3-2. The results ranged from (-800→-600) mV in high corrosion areas close to ground level to (-200→0) mV in low corrosion areas upwards (about 1.5 m from the ground level).

Figure 4-2 shows the results of half-cell potential survey for column 1 at the age of one year from the date of repairs. The results show the start of incipient anode formation around the repair zone. Half cell potential ranged from (-500- -300) mV at the location of formation of incipient anode to (-100- 100) mV at about 1.5 m above ground level). Comparison of the half cell potential values in Figure 4-2 of this column together with those of column 2 and column 3 will be used to assess the effects of sacrificial anodes in preventing incipient anode phenomena, as will be discussed in Section 4.4.

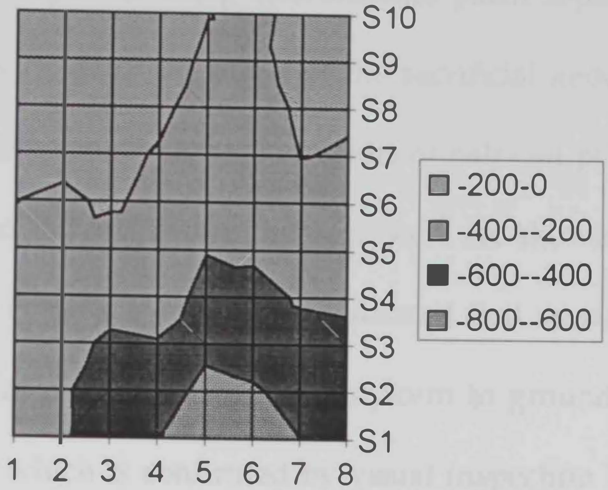


Figure 4-1 half-cell potential readings of column C1 before repair

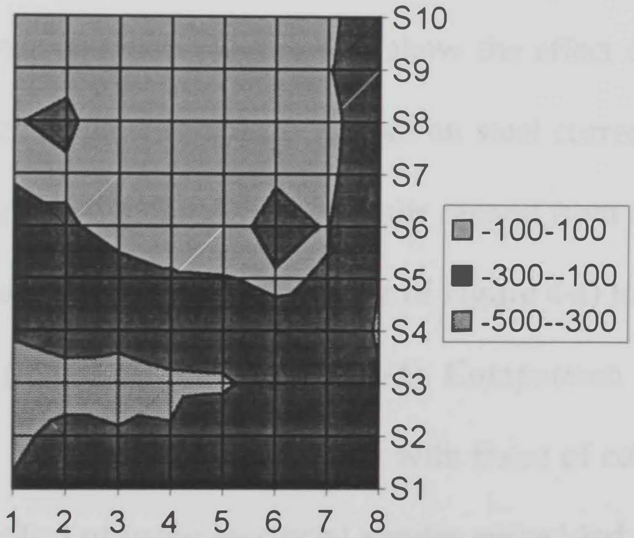


Figure 4-2 half-cell potential readings of column C1 at the age of 1 year

Column 2

This column was repaired using conventional patch repair with sacrificial embedded anodes to study the effect of the sacrificial anodes in preventing the incipient anode phenomenon. The results of half-cell potential survey for this column carried out just before repair process are shown in Figure 4-3. As was the case with column 1, the results indicated that maximum corrosion is concentrated at that part of the column adjacent to ground level. Corrosion decrease upward, which is confirmed by visual inspection in Figure 3-1 and delamination test in Figure 3-2. The results ranged from (-800→-600) mV in high corrosion areas close to ground level to (-200→0) mV in low corrosion areas upwards (about 1.5 m from the ground level).

Comparison of half-cell potential values before repair (Figure 4-3) with those recorded after 1 year of repair (Figure 4-4) show the effect of conventional patch repair with embedded sacrificial anodes on steel corrosion. Corrosion activities were reduced significantly. The results ranged from (-500- -300) mV in sacrificial anodes location (lower right side of Figure 4-4) to (-100-100) mV in protected areas (upper right side of Fig 4-4). Comparison of the half cell potential values in Figure 4-3 of this column with those of column 3 will be used to assess the effect of using sacrificial anodes embedded in patch repair in conjunction with global sacrificial anodes.

Column 3

This column was repaired using conventional patch repair with sacrificial embedded anodes in conjunction with global sacrificial anodes (GSA). The purpose of this to study the effect of the combination of both local and global

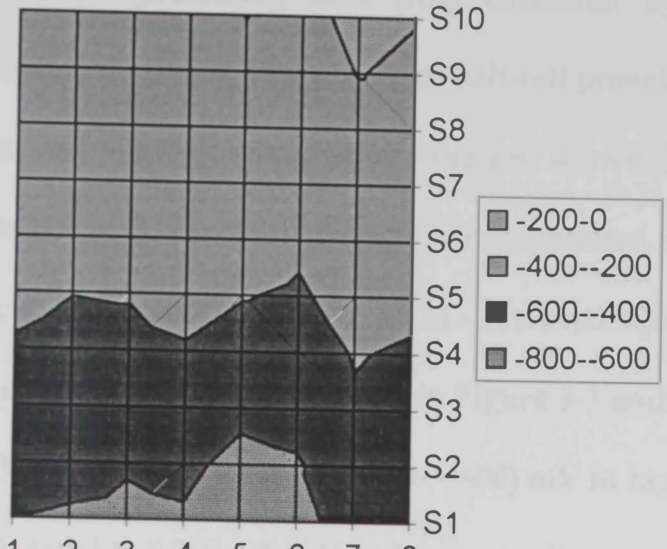


Figure 4-3 half-cell potential readings of C2 befre repair

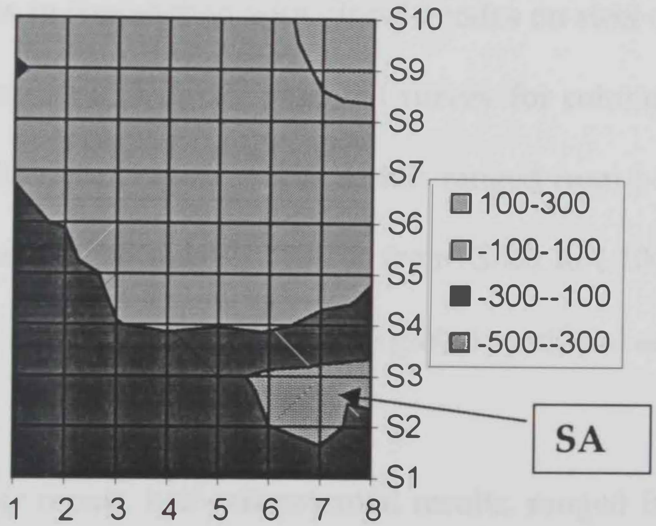


Figure 4-4 half-cell potential readings of C2 after 1 year of repair

sacrificial anodes in protecting steel from corrosion by preventing the formation of incipient anodes. The results of half-cell potential survey for this column carried out just before repair process are shown in Figure 4-5. The results indicated that maximum corrosion is concentrated at that part of the column adjacent to ground level. Corrosion decreased upwards which was confirmed by delamination test presented in Figure 3-2 and visual inspection (Figure 3-1). The results ranged from (-800→-600) mV in high corrosion areas close to ground level to (-200→0) mV in low corrosion areas upwards (about 1.5 m from the ground level).

Comparison of half-cell potential values in Figure 4-5 together with those in Figure 4-6 show the effect of conventional patch repair with embedded sacrificial anodes in conjunction with global anodes on steel corrosion. Figure 4-6 shows the results of half-cell potential survey for column 3 at the age of one year from the date of repairs. The results ranged from (-500- -300) mV in the location of sacrificial anodes (50 cm from G.L.) to (-100-100) mV in all protected zones. No signs of activity in the global sacrificial anodes zones.

Immediately after repair, half-cell potential results, ranged from a minimum of to a maximum of as illustrated in Appendix A. The developments of half-cell potential values were recorded in different time intervals as shown in Appendix A. The results showed high levels of corrosion before repair. The results dropped significantly after repair. As time passes, the results started to increase in column 1 which indicates that corrosion reactions are taking place,

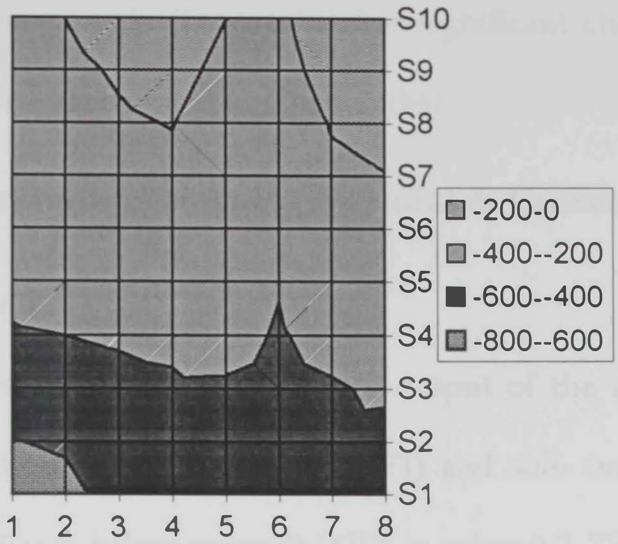


Figure 4-5 half-cell potential readings of C3 before repair

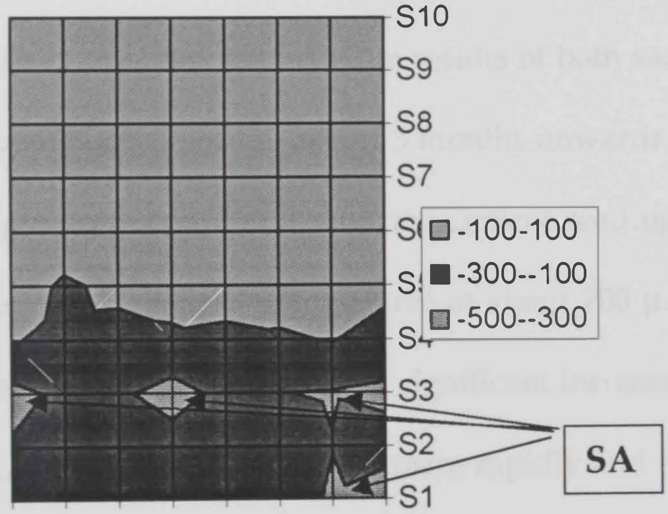


Figure 4-6 half-cell potential readings of C3 after 1 year of repair

while the results of columns 2 and 3 stabilized. Little changes appeared in the potentials in short periods (i.e. weeks) but significant changes were more apparent in relatively long periods (i.e. months).

4.2.2 Output measurements (Potential & Current)

Column 2

Figure 4-7 shows the potential difference output of the aeriated sacrifitial anode (placed 500 mm above ground) (XP1) and soil- immersed sacrifitial anode (placed 500 mm below ground) (XP2) in column 2. The initial output of XP1 anode was relatively high at about 250 mV. In the following three months the potential difference reading dropped 100 mV. To the contrary of this, potential difference of XP2 started with relatively low values at about 120 mV and increased slightly to about 150 mV. The results of both sacrificial anodes stabilized at about 120 mV from the age of 3 months onwards. The results of the potential output were confirmed with the current readings as shown in Figure 4-8. The aeriated anode reading startd at about 700 µA immediately after repair. At the end of the first month a significant increase was recorded at about 1300 µA. The results started to decrease rapidly and reached 500 µA at the end of 3 months from repair. The reading continued to drop, but with a much lower rate, see Figure 4-8. The immersed anodes current output was 400 µA initially then increased to 500 µA at the age of 1 month. The reading started to decrease and reached 200 µA at the age of 11 months.

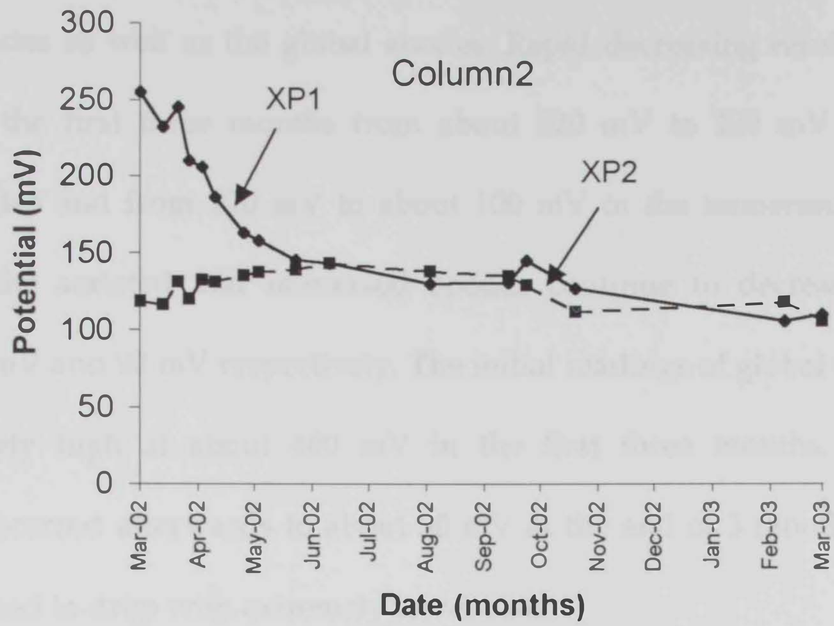


Figure 4-7 potential output of SA in C2

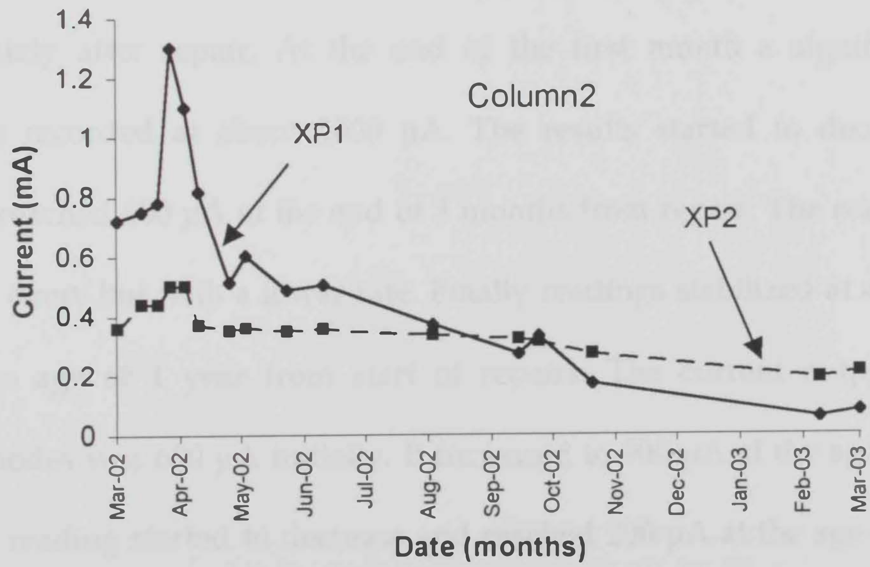


Figure 4-8 current output of SA in C2

Column 3

Figure 4-9 shows the potential difference results for the local (immersed and aeriated) anodes as well as the global anodes. Rapid decreasing results was observed in the first three months from about 320 mV to 220 mV in the aeriated anodes and from 220 mV to about 100 mV in the immersed ones. Afterwards the aeriated and immersed anodes continue to decrease and reached 125 mV and 90 mV respectively. The initial readings of global anodes were relatively high at about 400 mV in the first three months. Rapid decreasing occurred afterwards to about 50 mV at the end of 3 months. The curve continued to drop with extremely lower rate.

The current readings as shown in Figure 4-10 showed very similar trend to those of potential difference. The aeriated anode reading startd at about 700 µA immediately after repair. At the end of the first month a significant increase was recorded at about 1000 µA. The results started to decrease rapidly and reached 400 µA at the end of 3 months from repair. The reading continued to drop, but with a lower rate. Finally readings stabilized at about 50 µA at the age of 1 year from start of repairs. The current output of immersed anodes was 600 µA initially. It increased to 900 µA at the age of 1 month. The reading started to decrease and reached 200 µA at the age of 11 months.

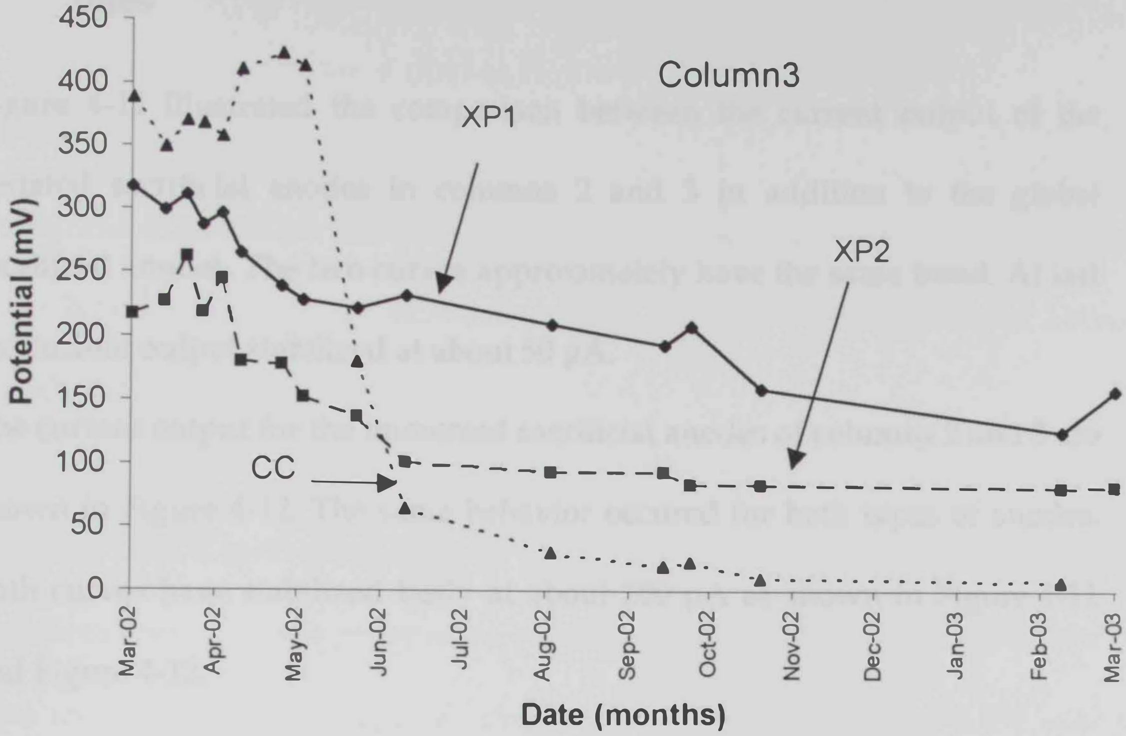


Figure 4-9 potential output of SA in C3

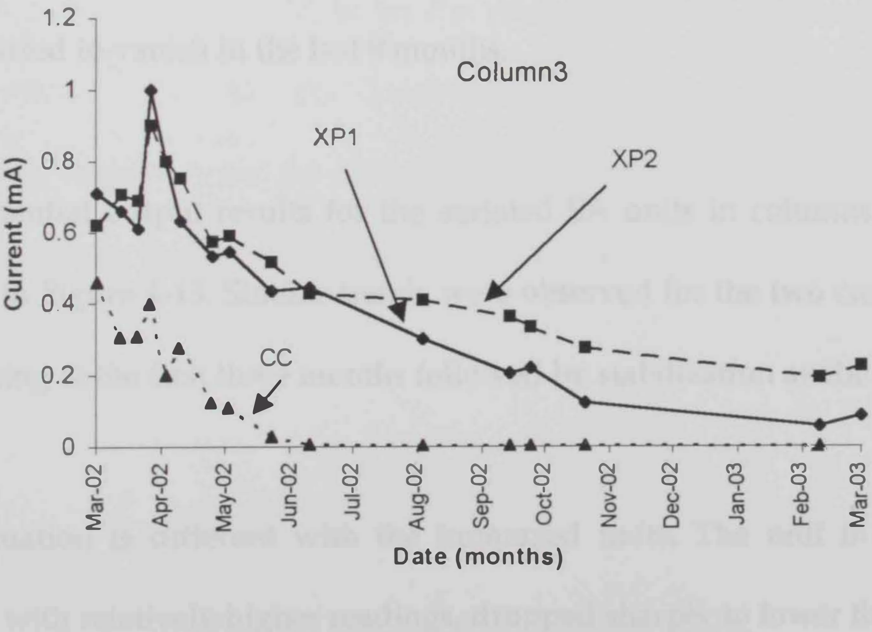


Figure 4-10 current output of SA in C3

4.2.3 The effect of using global anodes in addition to local ones

Figure 4-11 illustrated the comparison between the current output of the aeriated sacrificial anodes in columns 2 and 3 in addition to the global sacrificial anodes. The two curves approximately have the same trend. At last the current output stabilized at about 50 μA.

The current output for the immersed sacrificial anodes of columns 2 and 3 are shown in Figure 4-12. The same behavior occured for both types of anodes. Both curves have stabilized lastly at about 200 μA as shown in Figure 4-11 and Figure 4-12.

The difference between the aeriated and immersed anodes could be caused by the changes in capillary action and moisture content in this zone.

The global units current output decreased in the first three months rapidly then started to vanish in the last 9 months.

The potential output results for the aeriated SA units in columns 2 & 3 are shown in Figure 4-13. Similar trends were observed for the two curves, rapid decreasing at the first three months followed by stabilization at about 150 mV.

The situation is different with the immersed units. The unit in column 3 started with relatively higher readings, dropped sharply to lower than ones in column 2 and stabilized at about 100 mV. While in column 2 there was slight increasing in the first three months followed by slight decreasing in the remaining months and the readings stabilized at about 120 mV. This is confirmed with the current output in Figure 4-11 and Figure 4-12.

The global units started with very high readings in average 400 mV in the first three months followed by rapid decreasing in the remaining months and stabilization at about 11 mV.

From the above discussion it could be concluded that there is no extra or significant effect on the passivation state of steel and in turn the protection from corrosion due to using of the global anodes in conjunction with the local ones specifically in this cases. This could be attributed to the intense and quite widespread area of influences created by the embedded anodes that prevail over the global anodes zones. So that the global anodes still not yet needed in this stage. Emphasis should be on the studying during the design stage to such systems. Also the dry condition existed upwards in the column participate negatively on the effectiveness of this type which need a dry-wet cycle for better performance, the case found in the capillary zone in the column.

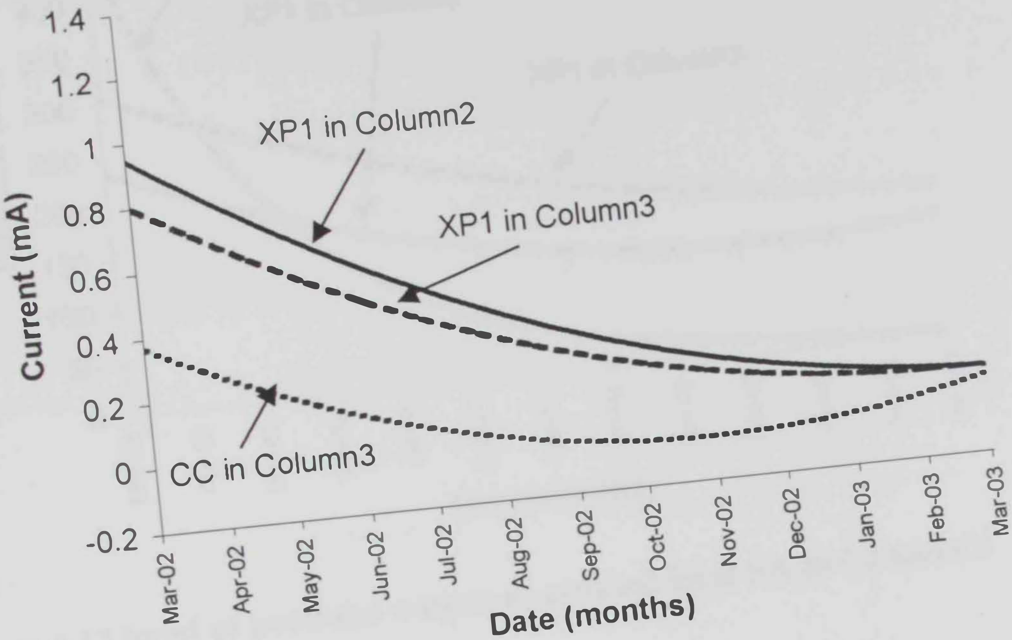


Figure 4-11 trend of current output of aerated local SA in C2 and C3

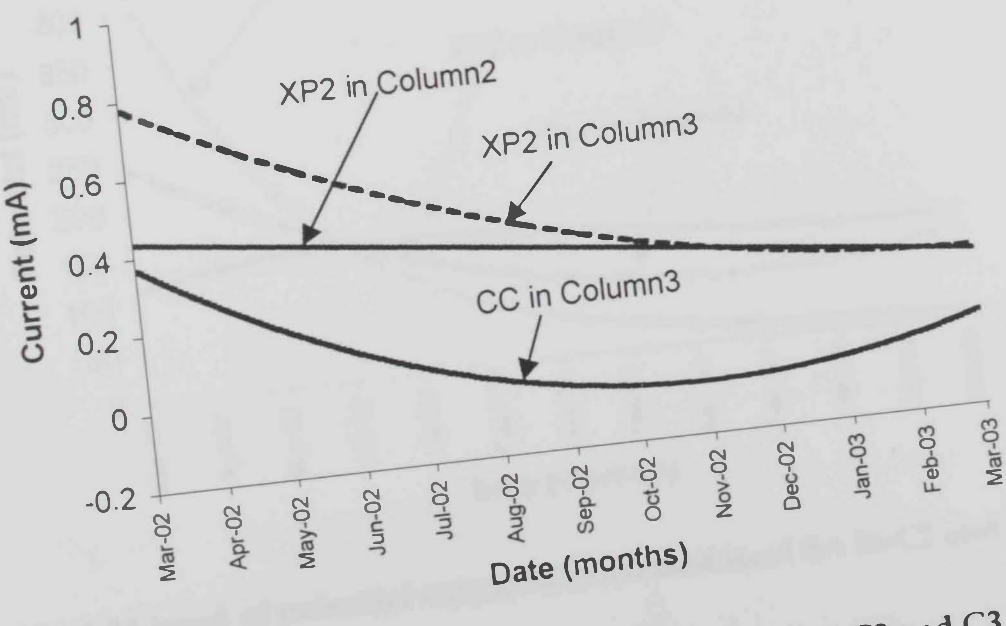


Figure 4-12 trend of current output of immersed local SA in C2 and C3

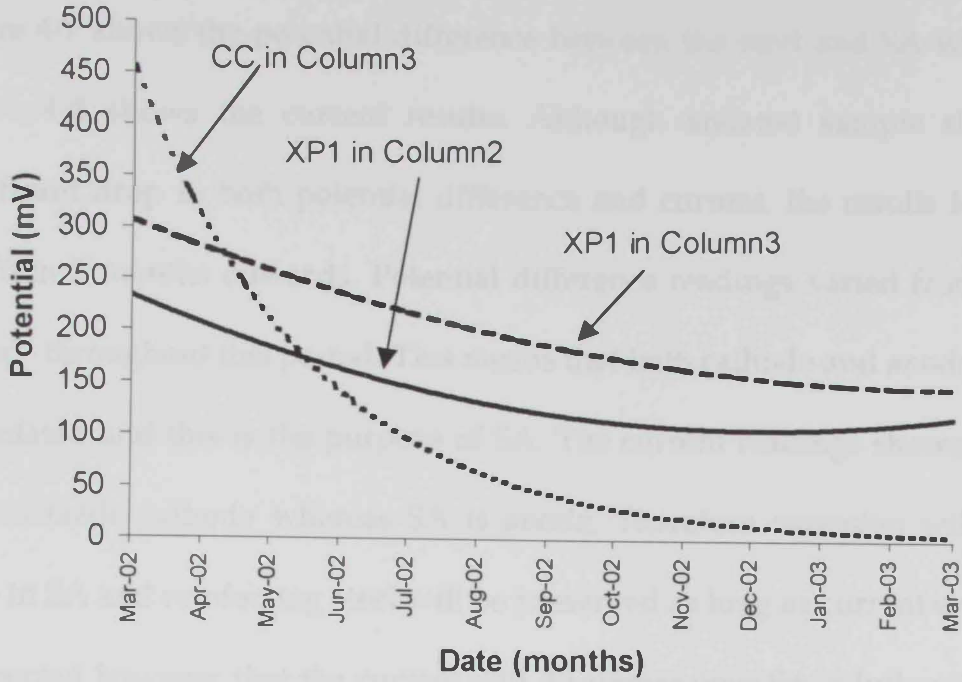


Figure 4-13 trend of potential output of aerated local SA in C2 and C3

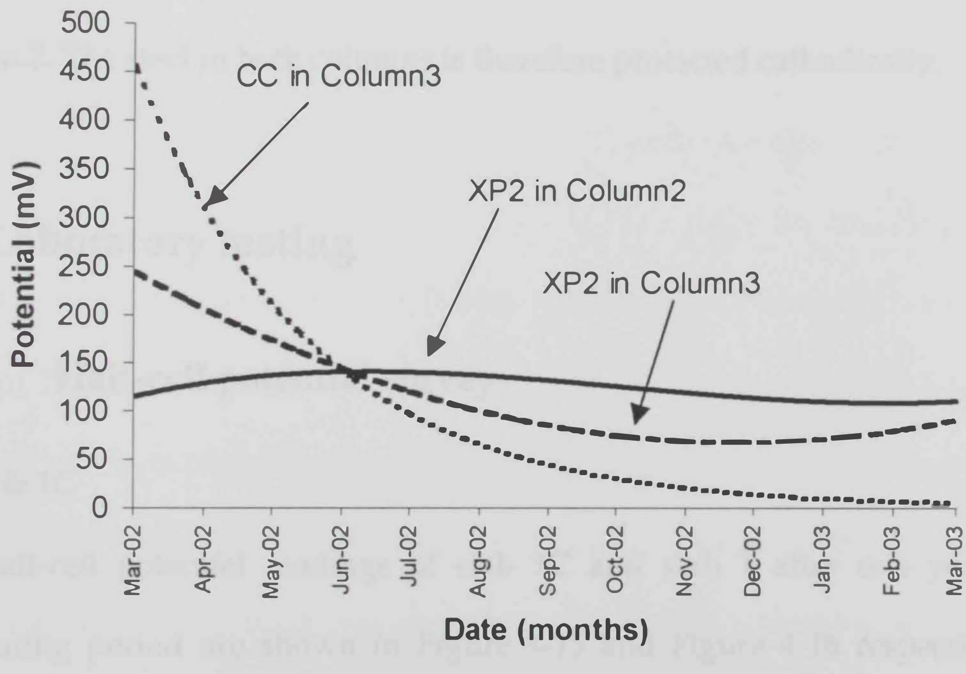


Figure 4-14 trend of potential output of immersed local SA in C2 and C3

Figure 4-7 shows the potential difference between the steel and SA whereas Figure 4-8 shows the current results. Although areiated sample showed significant drop in both potential difference and current, the results leveled out from 3 months onwards. Potential difference readings varied from 120-140 mV throughout this period. This means that both cathode and anode were formulated and this is the purpose of SA. The current readings showed that steel is made cathode whereas SA is anode. Therefore corrosion will take place in SA and reinforcing steel will be preserved as long as current exists. It is expected however that the current will disappear once SA is fully utilized. The same can be said about immersed SA.

The results of column 3 demonstrated very similar effect to those recorded for column 2. The steel in both columns is therefore protected cathodically.

4.3 Laboratory testing

4.3.1 Half-cell potential survey

Slab 1 & 1C

The half-cell potential readings of slab 1C and slab 1 after one year of monitoring period are shown in Figure 4-15 and Figure 4-16 respectively. Area of relatively high potential readings is concentrated almost at repair zone and extended around in slab 1. The relatively high potential readings in this area are as a result of sacrificial anodes acting in this location. In slab 1C, the relatively high potential readings area is outside the repair zone, far near the right edge of the slab. This could be attributed to the formation of incipient anode. Figure 4-27 shows that 50 % of total area is in the range -200 to -350 mV

Slab 2 & 2C

The half-cell potential readings mapping of slab 2C and slab 2 are shown in Figure 4-17 and Figure 4-18 respectively. Only a relatively small area at the far right of slab 2C about 10 % of the total area of the slab where readings exceeded -200 mV as shown in Figure 4-27. This location could be considered as an incipient anode zone. The half-cell potential readings more than -200 mV were about 70 % of the total area of slab2 see Figure 4-27. This could be attributed to the activation of the sacrificial anodes in the slab.

Slab 3 & 3C

The half-cell potential readings of slab 3C and 3 are shown in Figure 4-19 and Figure 4-20 respectively. The relative high readings are limited only in the zone of contaminated concrete in slab 3C. The area of these high readings is about 20 % of total area of the slab as shown in Figure 4-21. The half-cell potential readings of slab 3 more than -200 mV appeared in the contaminated concrete area and extended downwards. Figure 4-21 illustrate that such area represents 50 % of the total area of the slab. This could be attributed to large cathode anode ratio and because of the current delivered is not yet enough to protect the steel.

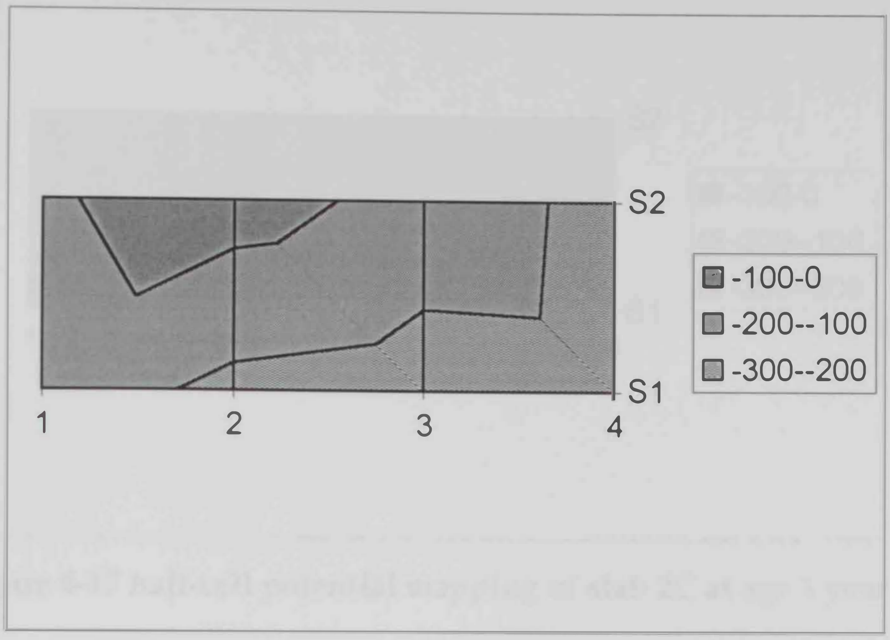


Figure 4-15 half-cell potential mapping of slab 1C at age 1 year

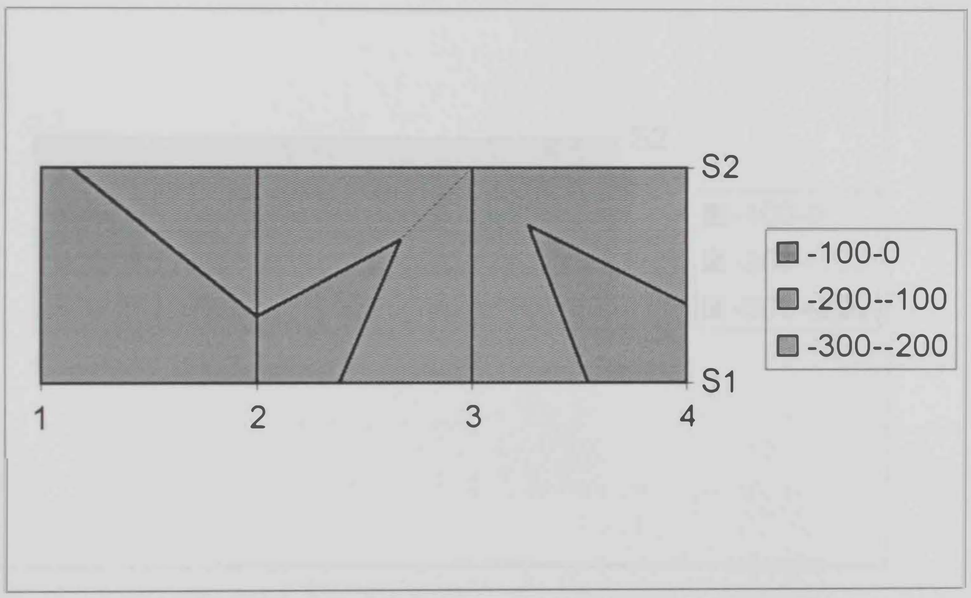


Figure 4-16 half-cell potential mapping of slab 1 at age 1 year

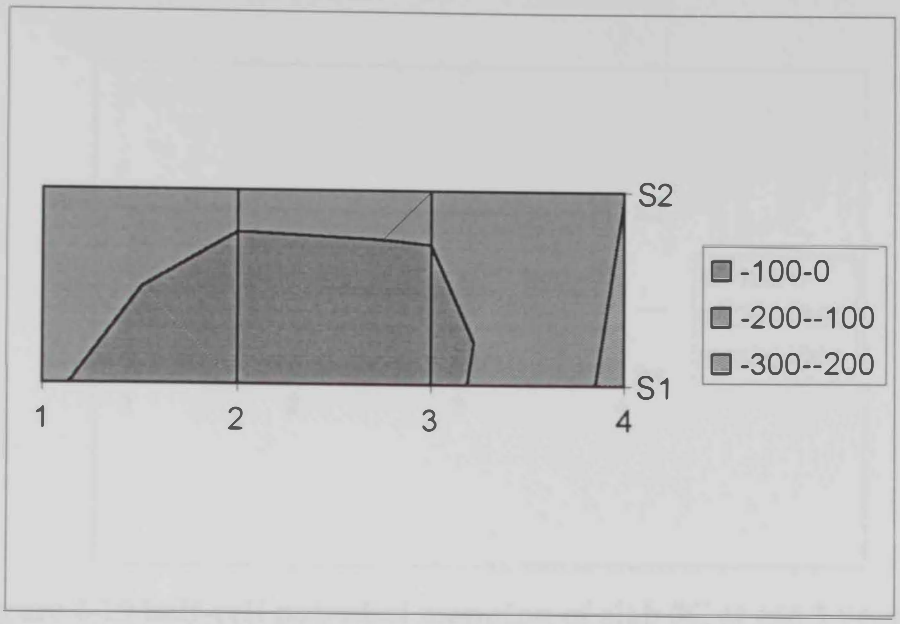


Figure 4-17 half-cell potential mapping of slab 2C at age 1 year

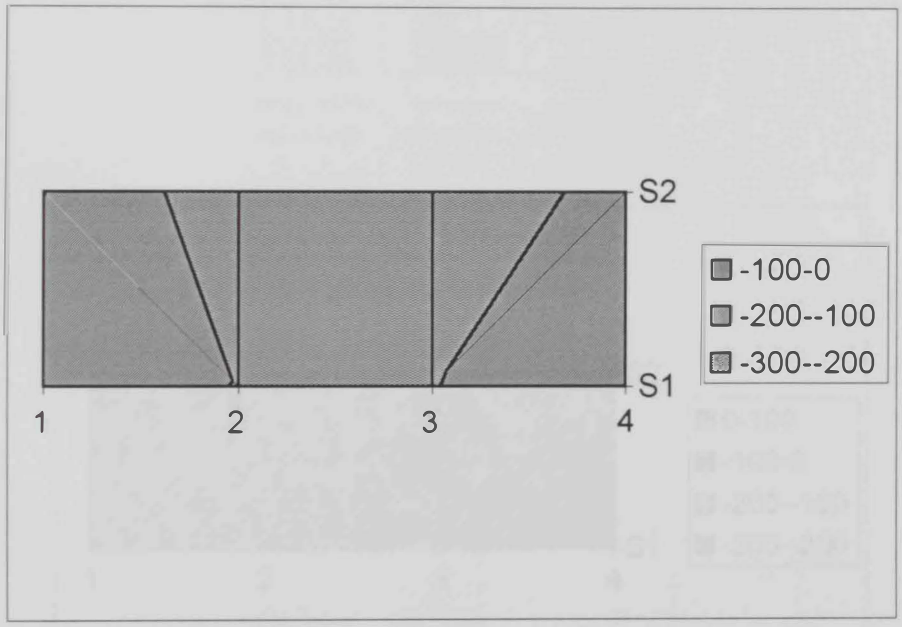


Figure 4-18 half-cell potential mapping of slab 2 at age 1 year

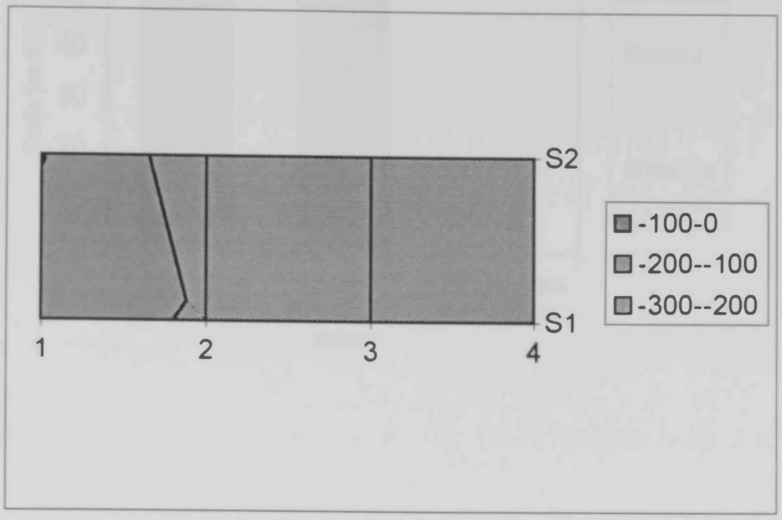


Figure 4-19 half-cell potential mapping of slab 3C at age 1 year

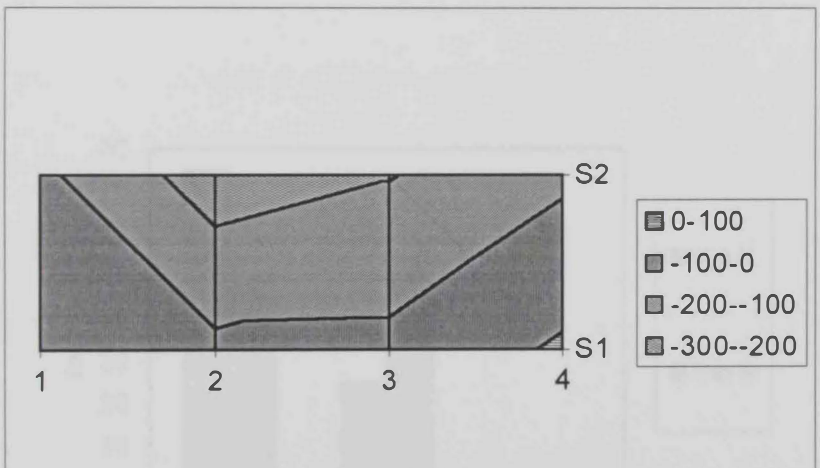


Figure 4-20 half-cell potential mapping of slab 3 at age 1 year

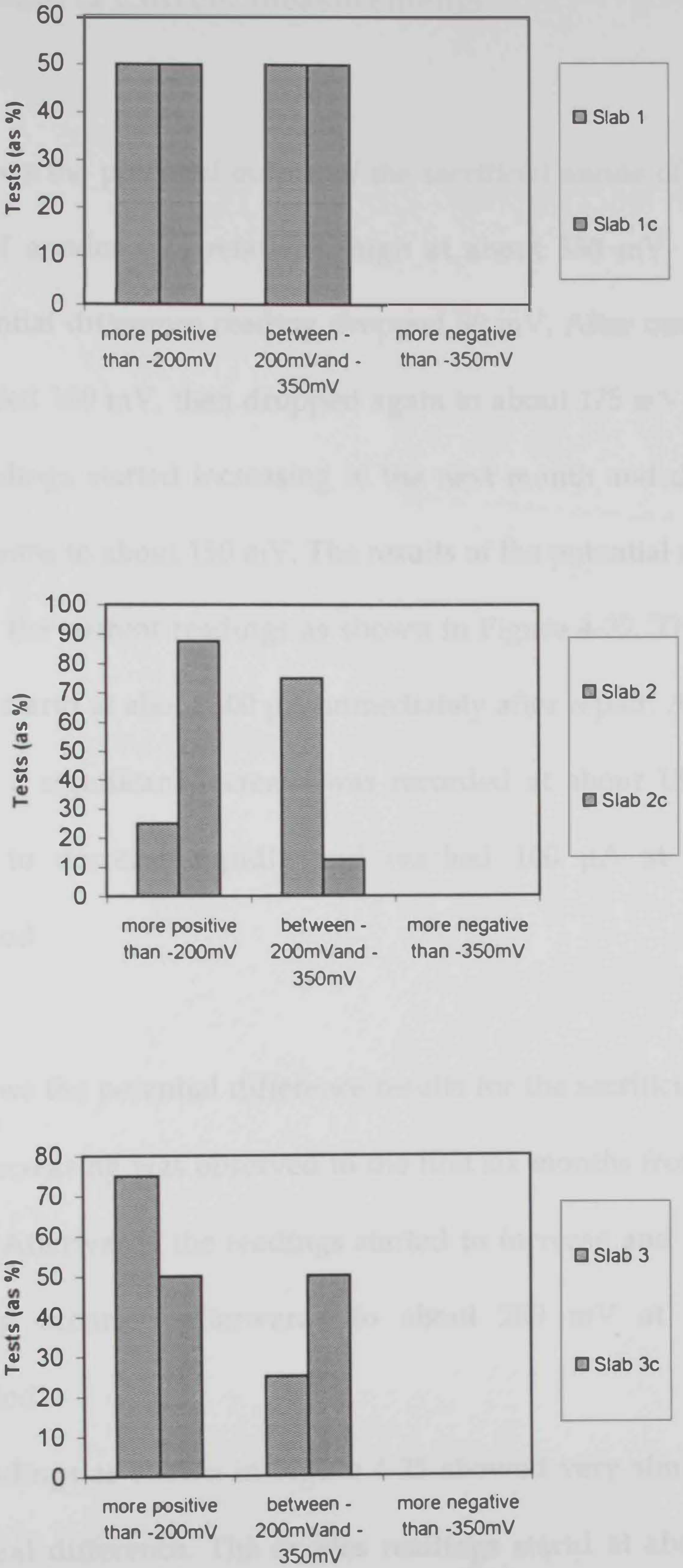


Figure 4-21 Cumulative frequency of slabs

4.3.2 Potential & Current measurements

Slab 1

Figure 4-23 shows the potential output of the sacrificial anode of slab 1. The initial output of anodes was relatively high at about 350 mV. In the first month the potential difference reading dropped 50 mV. After one month the readings increased 100 mV, then dropped again to about 175 mV in the sixth month. The readings started increasing in the next month and decreased in the last four months to about 150 mV. The results of the potential output were confirmed with the current readings as shown in Figure 4-22. The sacrificial anodes reading startd at about 300 µA immediately after repair. At the end of the first month a significant increase was recorded at about 1300 µA. The results started to decrease rapidly and reached 100 µA at the end of monitoring period.

Slab 2

Figure 4-24 shows the potential difference results for the sacrificial anodes of slab 2. Rapid decreasing was observed in the first six months from about 550 mV to 220 mV Afterwards the readings started to increase and reached 300 mV. Decreasing occurred afterwards to about 200 mV at the end of monitoring period.

The current readings as shown in Figure 4-25 showed very similar trend to those of potential difference. The anodes readings startd at about 1900 µA immediately after repair. At the first month a significant decrease was recorded at about 1200 µA followed by increase again to 1900 µA. The results

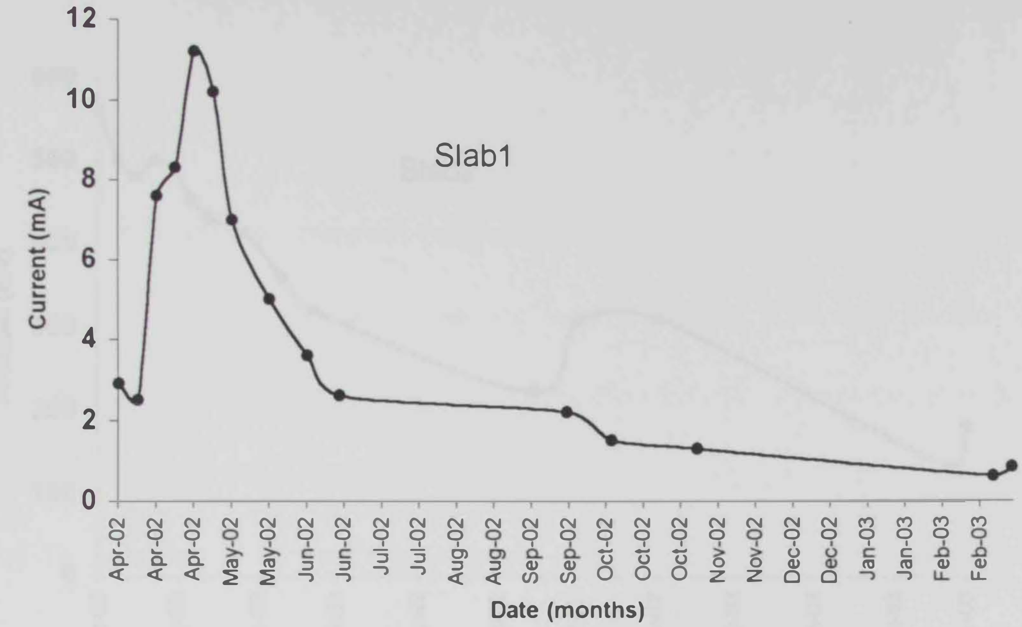


Figure 4-22 current output of slab 1

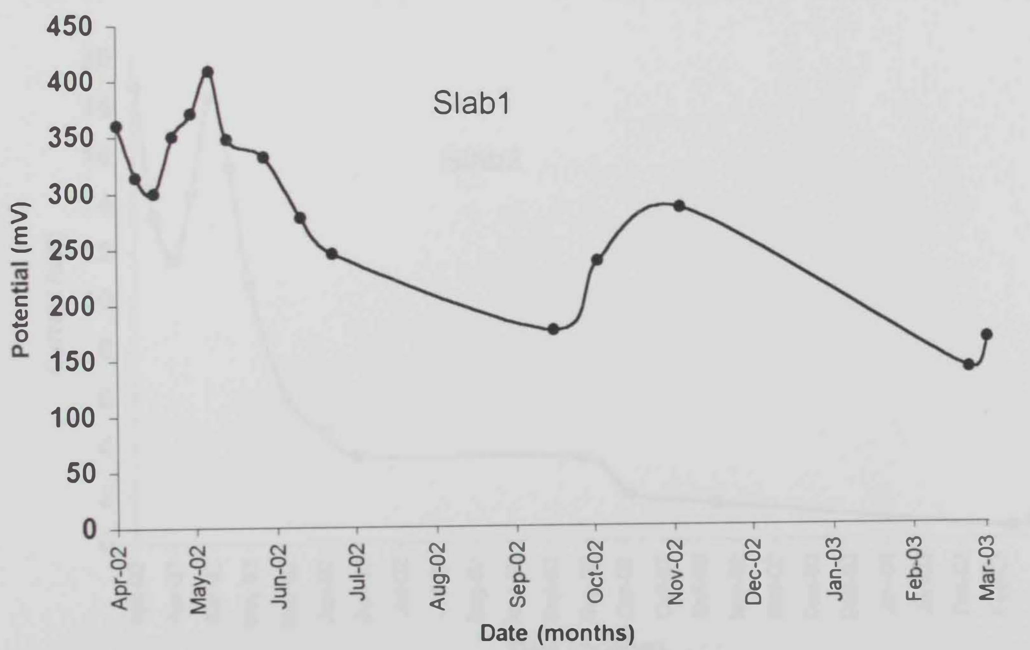


Figure 4-23 potential output of slab 1

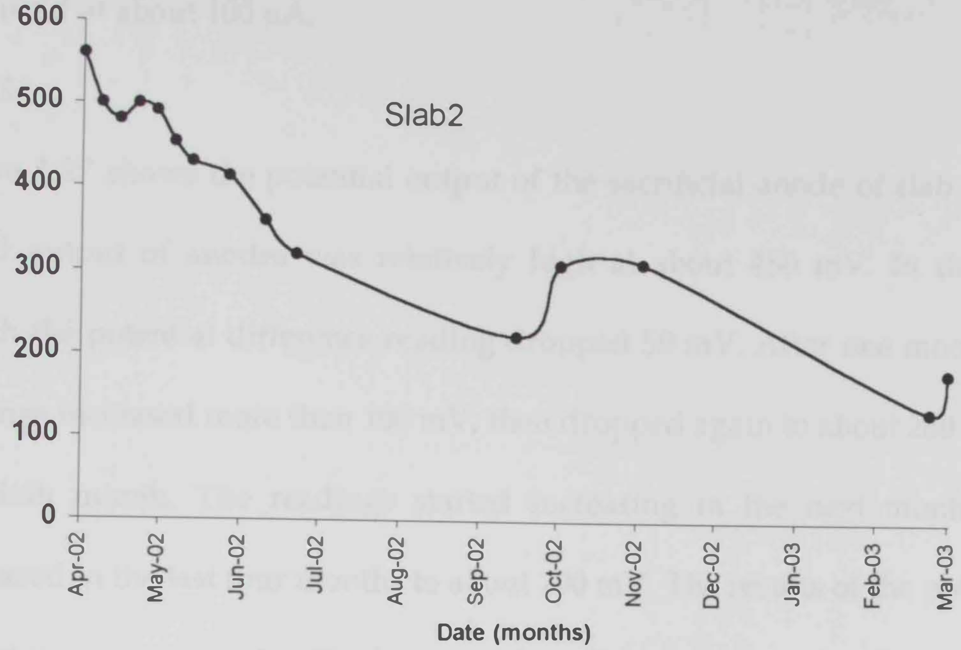


Figure 4-24 potential output of slab 2

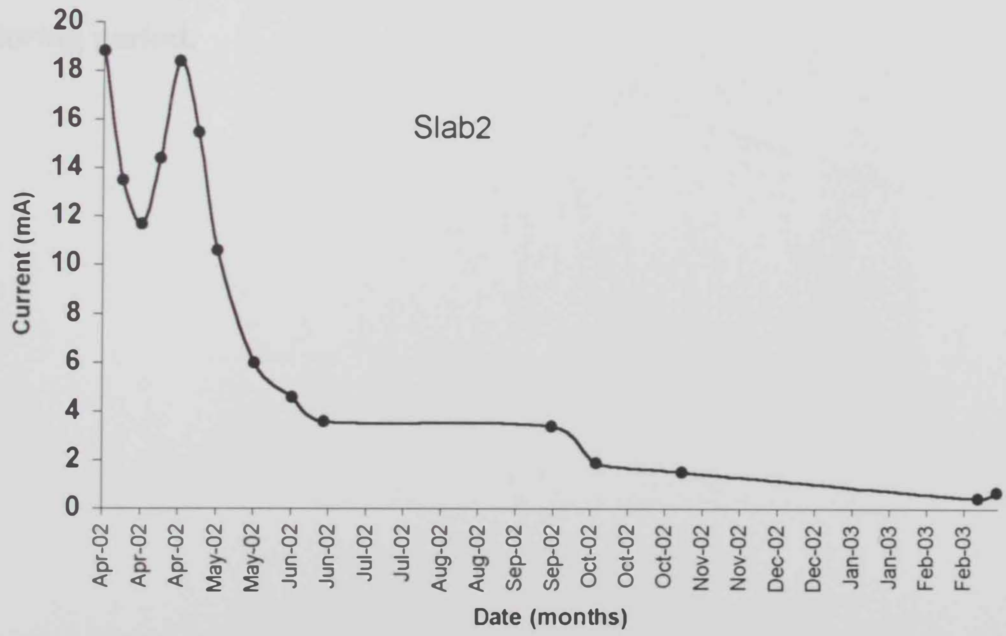


Figure 4-25 current output of slab 2

started to decrease rapidly and reached 400 μA at the end of 3 months from repair. The reading continued to drop, but with a lower rate. Finally readings stabilized at about 100 μA.

Slab 3

Figure 4-27 shows the potential output of the sacrificial anode of slab 3. The initial output of anodes was relatively high at about 450 mV. In the first month the potential difference reading dropped 50 mV. After one month the readings increased more than 100 mV, then dropped again to about 280 mV in the sixth month. The readings started increasing in the next month and decreased in the last four months to about 200 mV. The results of the potential output were confirmed with the current readings as shown in Figure 4-26. The sacrificial anodes reading startd at about 300 μA immediately after repair. At the end of the first month a significant increase was recorded at about 700 μA. The results started to decrease rapidly and reached 100 μA at the end of monitoring period.

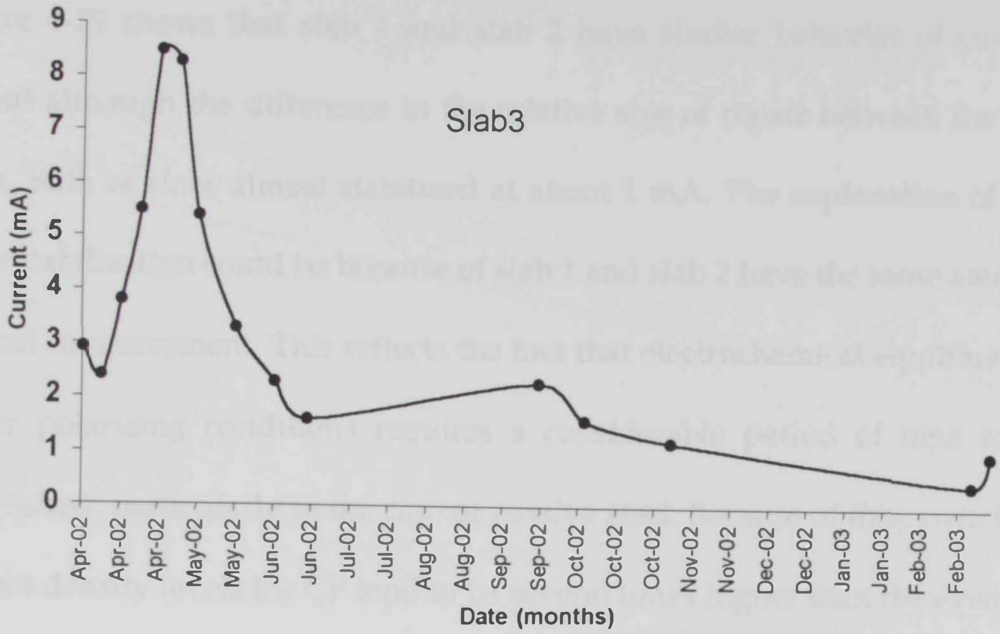


Figure 4-26 current output of slab 3

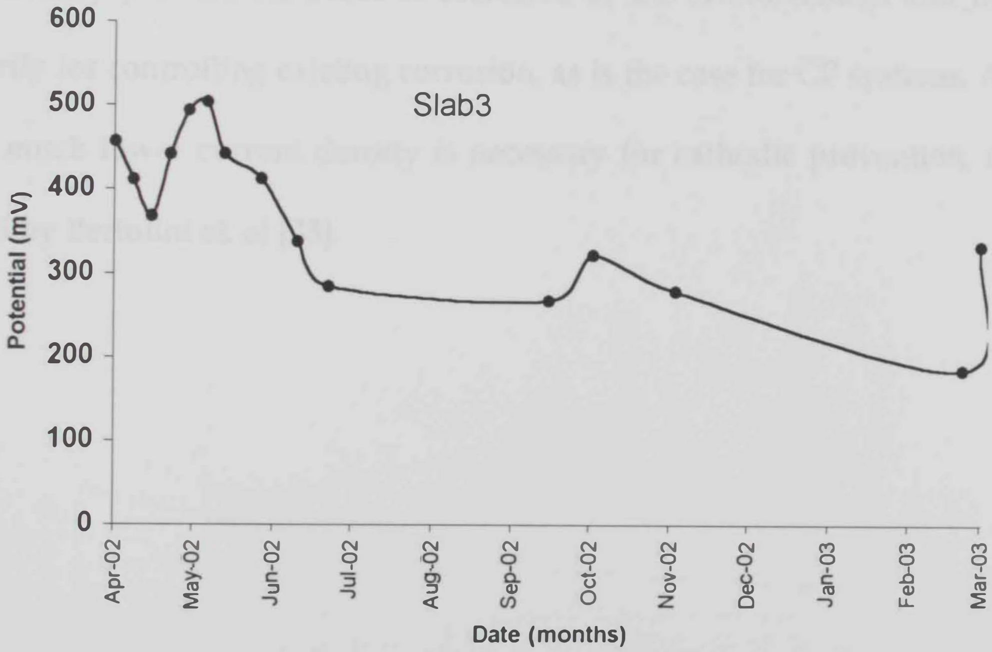


Figure 4-27 potential output of slab 3

4.3.3 Effect of relative size of repair on SA performance

Figure 4-29 shows that slab 1 and slab 2 have similar behavior of current output although the difference in the relative size of repair between the two slabs. Both of slabs almost stabilized at about 1 mA. The explanation of this same stabilization could be because of slab 1 and slab 2 have the same amount of steel reinforcement. This reflects the fact that electrochemical equilibration under polarizing conditions requires a considerable period of time to be established, particularly in the case of passive steel. Because of this, switch-on current density levels for CP tend to be several times higher than the eventual operating levels. Clearly, other criteria for determining the effectiveness of cathdic prevention system needs to be developed. Such systems are required to cathodically prevent the onset of corrosion of the reinforcement and not necessarily for controlling existing corrosion, as is the case for CP systems. As such, a much lower current density is necessary for cathodic prevention, as reported by Bertolini et. al [33].

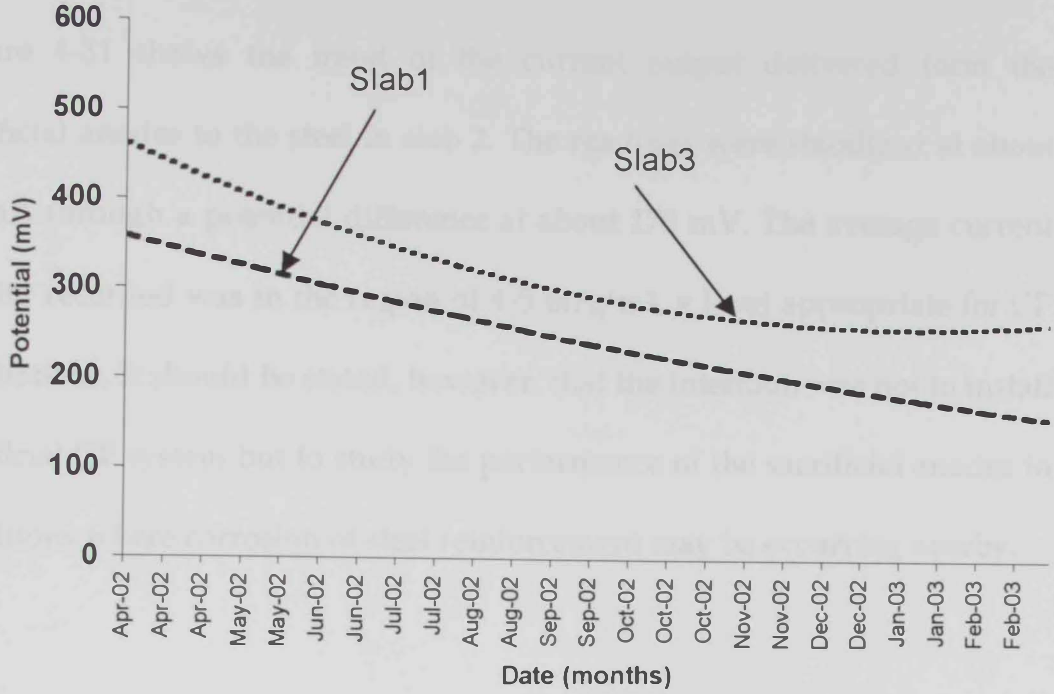


Figure 4-28 trend of potential output of slab 1 and slab 3

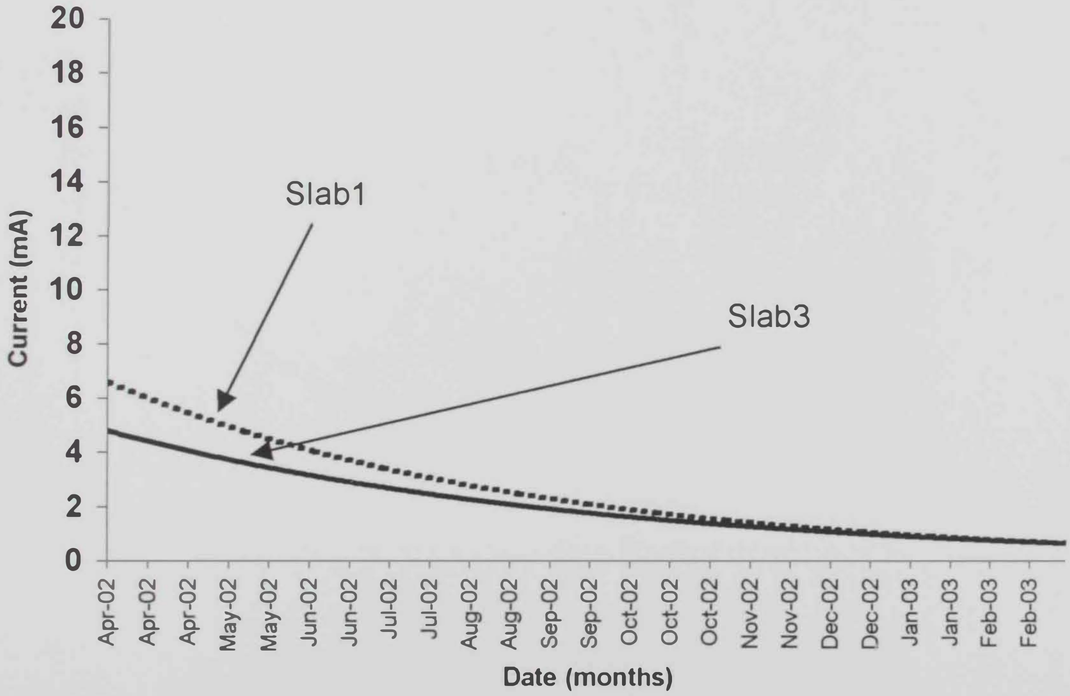


Figure 4-29 trend of current output of slab 1 and slab 3

4.3.4 Effect of using SACP anodes in new construction

Figure 4-31 shows the trend of the current output delivered form the sacrificial anodes to the steel in slab 2. The readings were stabilized at about 0.5 mA through a potential difference at about 175 mV. The average current density recorded was in the region of 4-5 mA/m^2, a level appropriate for CP installations. It should be stated, however, that the intention was not to install sacrificial CP system but to study the performance of the sacrificial anodes in conditions where corrosion of steel reinforcement may be occurring nearby.

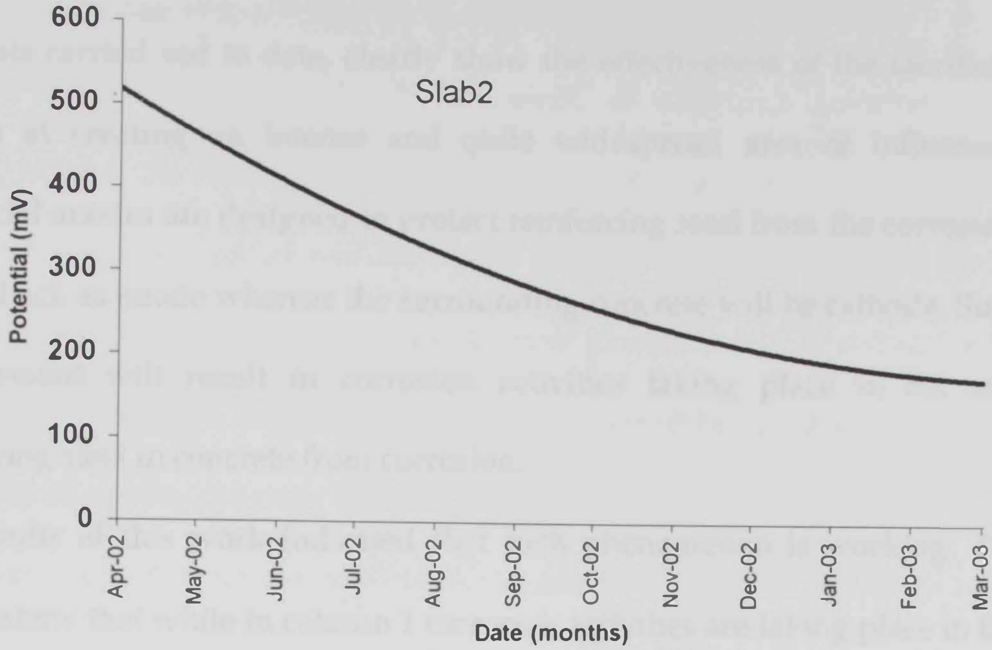


Figure 4-30 trend of potential output of slab 2

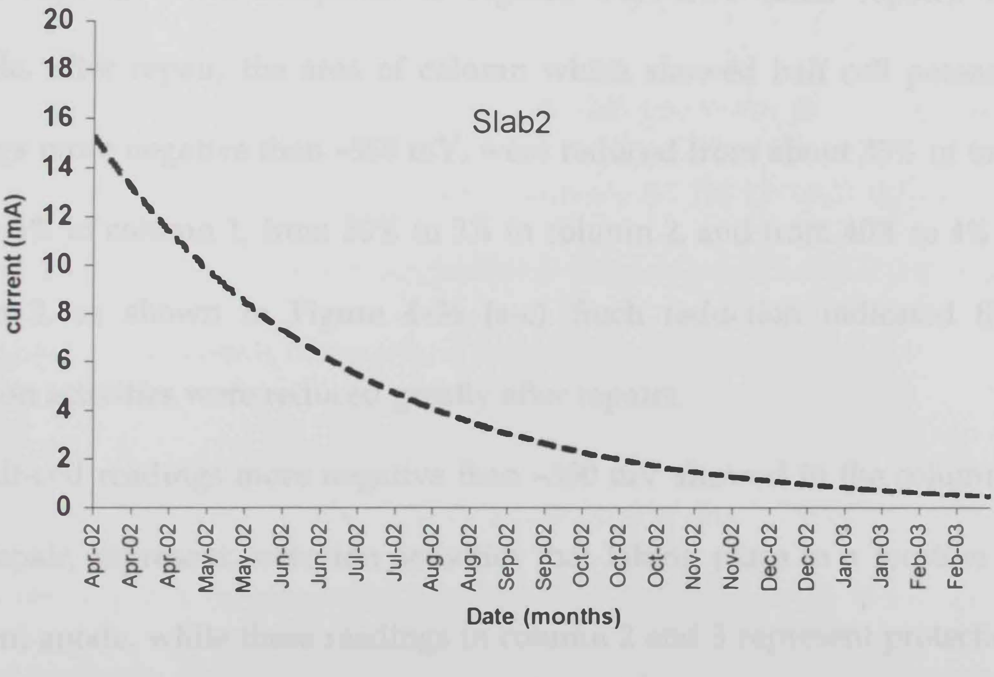


Figure 4-31 trend of current output of slab 2

4.4 Effect of SACP on protecting steel from corrosion

The tests carried out to date, clearly show the effectiveness of the sacrificial anodes at creating an intense and quite widespread area of influences. Sacrificial anodes are designed to protect reinforcing steel from the corrosion. SA will act, as anode whereas the surrounding concrete will be cathode. Such arrangement will result in corrosion activities taking place in SA and preserving steel in concrete from corrosion.

The results of this work indicated that such phenomenon is working. The results show that while in column 1 corrosion activities are taking place in the reinforcing steel in a form of incipient anode, SA in columns 2 and 3 were protecting steel from corrosion.

Repair reduced corrosion activities significantly; see Figures 4-1,4-3,4-5 (before repair), when compared to Figures 4-2,4-4,4-6 (after repair). For example, after repair, the area of column which showed half cell potential readings more negative than -350 mV, were reduced from about 35% of total area to 5% in column 1, from 50% to 3% in column 2, and from 40% to 4% in column 3, as shown in Figure 4-36 (a-c). Such reduction indicated that corrosion activities were reduced greatly after repairs.

The half-cell readings more negative than -350 mV showed in the column 1 after repair, represent corrosion activities that taking place in a location of incipient anode, while these readings in column 2 and 3 represent protection activities taking place in the location of SA. This could be evidenced by the half cell potential mapping shown in Fig 4-5 and Fig 4-6, where a high corrosion zone are clear near repair area in Figure 4-5, while these high corrosion areas are concentrated in SA zones in Figure 4-6.

SA will be effective only in the presence of corrosion activities. The development of the results as shown in appendix A indicated clear maximum reading in the location of one SA anode only immediately after repair of column 3. At the age of 6 months, another maximum reading was clear at the location of second SA. The third SA was also clear at the age of one year (see appendix A). Such progress indicated that these anodes were activated as time goes by, moreover the reading in the surrounding concrete were more less constant. Half-cell potential readings in column 1 were to the contrary of those of column 3. Such readings were very clear. In column 1, no such observation was seen. Corrosion activities were very wide spread throughout the column.

To clarify the effect of SA, the maximum half-cell potentials in each mapping were recorded in the SA surrounding concrete. As the recording locations were equally spaced, the maximum potential value would be expected to be a reasonable representation of the whole area of the columns.

Figures 4-34, 4-35 showed that half-cell potential of all columns were very similar for about 3 months after repairs. After this, the result of column 1 showed corrosion activities in the reinforcing steel as the result of incipient anode formation. For example, result were approximately -300 mV after 3 months of repair of column 1 (no SA installed). The results were increased negatively to about -500 mV at the end of sex months. On the contrary, columns 2 and 3 showed no significant corrosion activities. Results stay almost constant throughout the testing age (approximately -300 mV). The SA in column 2 and 3 are protecting the reinforcing steel in the concrete by supplying a stable current to the steel through a sufficient potential difference to keep the steel in a passivation state.

These results confirm with other researchers findings. For example L. Page and G. Sergi published data similar in trend to this work [21].

Potential difference shift of over 100 mV from the initial ambient were observed in the tests at age of 1 year as shown in Figures 4-37, 4-38 The potential gradients, which the anodes have set up, are significant and are therefore likely to be sufficient to ensure that the corrosion in the protected area of influence becomes focused on the sacrificial anodes. Throughout the test period the anodes can be observed to have been protecting the other areas within their area of influence from becoming susceptible to further corrosion. As might be anticipated, the intensity of the effect can be observed to be reducing as time progresses.

This is commensurate with the observed anode currents, which have declined in a similar fashion as the tests have progressed. The recorded current values within the monitoring period of one year averaged about 200 μA for each individual anode embedded within the repair and and 50 μA for sacrificial anodes immersed in soil. This translated to current density of about for the columns, a value compatible with reported cathodic prevention levels.

Initially, currents of immersed anodes observed to be flowing from the anodes and through the repairs were found to be somewhat high by comparison with aeriated anodes currents. The reason of this could be as a result of relatively higher corrosion activity cells existed adjacent to ground and the moisture content changes due to capillary action.

The tests clearly demonstrate that passivation effects, which have stopped earlier attempts the indications, are that anode currents are stabilizing at between 50 μA and 200 μA.

To contrary, CP criteria should apply in the case of the slabs, as some corrosion activity of the steel would have been present at 'switch-on'. The anode arrangement here should therefore be expected to operate as a CP system. Even though the average current density recorded was in the region of 4-5 mA/m^2, a level appropriate for CP installations, the mean depolarsation potentials ranged between 40 and 60 mV, considerably short of the required level. It should be stated, however, that the intention was not to install sacrificial CP system but to study the performance of the sacrificial anodes in conditions where corrosion of steel reinforcement may be occurring nearby.

This reflects the fact that electrochemical equilibration under polarizing conditions requires a considerable period of time to be established, particularly in the case of passive steel. Because of this, switch-on current density levels for CP tend to be several times higher than the eventual operating levels. Clearly, other criteria for determining the effectiveness of cathodic prevention system needs to be developed. Such systems are required to cathodically prevent the onset of corrosion of the reinforcement and not necessarily for controlling existing corrosion, as is the case for CP systems. As such, a much lower current density is necessary for cathodic prevention, as reported by Bertolini et. al [33].

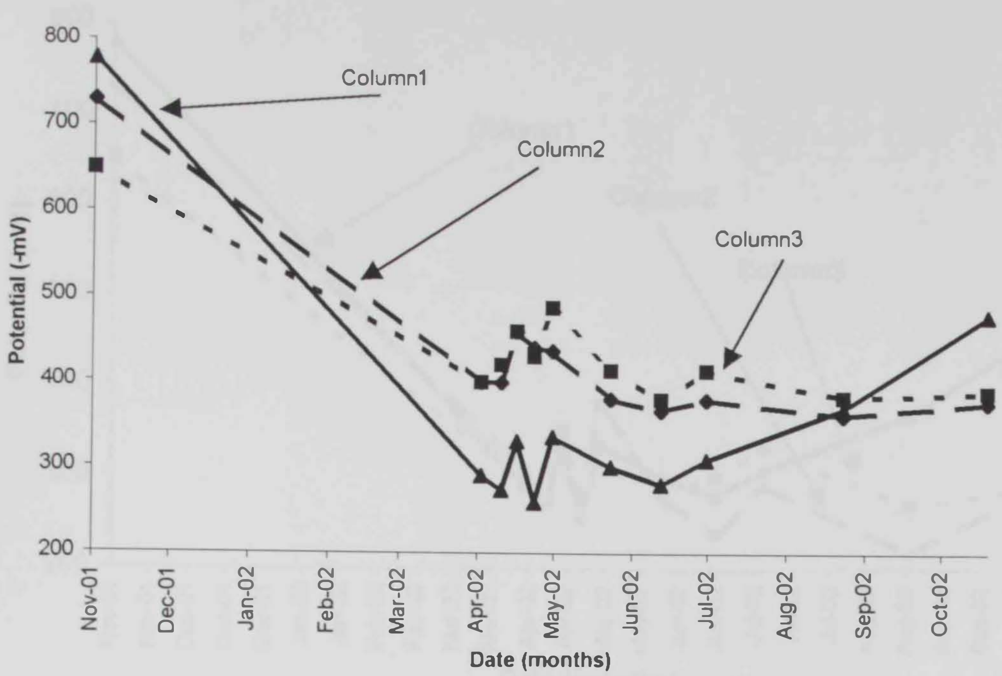


Figure 4-32 maximum half-cell readings in and around SA zones

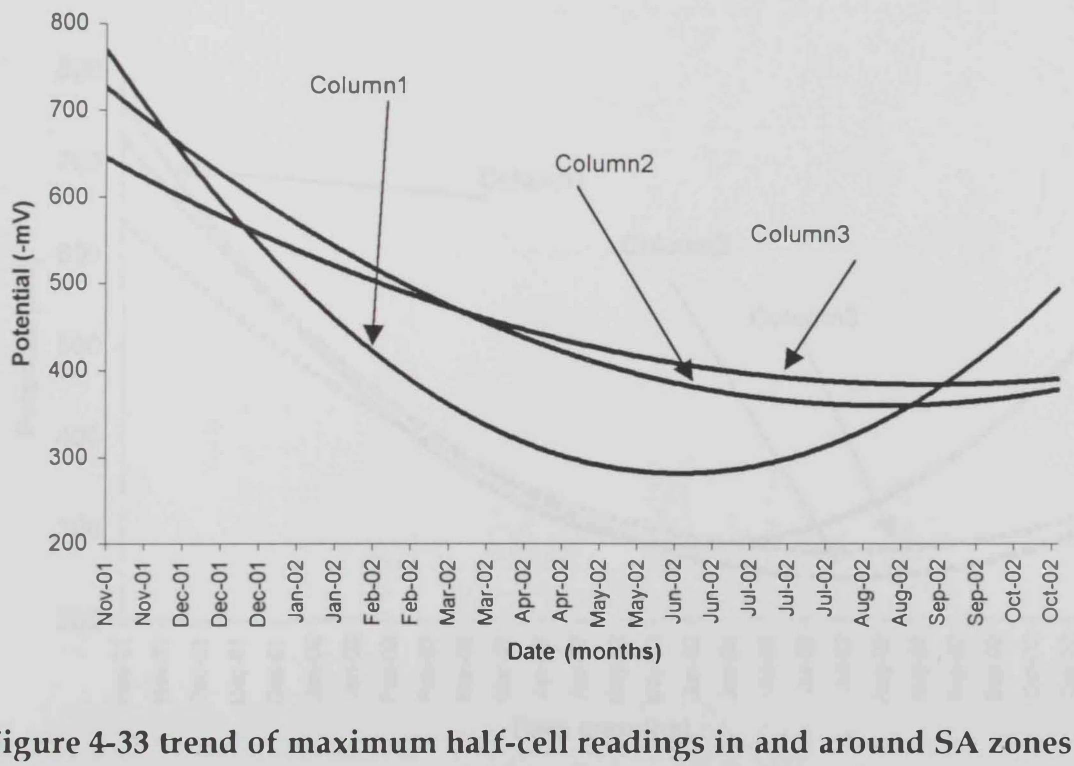


Figure 4-33 trend of maximum half-cell readings in and around SA zones

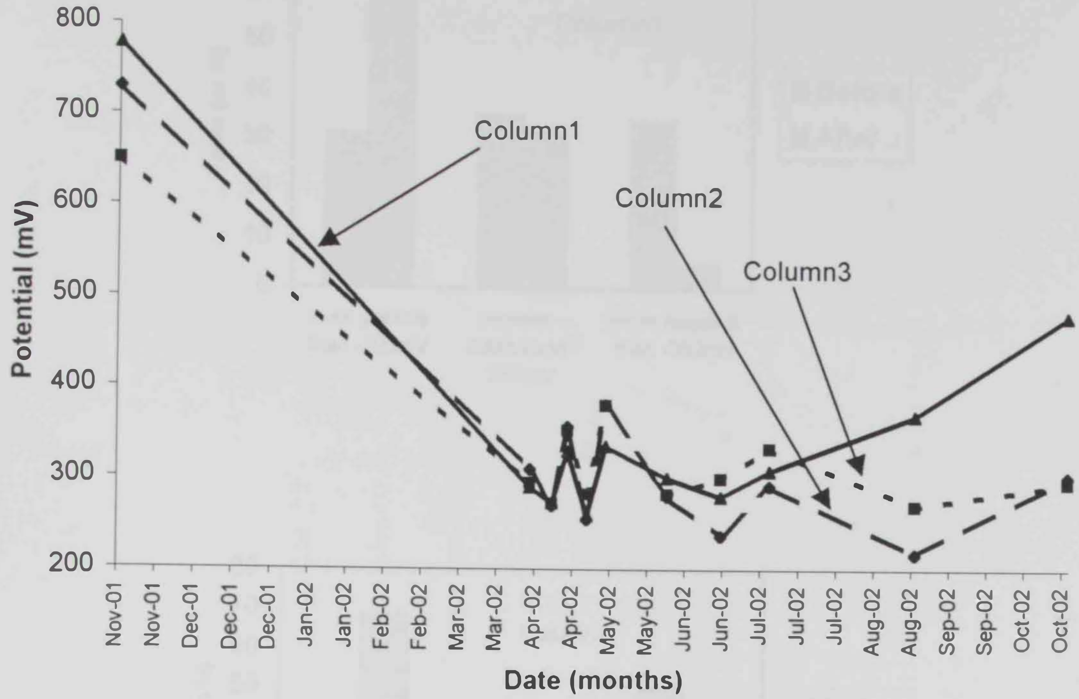


Figure 4-34 maximum half-cell readings around SA zones

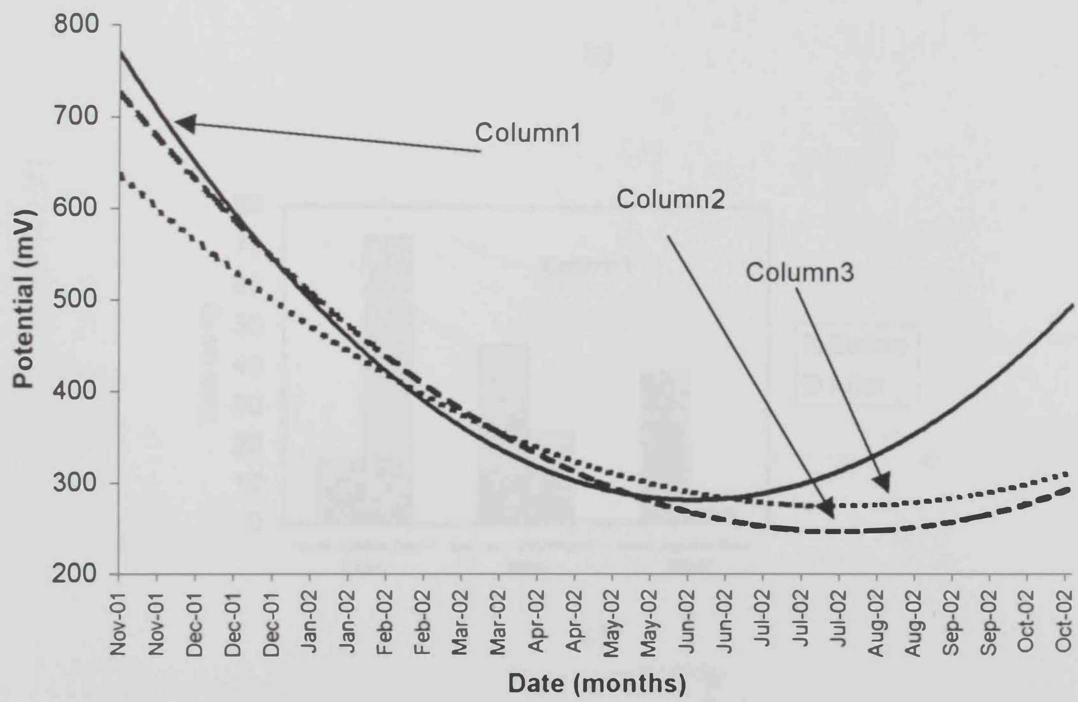
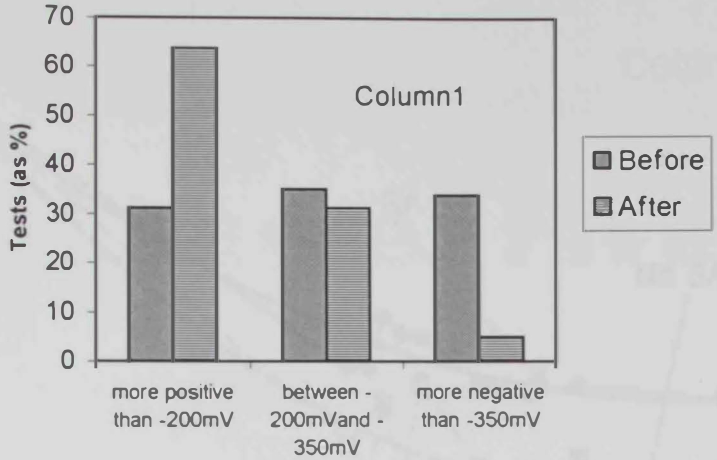
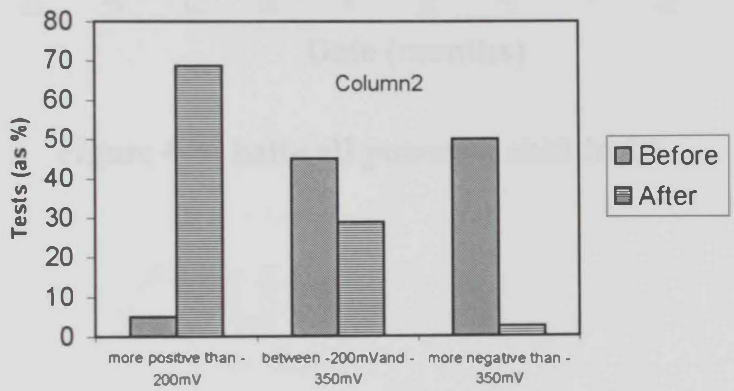


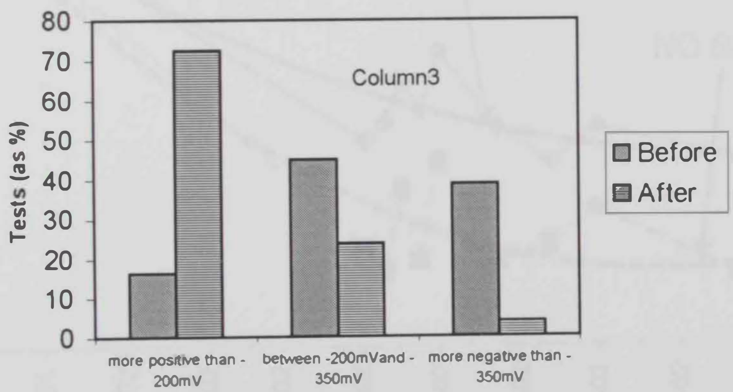
Figure 4-35 trend of maximum half-cell readings around SA zones



a)



b)



c)

Figure 4-36 cumulative frequency before and after repair of the columns

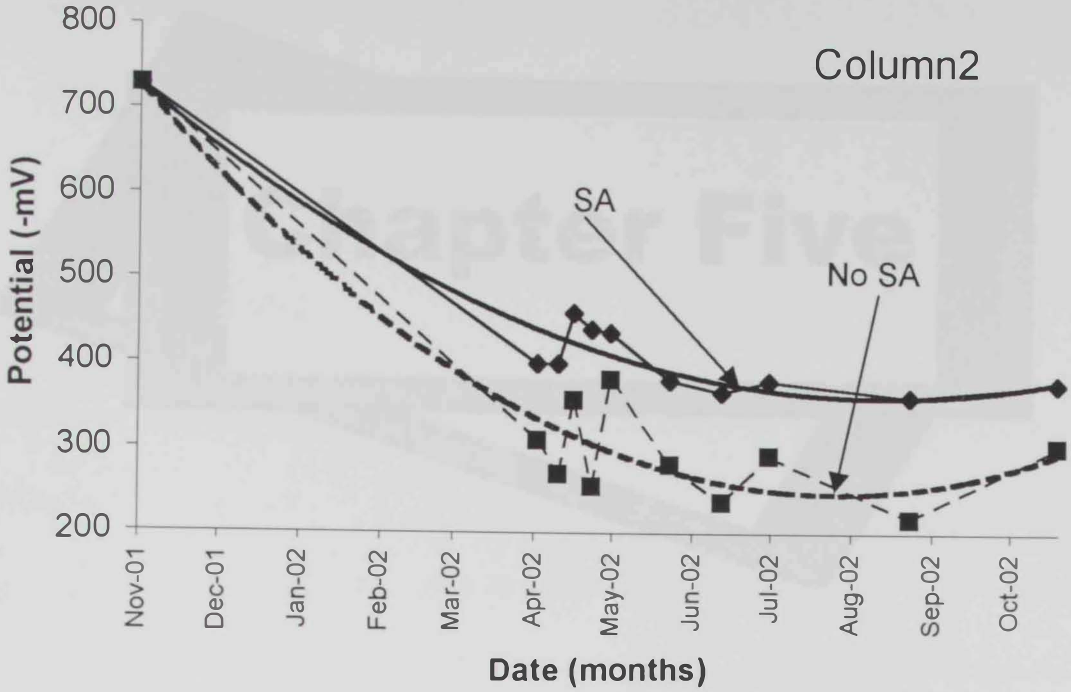


Figure 4-37 half-cell potential shift in C2

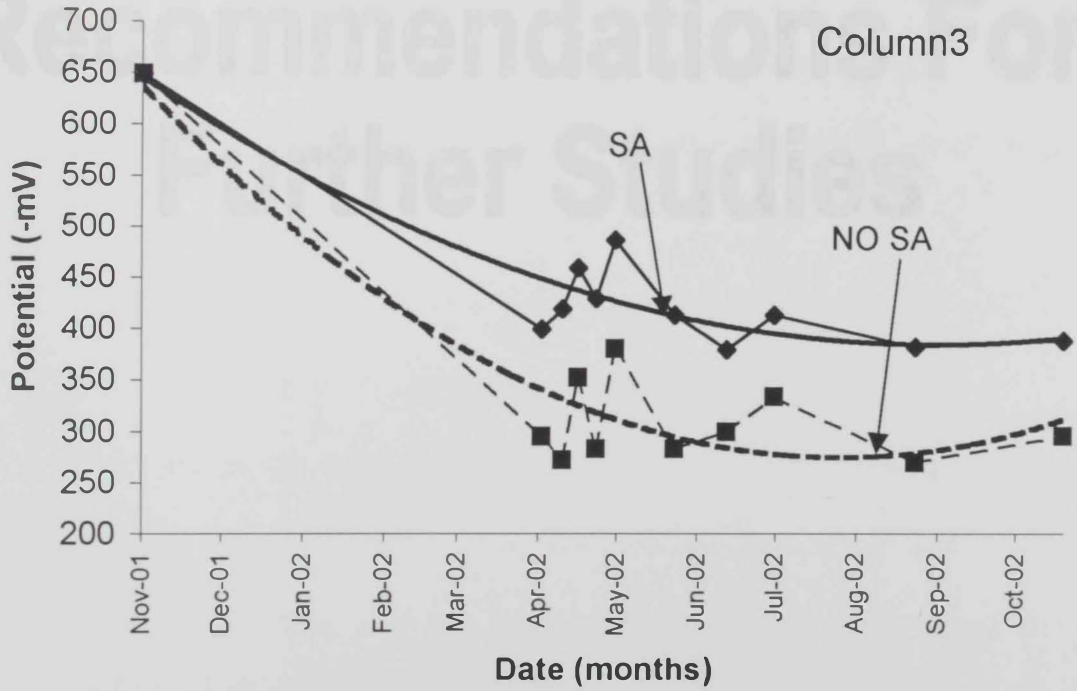


Figure 4-38 half cell-potential shift in C3

Chapter Five

Conclusions and Recommendations For Further Studies

5 CONCLUSIONS, RECOMMENDATIONS FOR FURTHER STUDIES

5.1 Conclusions

Based on the previous results and discussion, the following conclusive remarks can be given:

1. The use of SACP in patch repairs has been proved to give cathodic protection to concrete. An electrochemical cell was formed in which SACP was anode and surrounding steel was cathode as was seen from the potential results. This was clearer in the 20-year-old column than in newly cast laboratory slabs.
2. The results of this work did not show any further benefit from using global SACP. The reason could be attributed to the testing durations of this work. It may be expected that after longer period, its benefit will be apparent.
3. The results of SACP in new constructed slab showed positive effect in preventing steel from corrosion.
4. Throughout the tests to date, the anodes have been found to be an effective method for controlling the problems associated with incipient anode generation and the premature failure of areas surrounding repairs in concrete, which are suffering from chloride, related corrosion.

5.2 Recommendations for further studies

The developments of cathodic protection anode systems for above ground reinforced concrete structures have enabled the establishment of a significant business activity which is important in its ability to extend the life of valuable structures at a cost lower than alternative techniques. Although the achievements of these developments there is an ongoing need for research and development in this field. It is recommended that the following areas could have further studies:

- The influence of temperature and humidity on the effectiveness of SACP.
- The performance of such SACP in marine structures; submerged, tidal zone, and dry areas in both new constructions and repairs.
- Criteria of design and material specifications:

The number and amount of required sacrificial anodes should receive more attention and care. Circle of influence of each anode and in turn required distance between each of them is poorly studied over long period of time.

- The inter-relation of repair materials and SACP:

The characterization of the electrical properties of cementitious materials has received a little care over a long period of time, and a little consideration has made for the distribution of current through such repairs.

- Correlation between accelerated testing procedures and real life structures

- Criteria of protection and methods of assessment:

The criteria of assessment of cathodic protection of steel in concrete still yet not well established from the theoretical perspective and the practice point of view. Potential decay jointly with absolute potential measurements are the promising technique but a big debate on the theoretical basis of these techniques and the most appropriate monitoring equipment and methods for accurate measurement.

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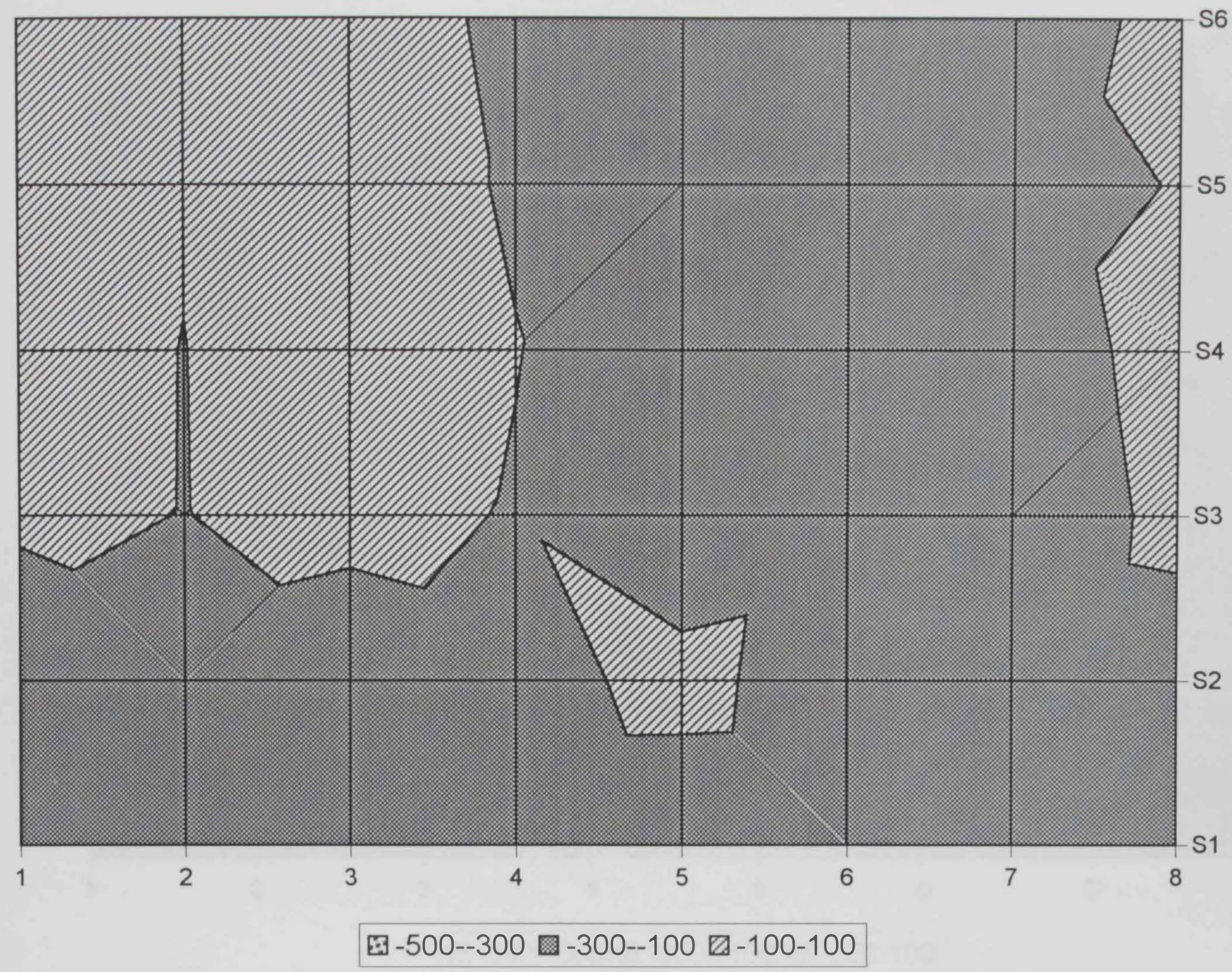
Appendix A

C1- 6/4



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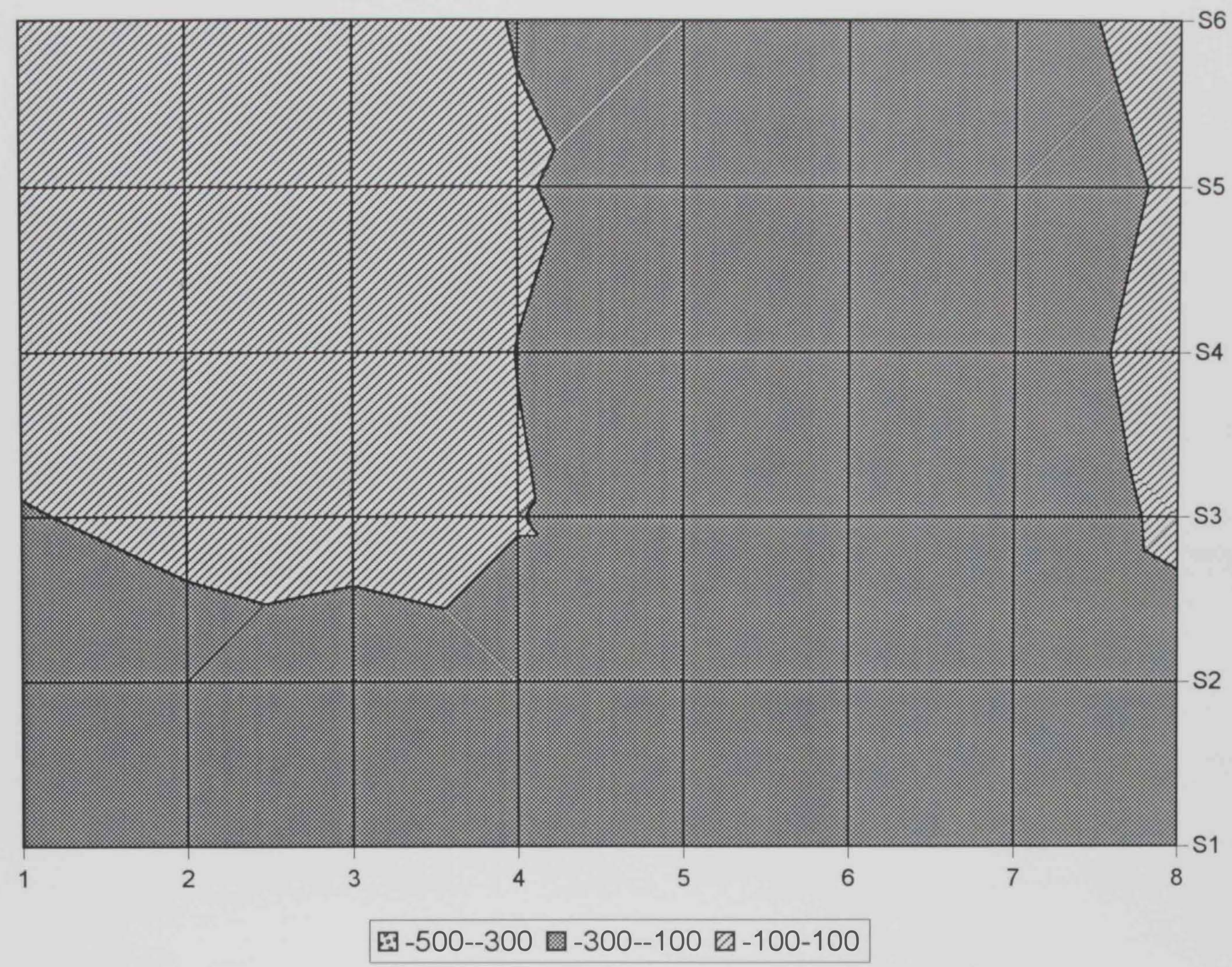

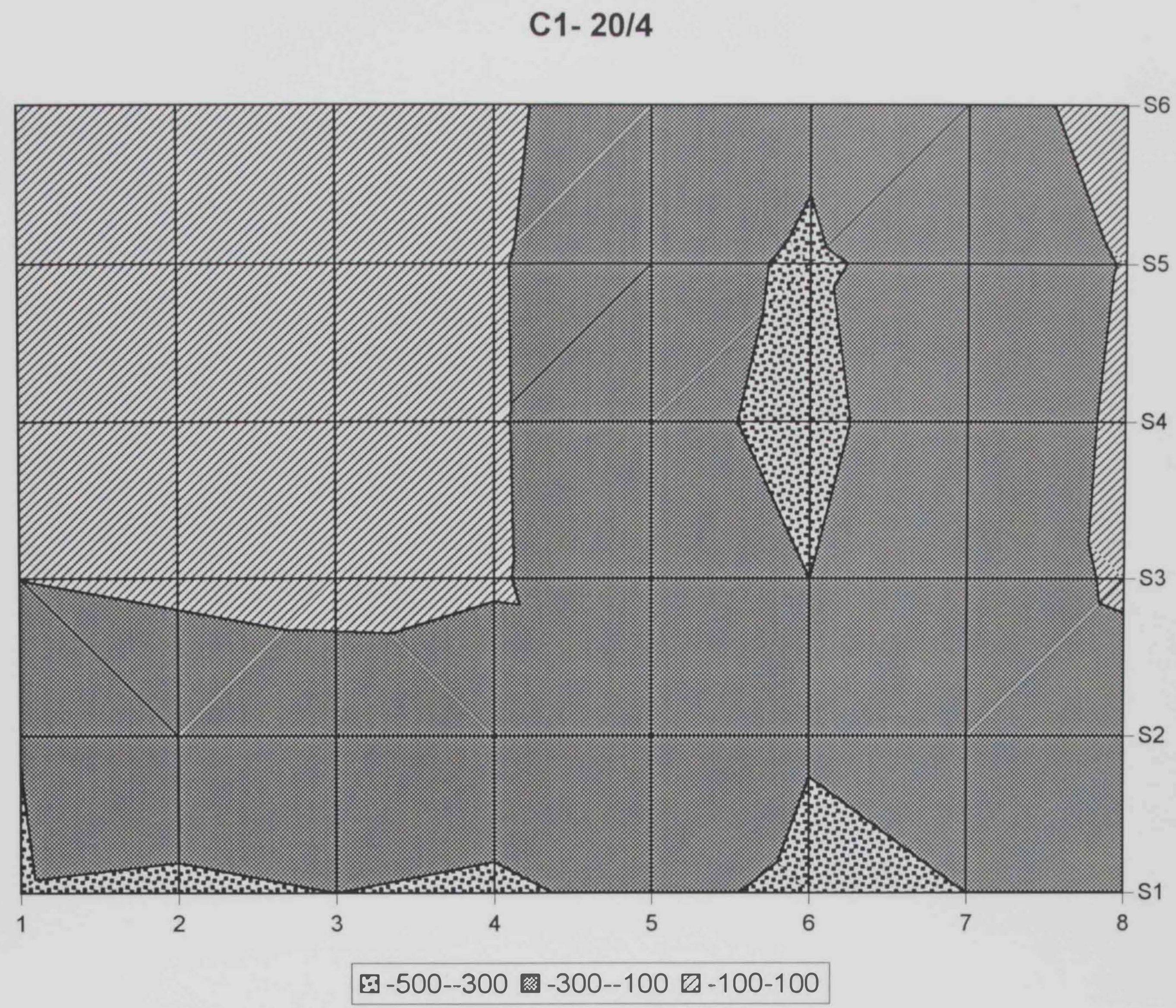
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S6
S5
S4
S3
S2
S1
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2
3
4
5
6
7
8
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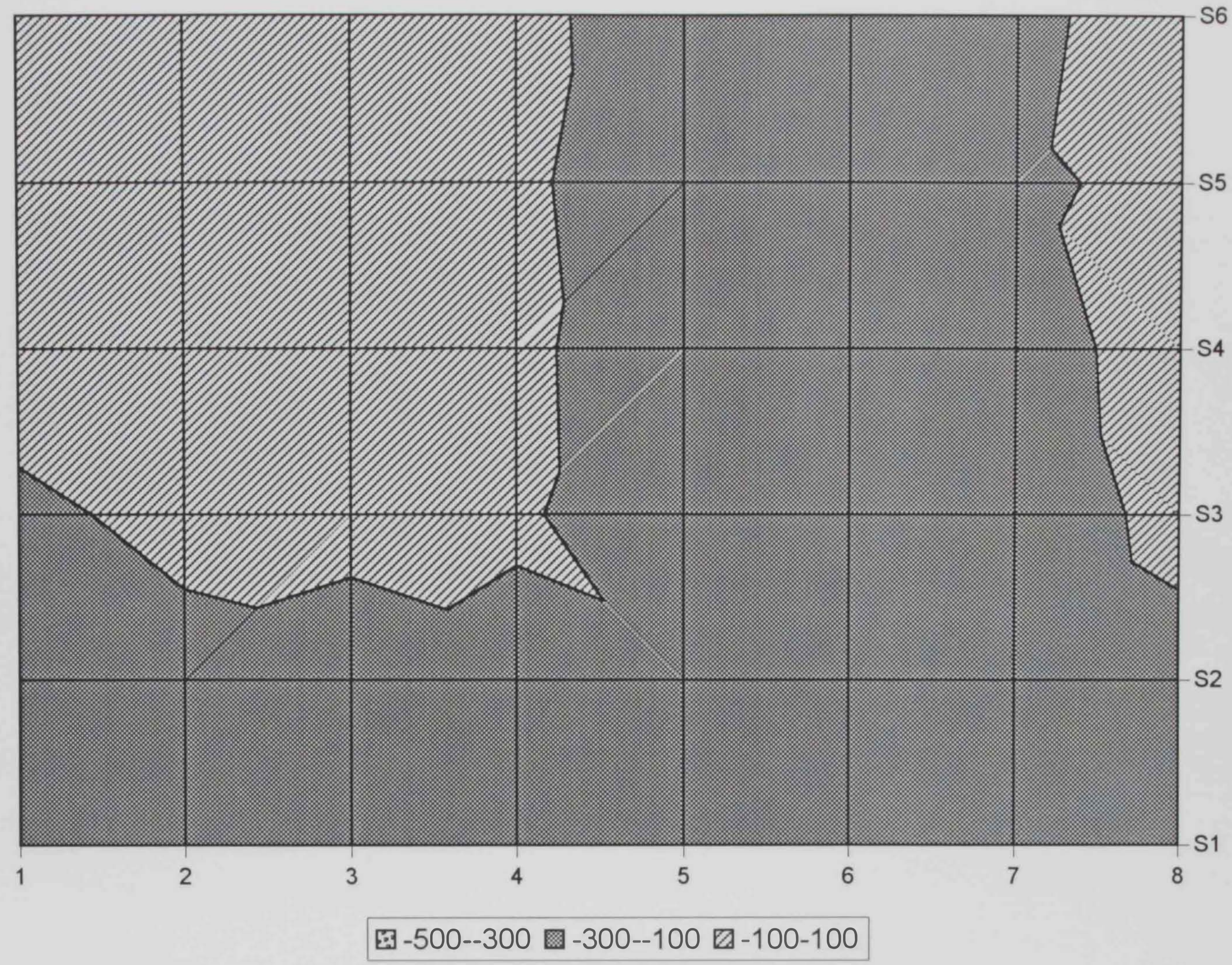
-100-100

C1- 27/4



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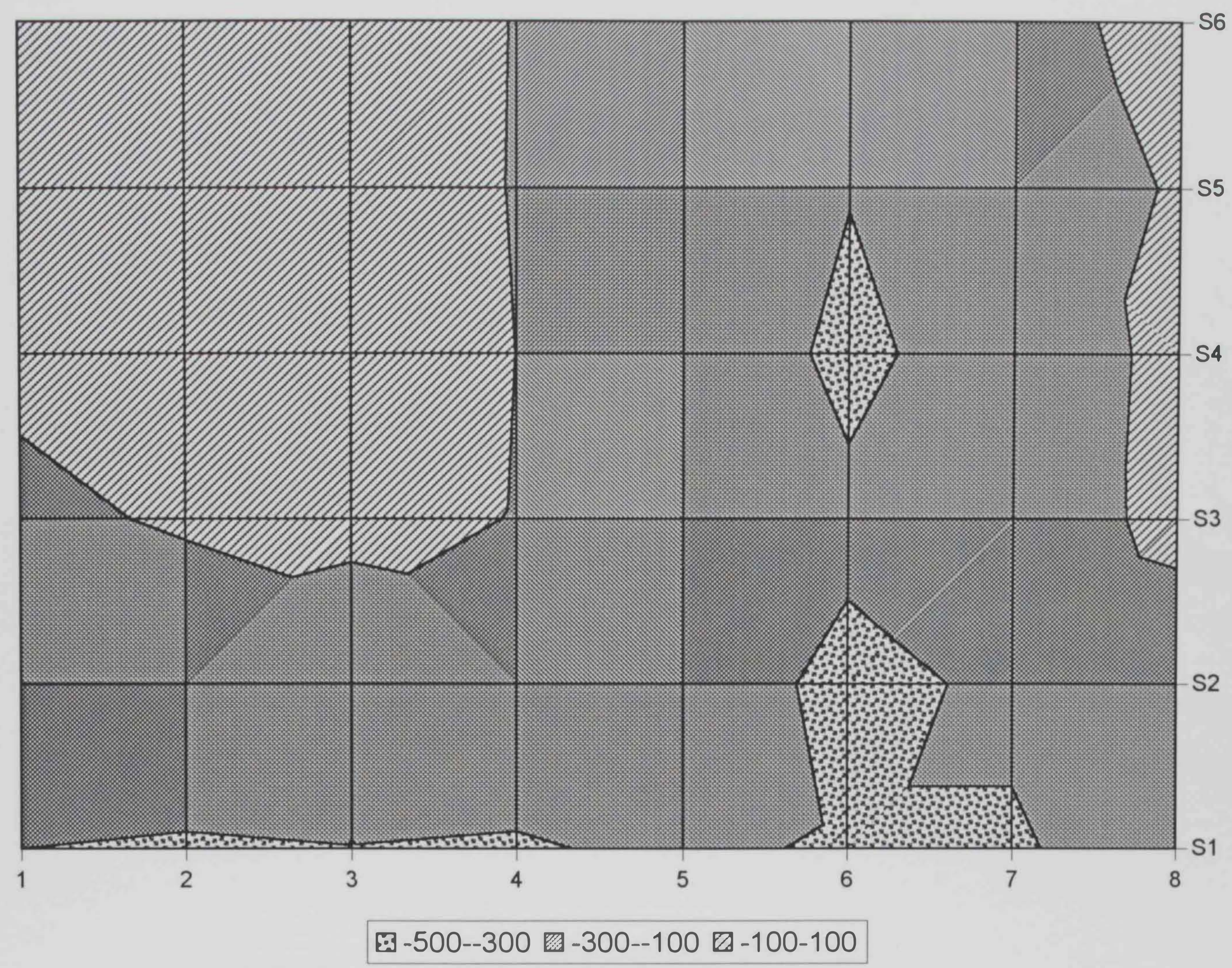

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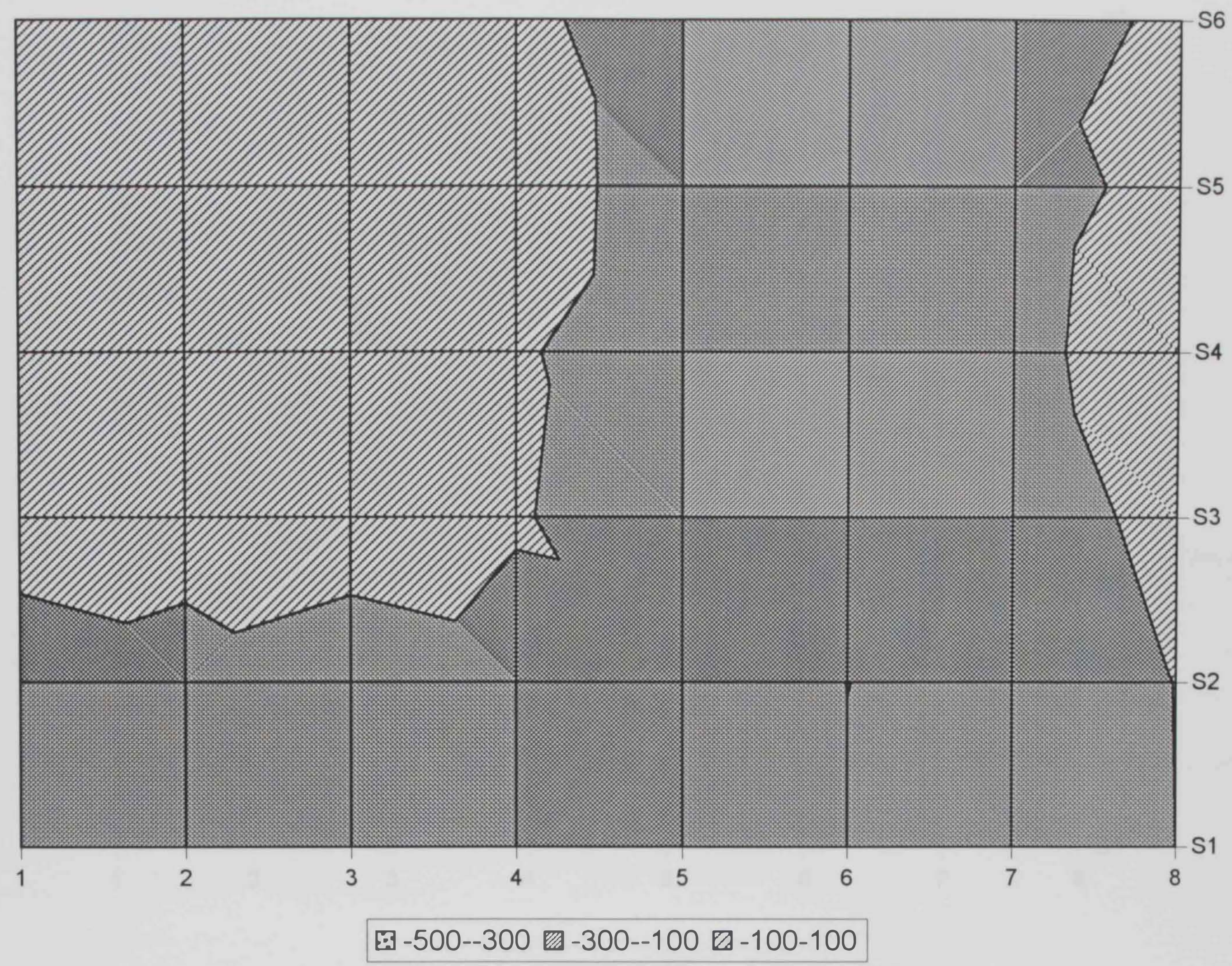

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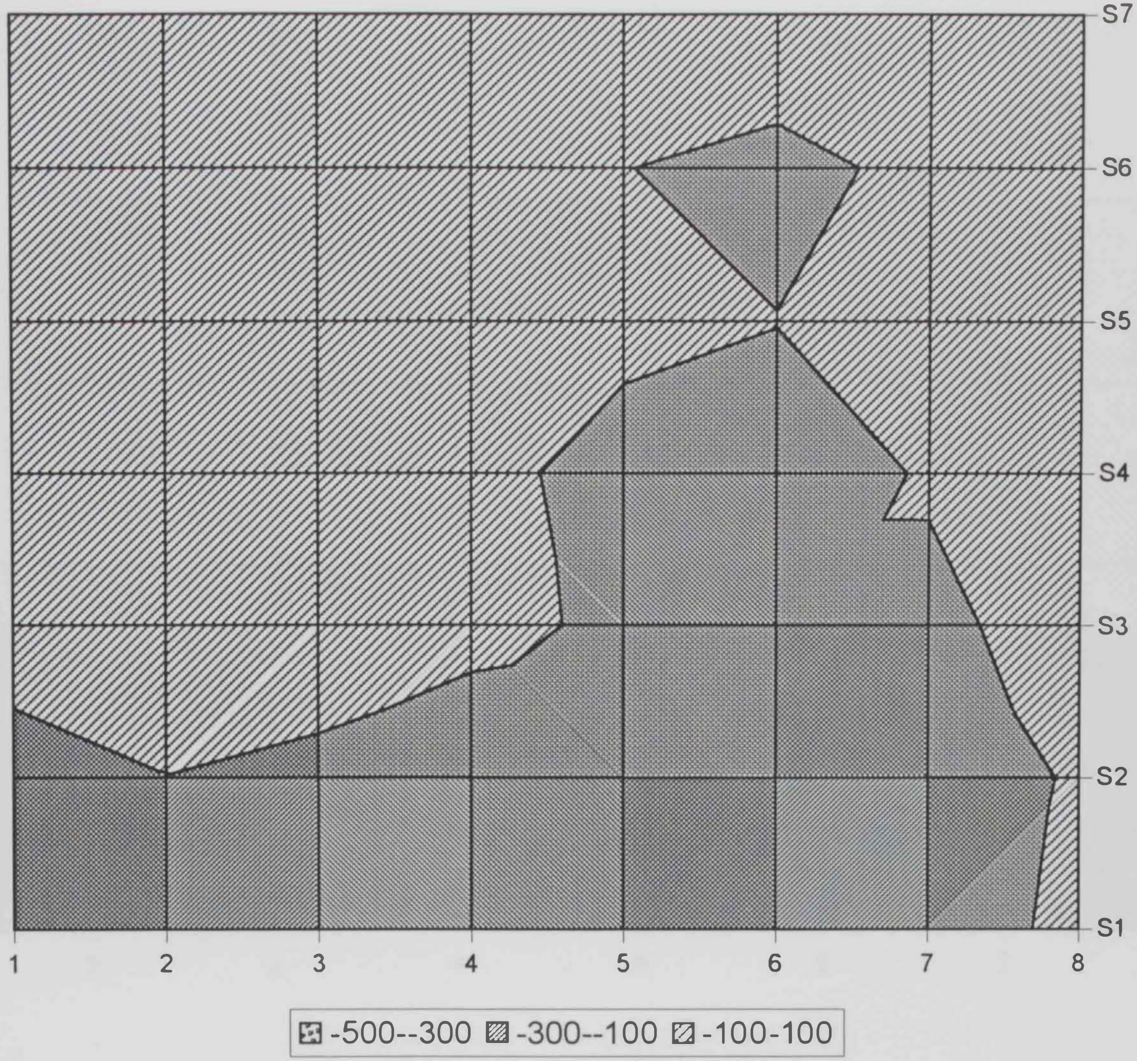

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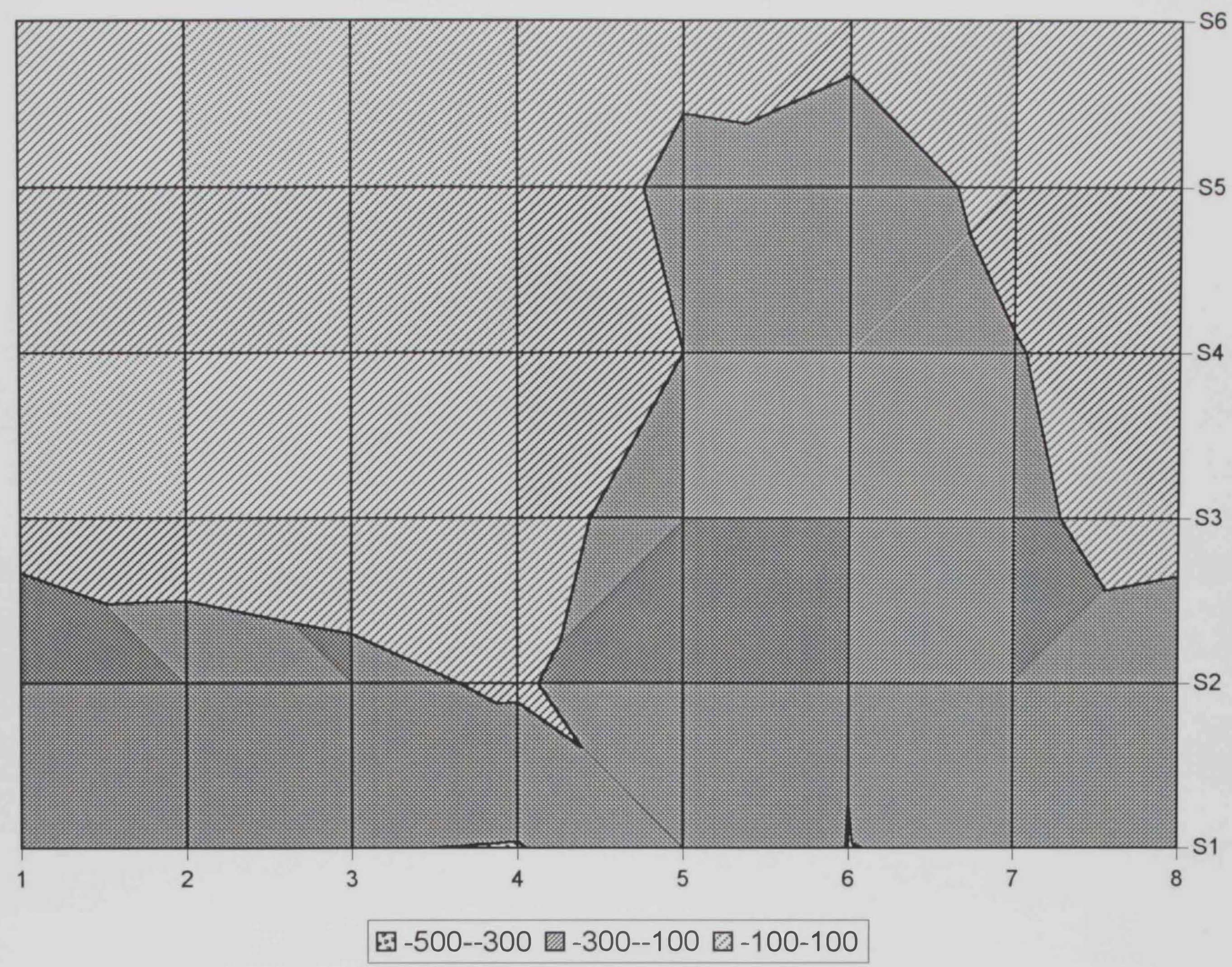

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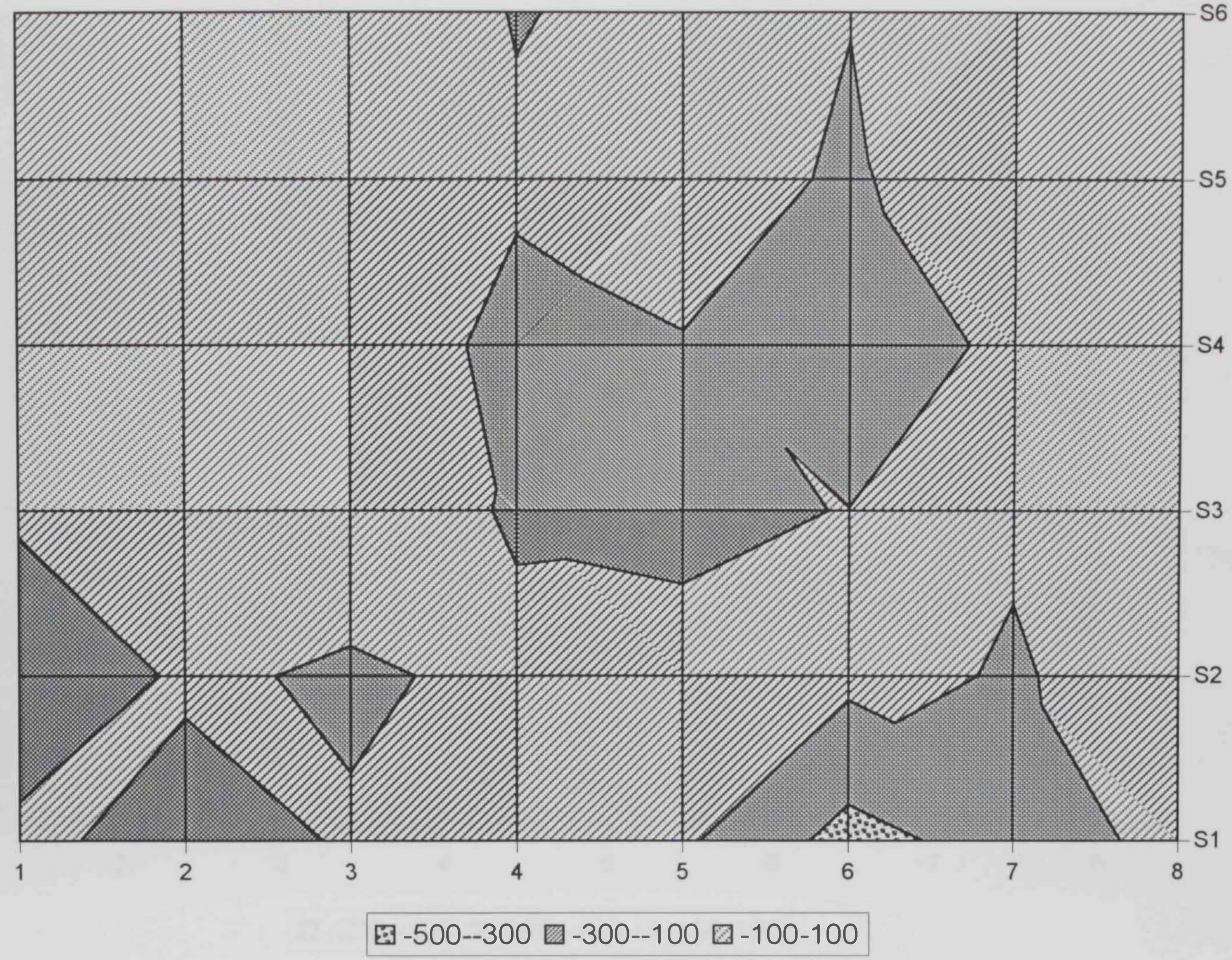

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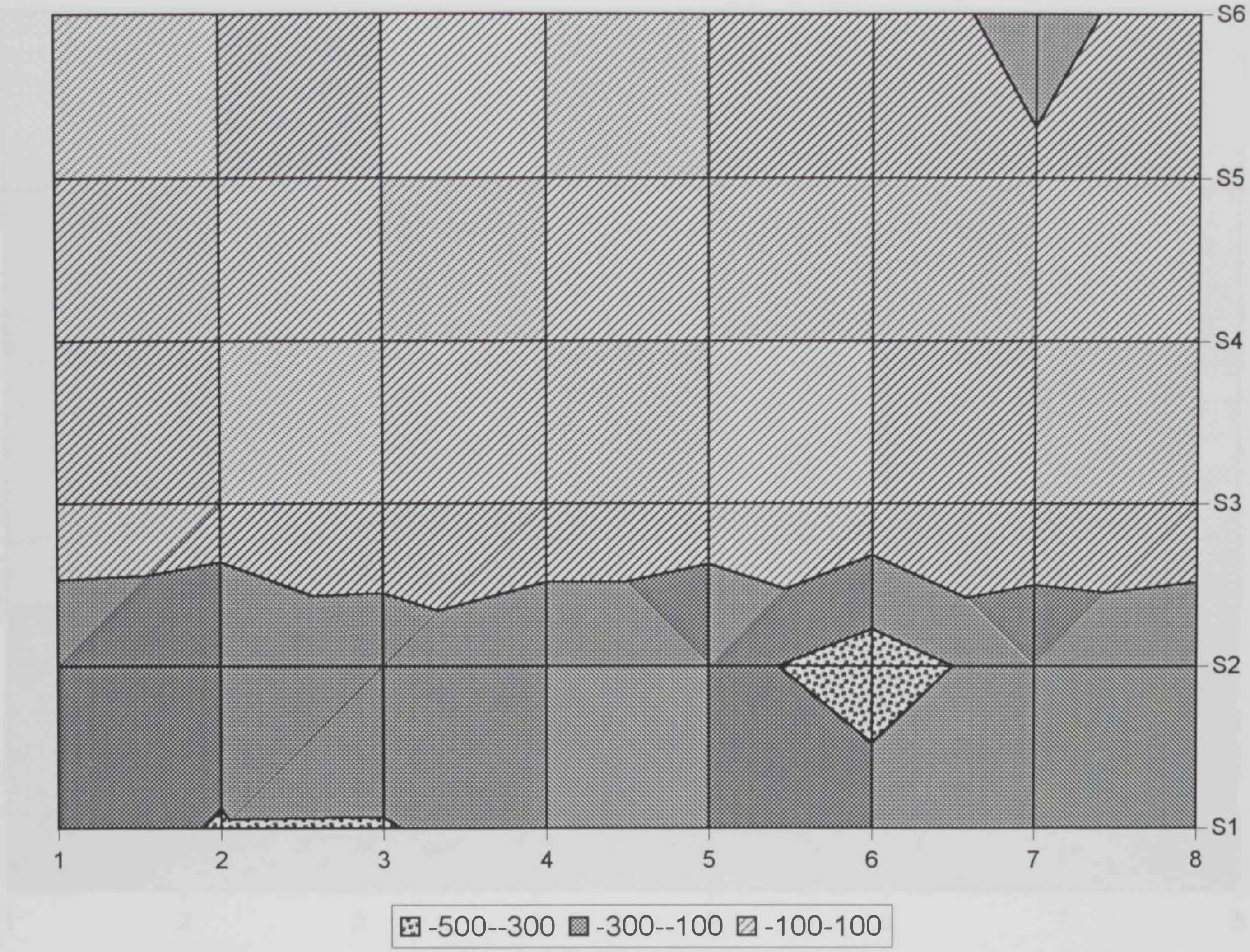

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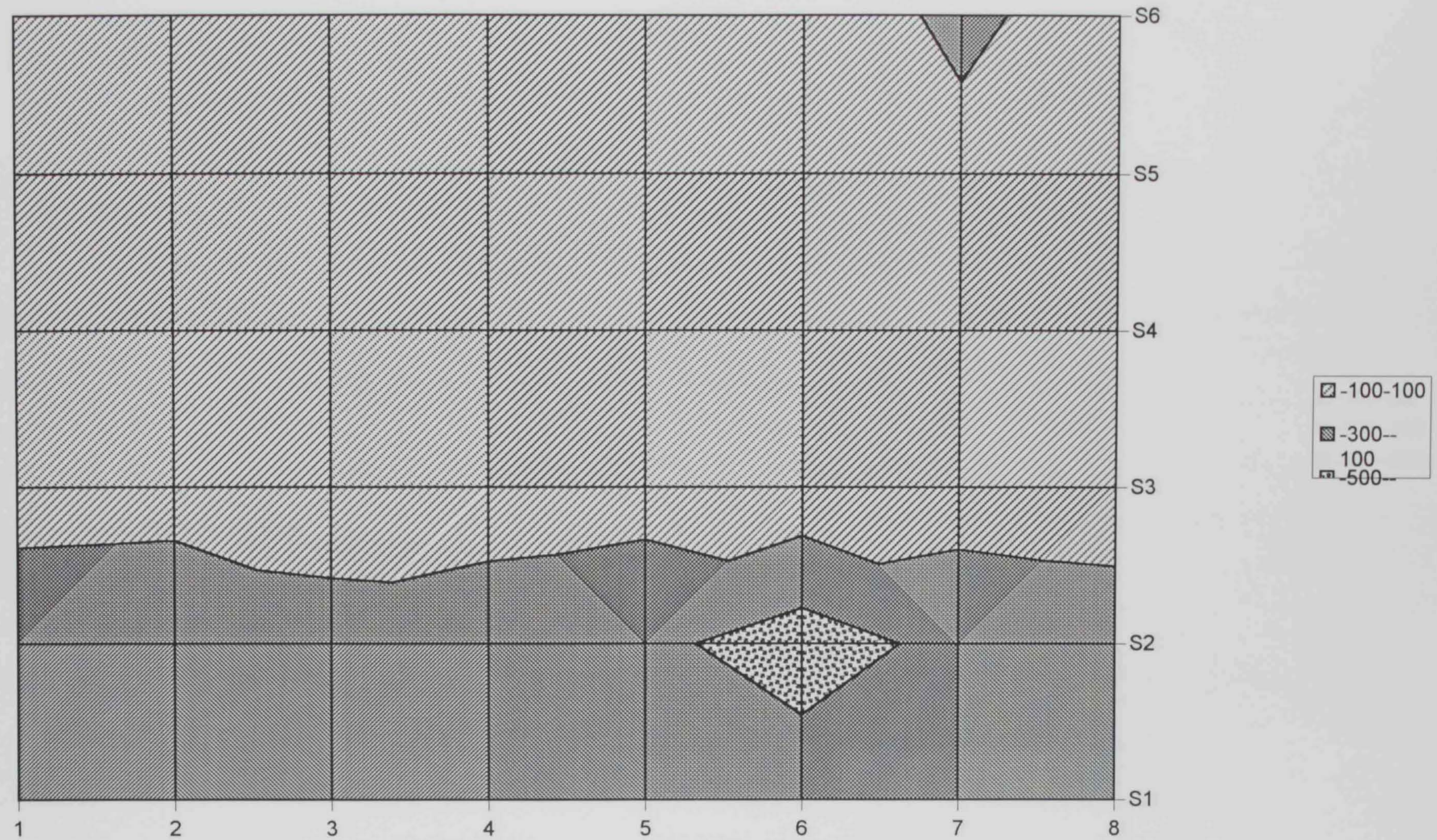

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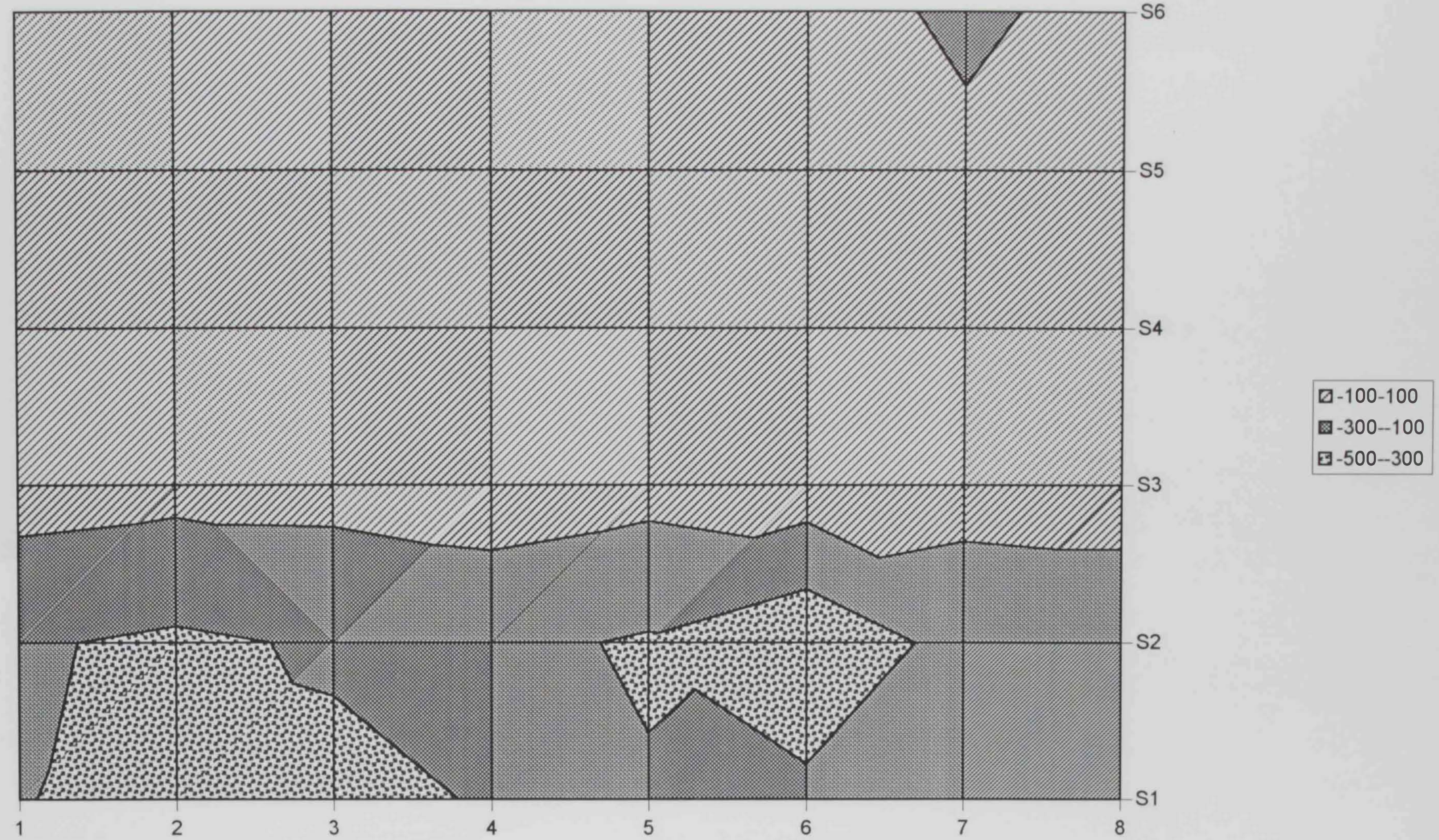

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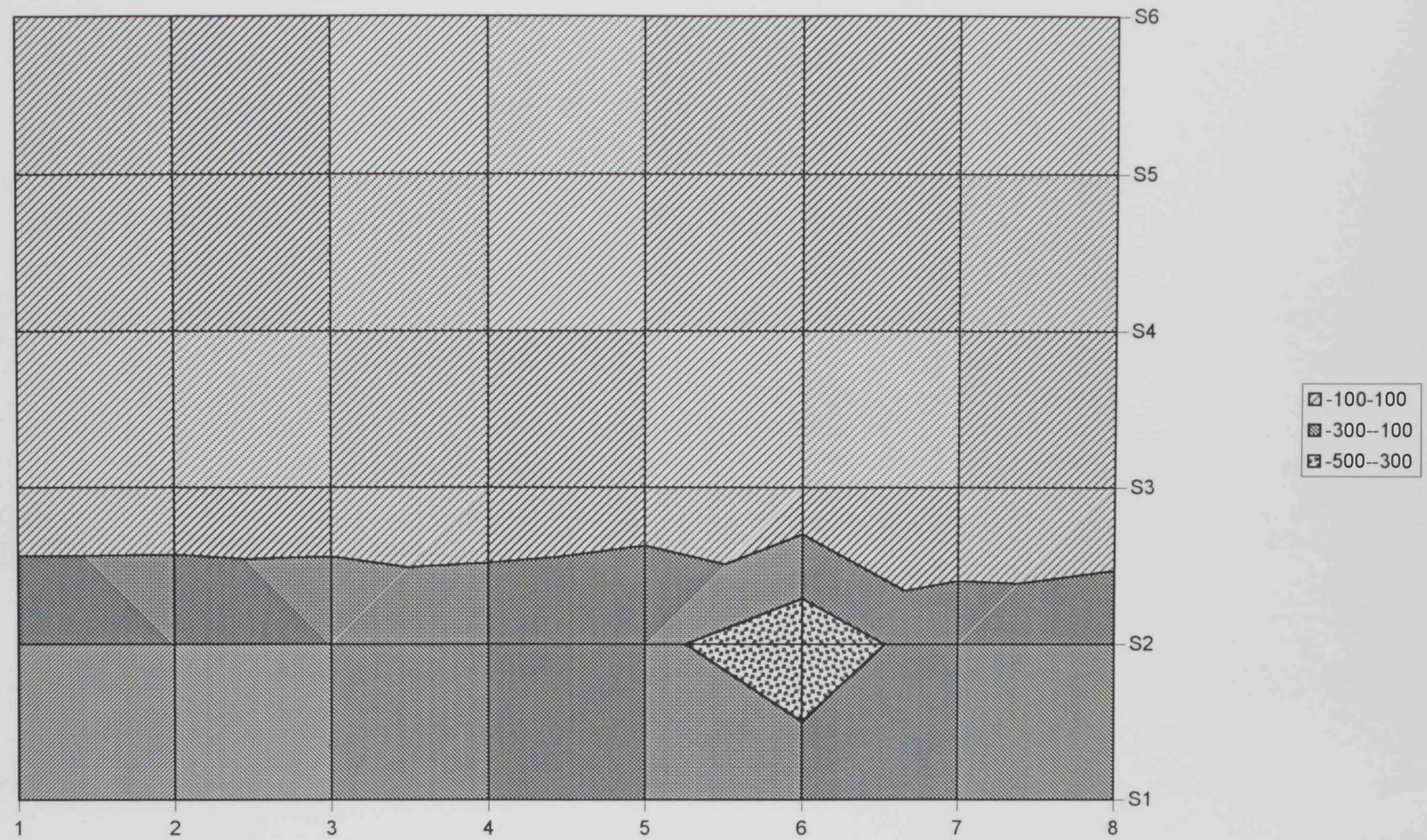

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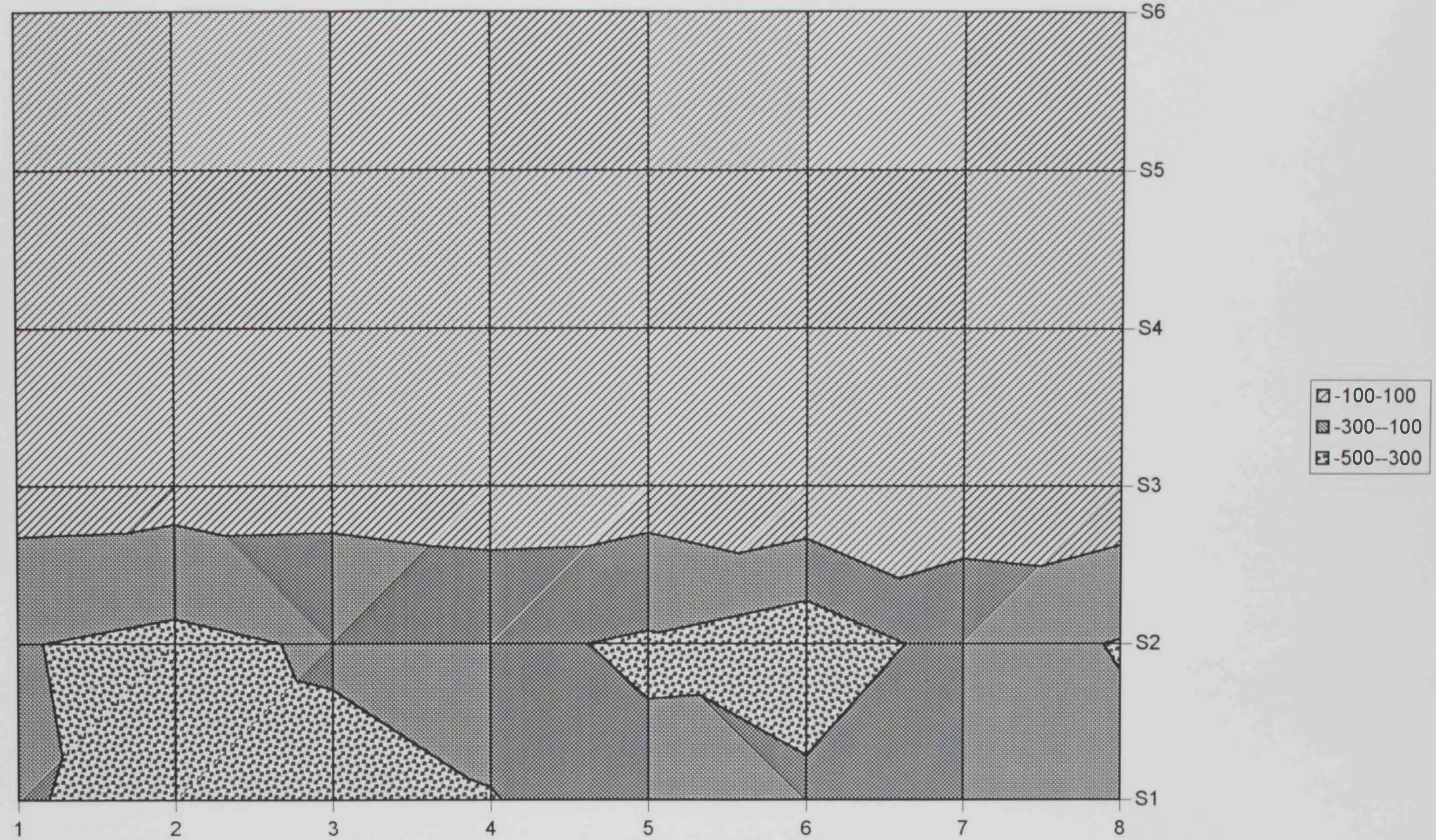

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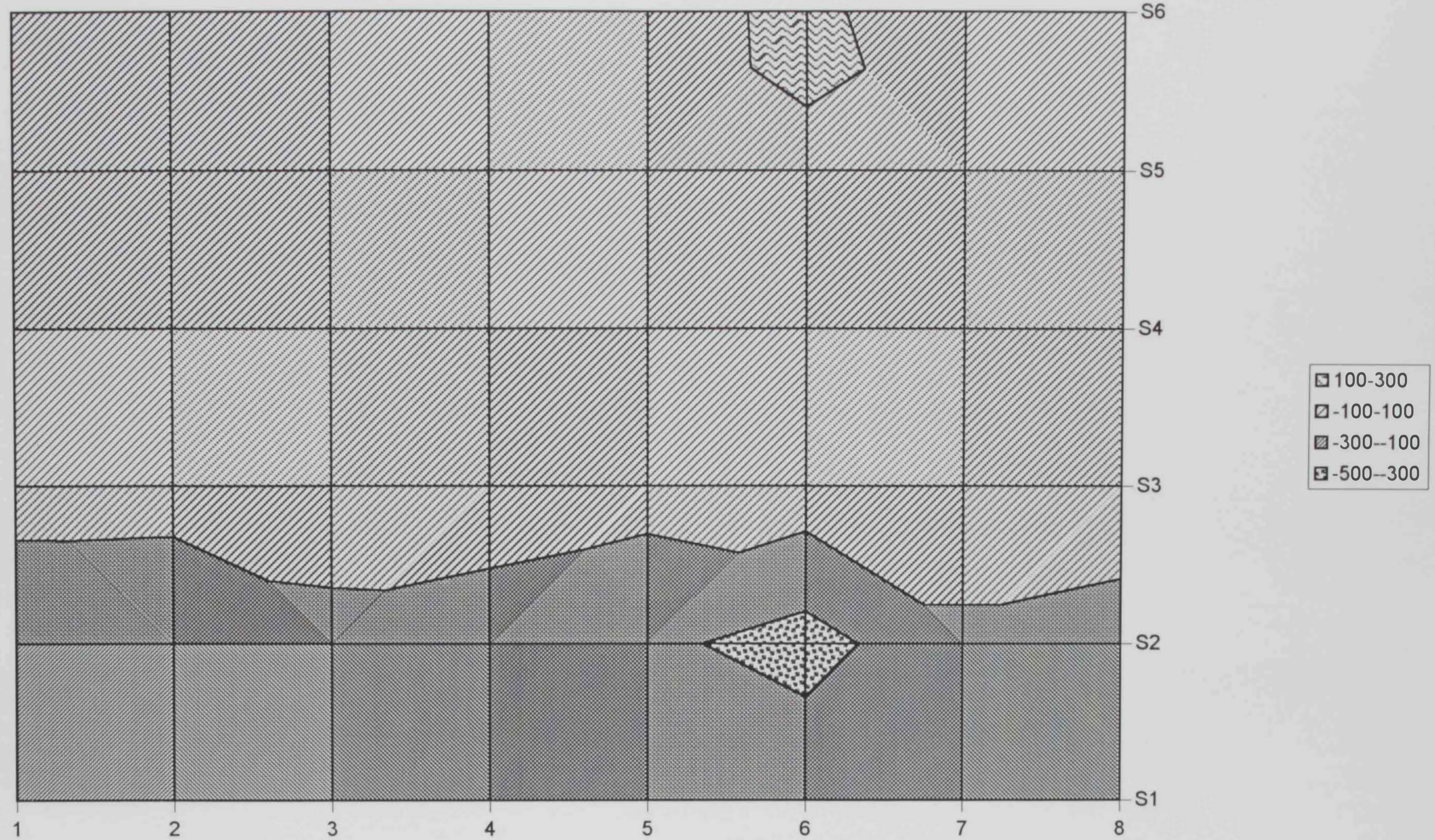

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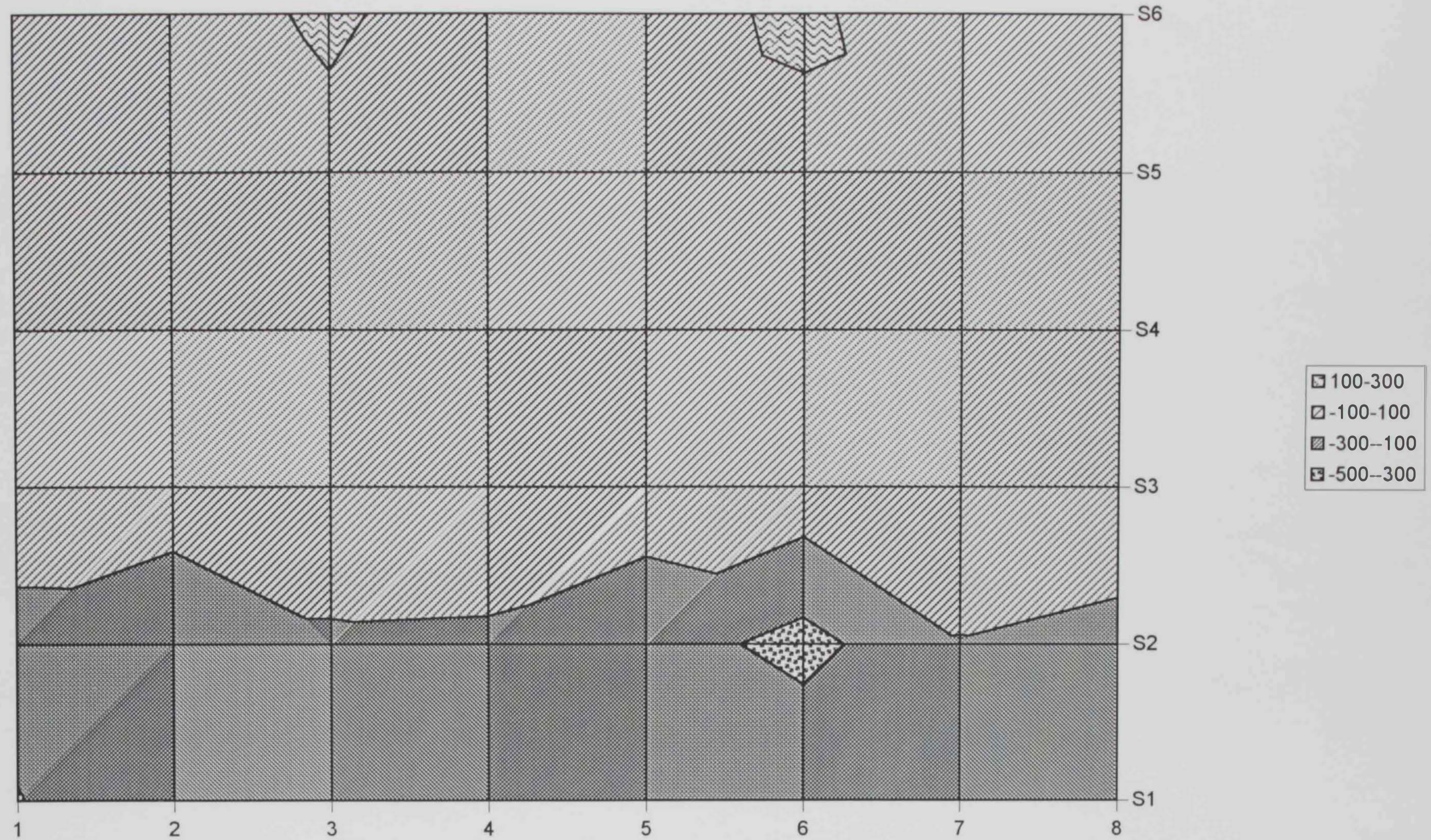

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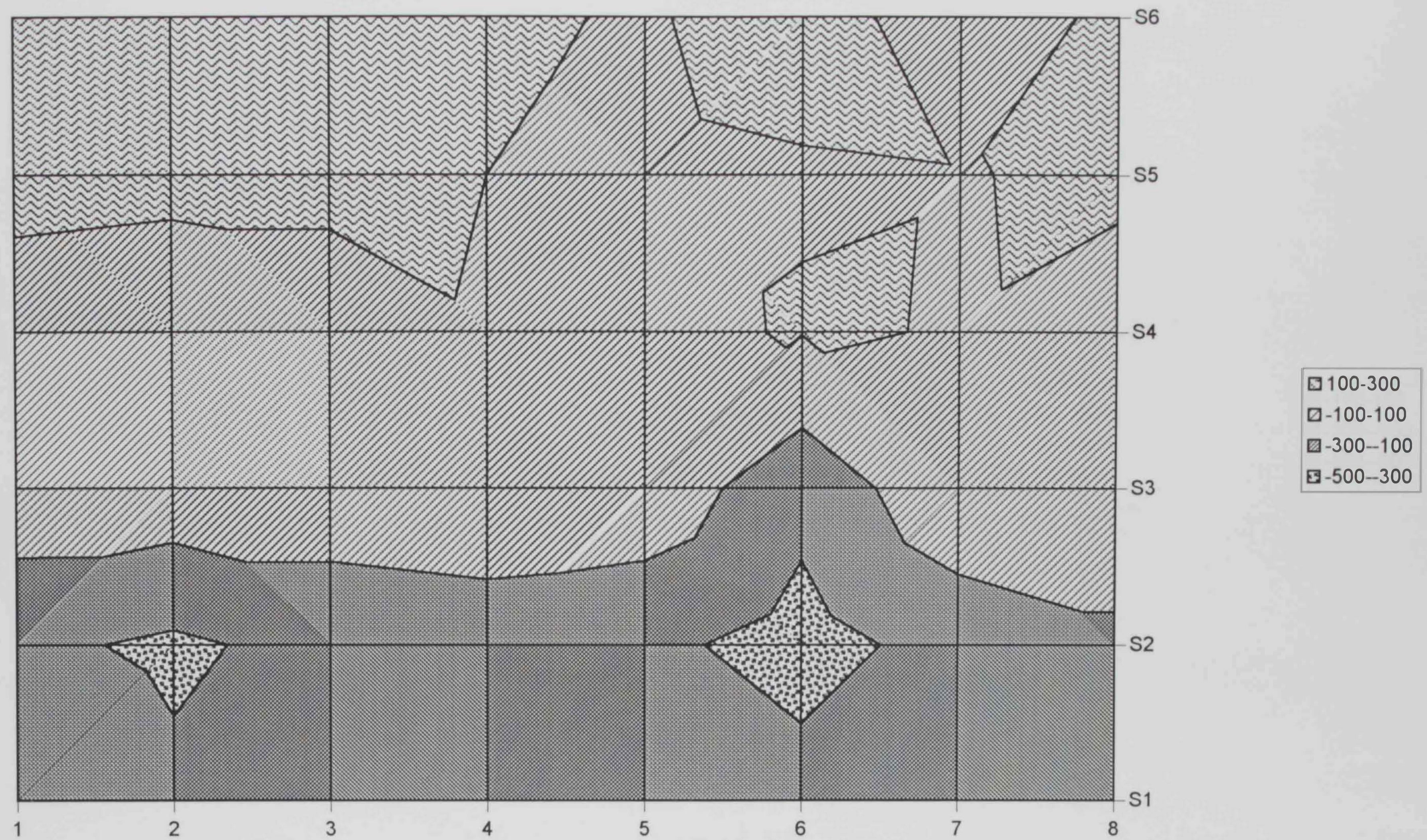

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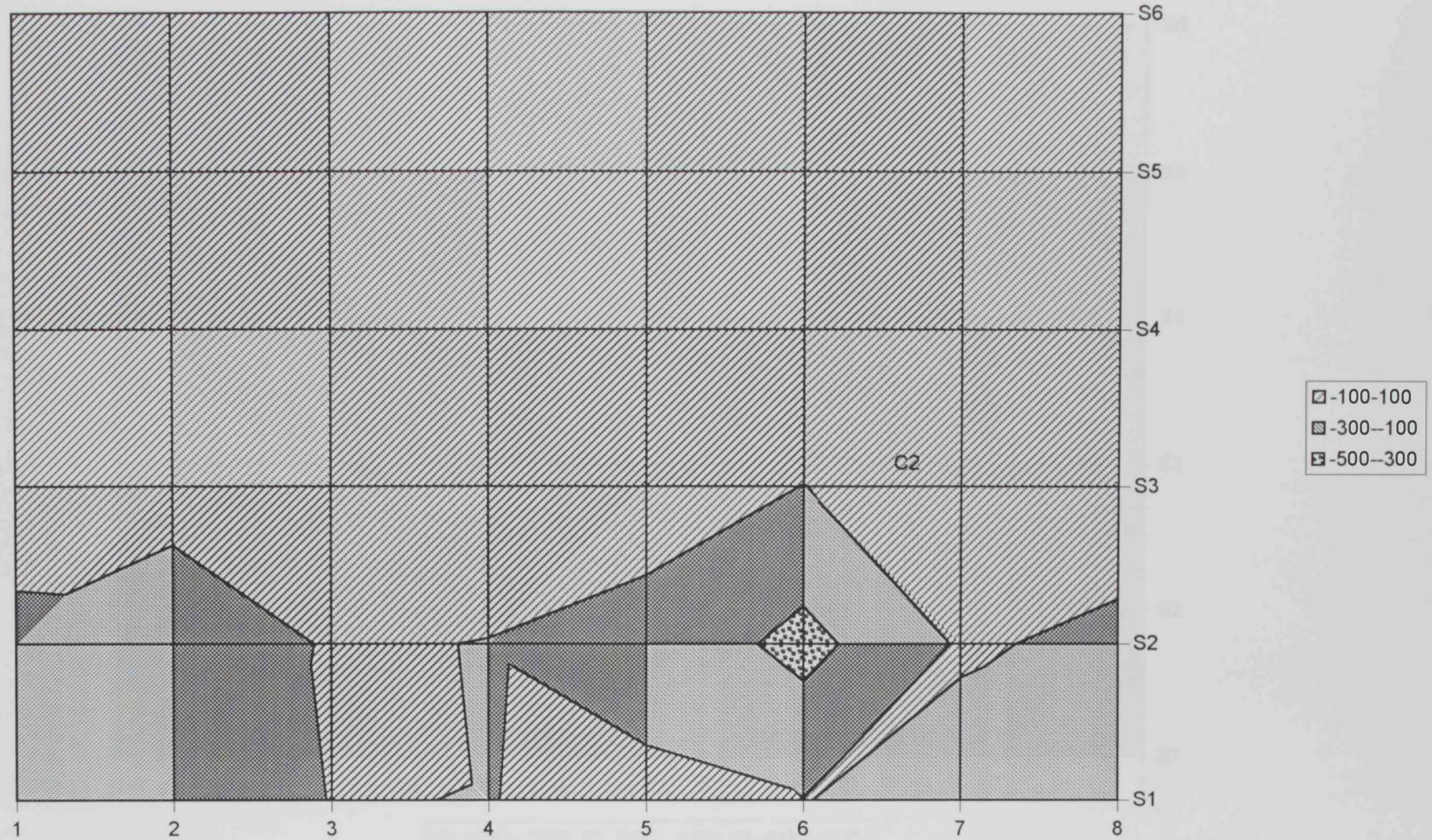

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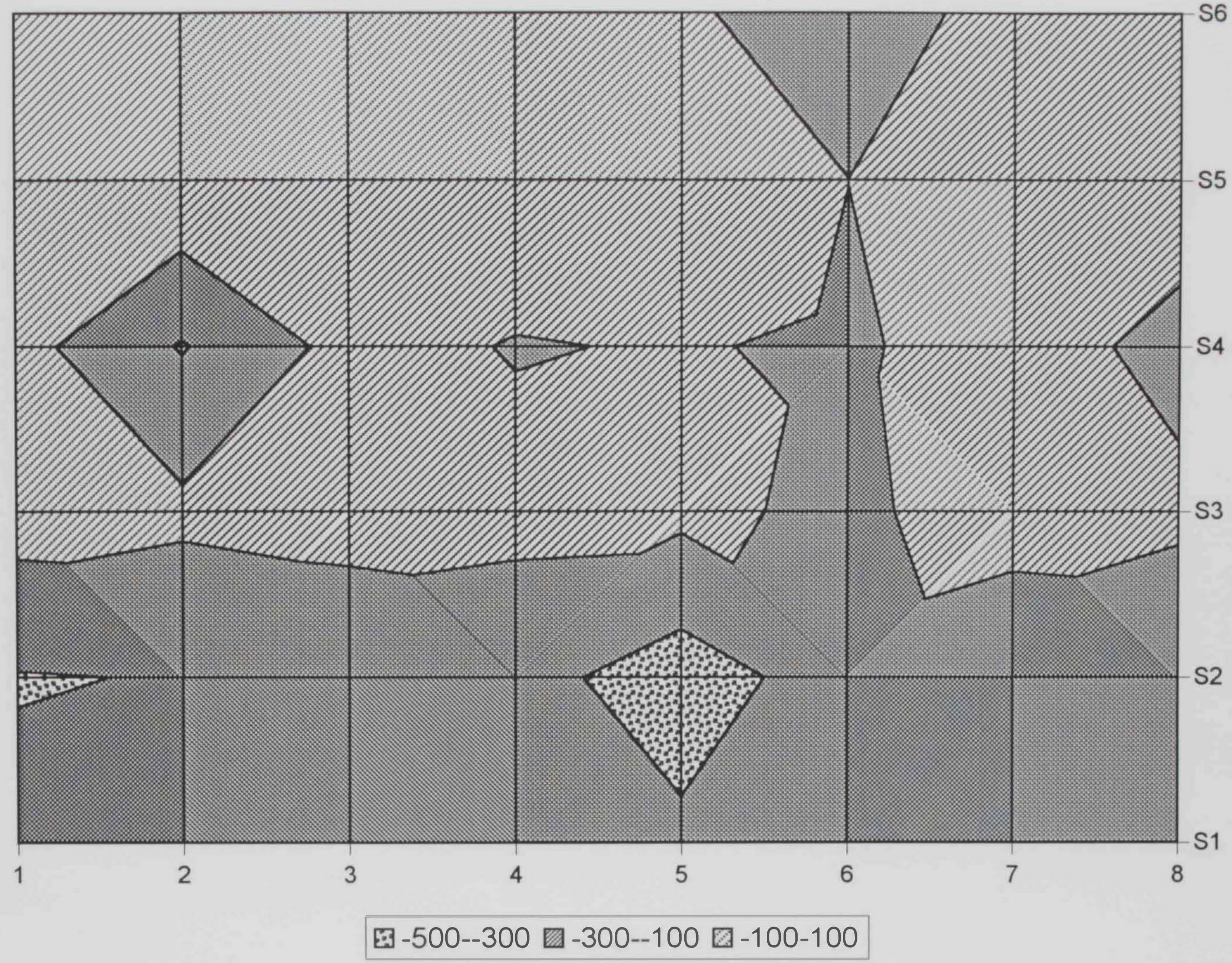

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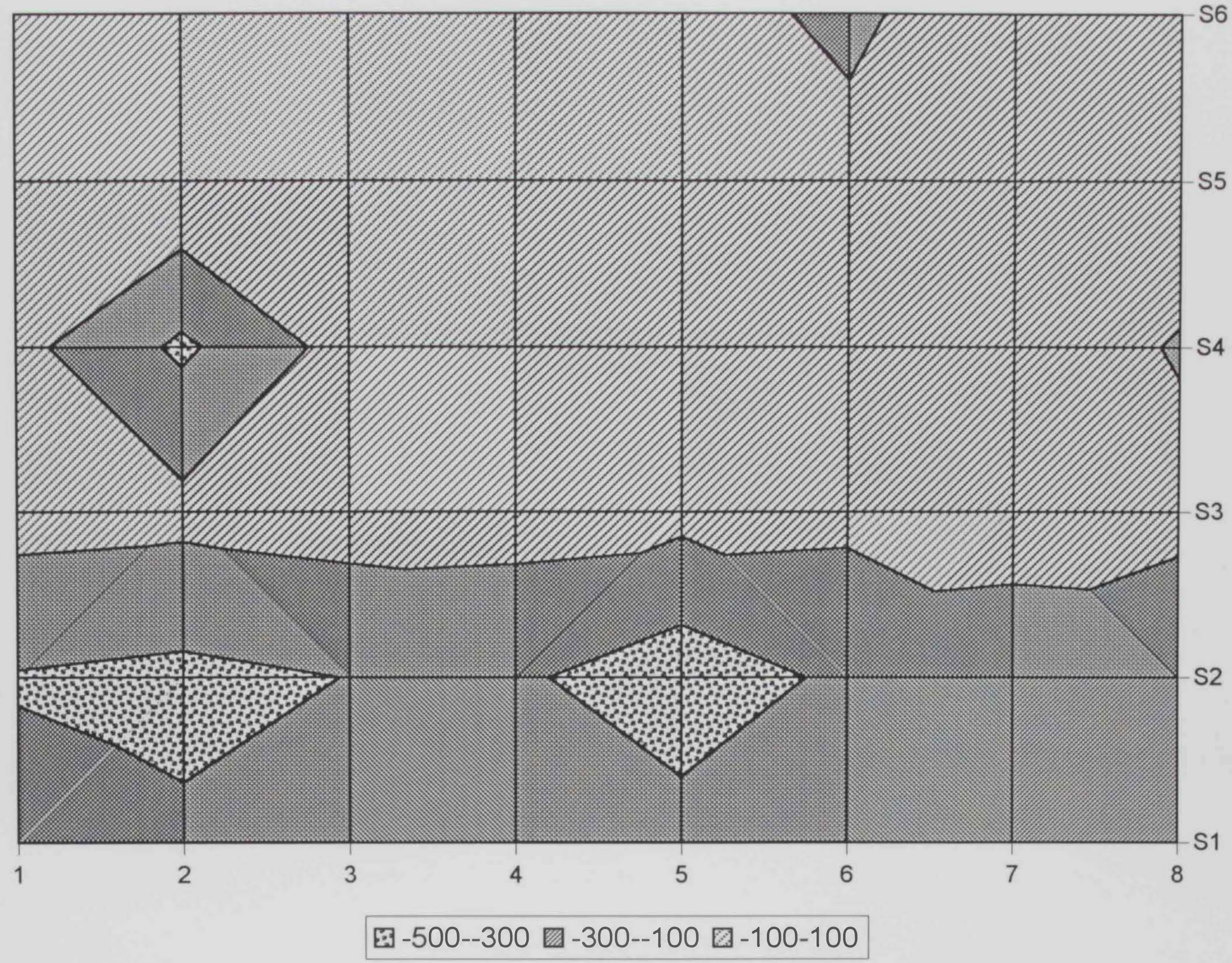

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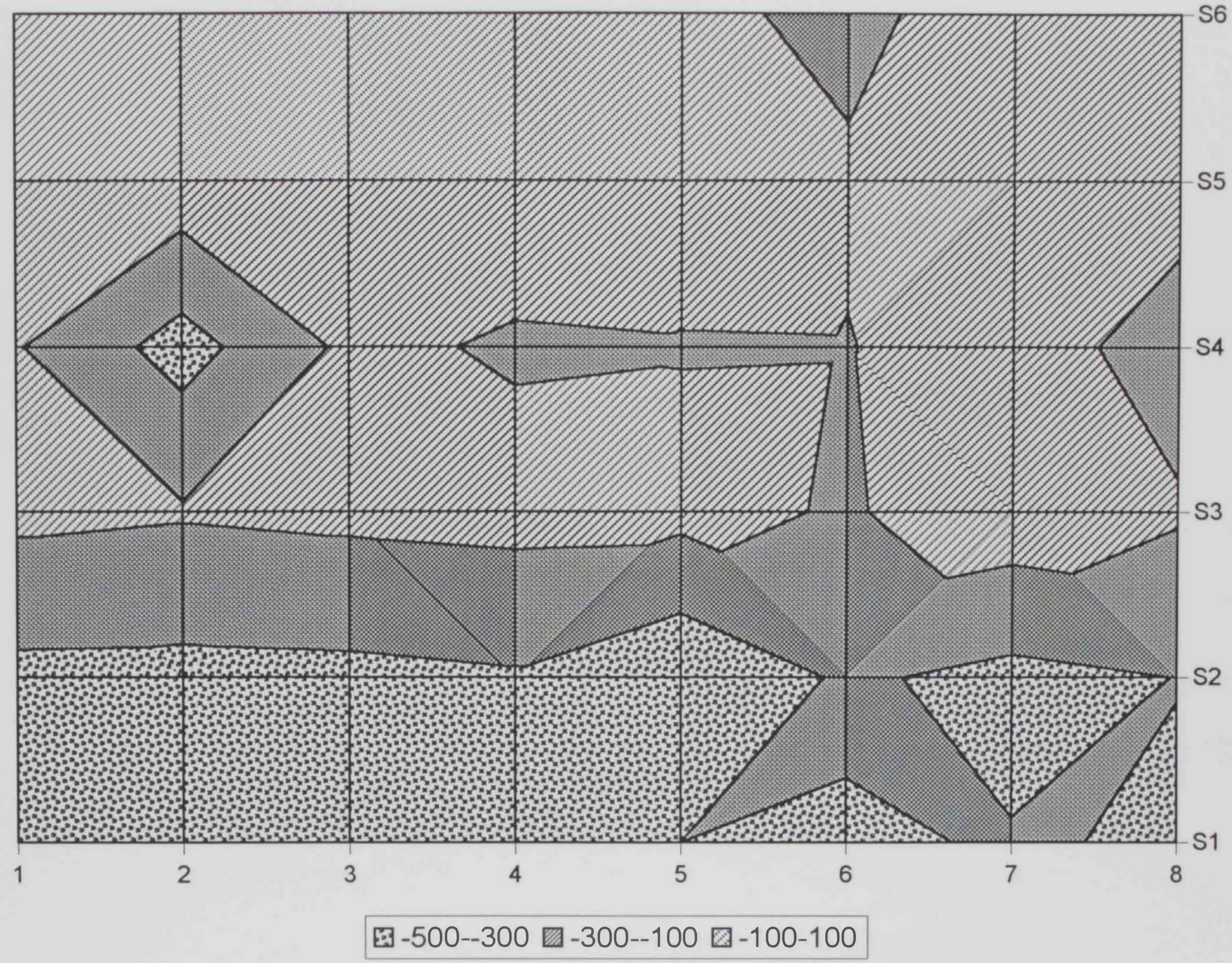

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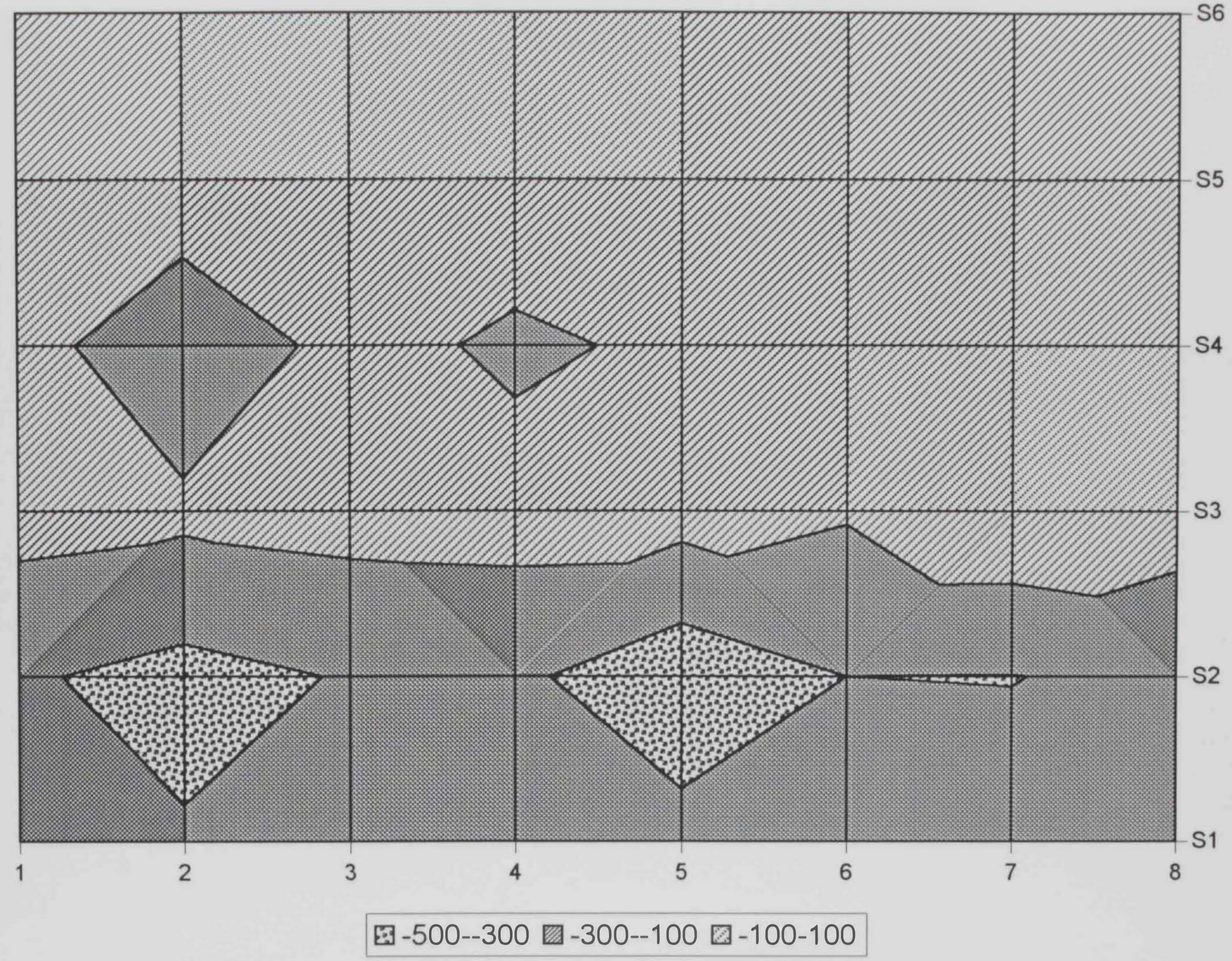

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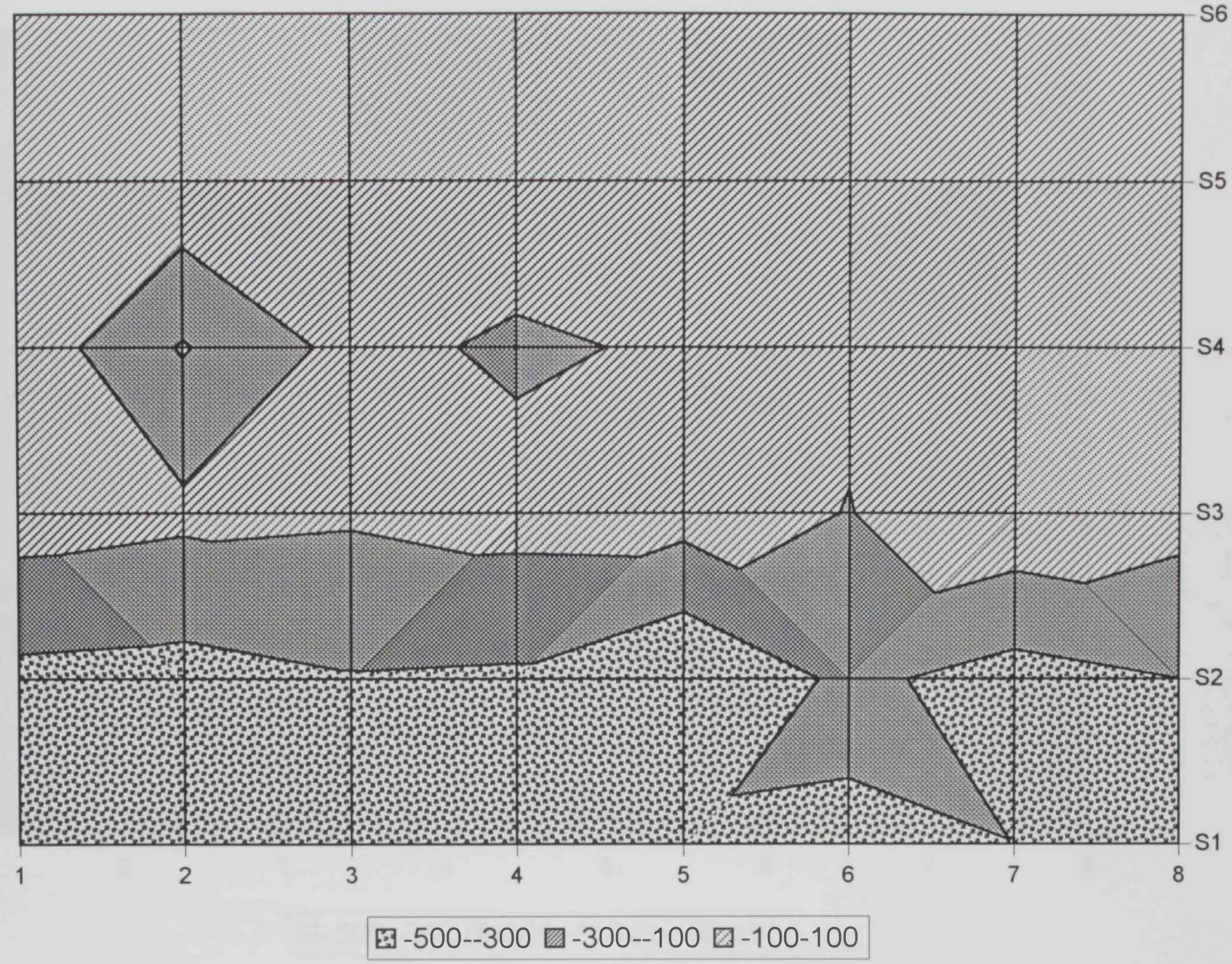

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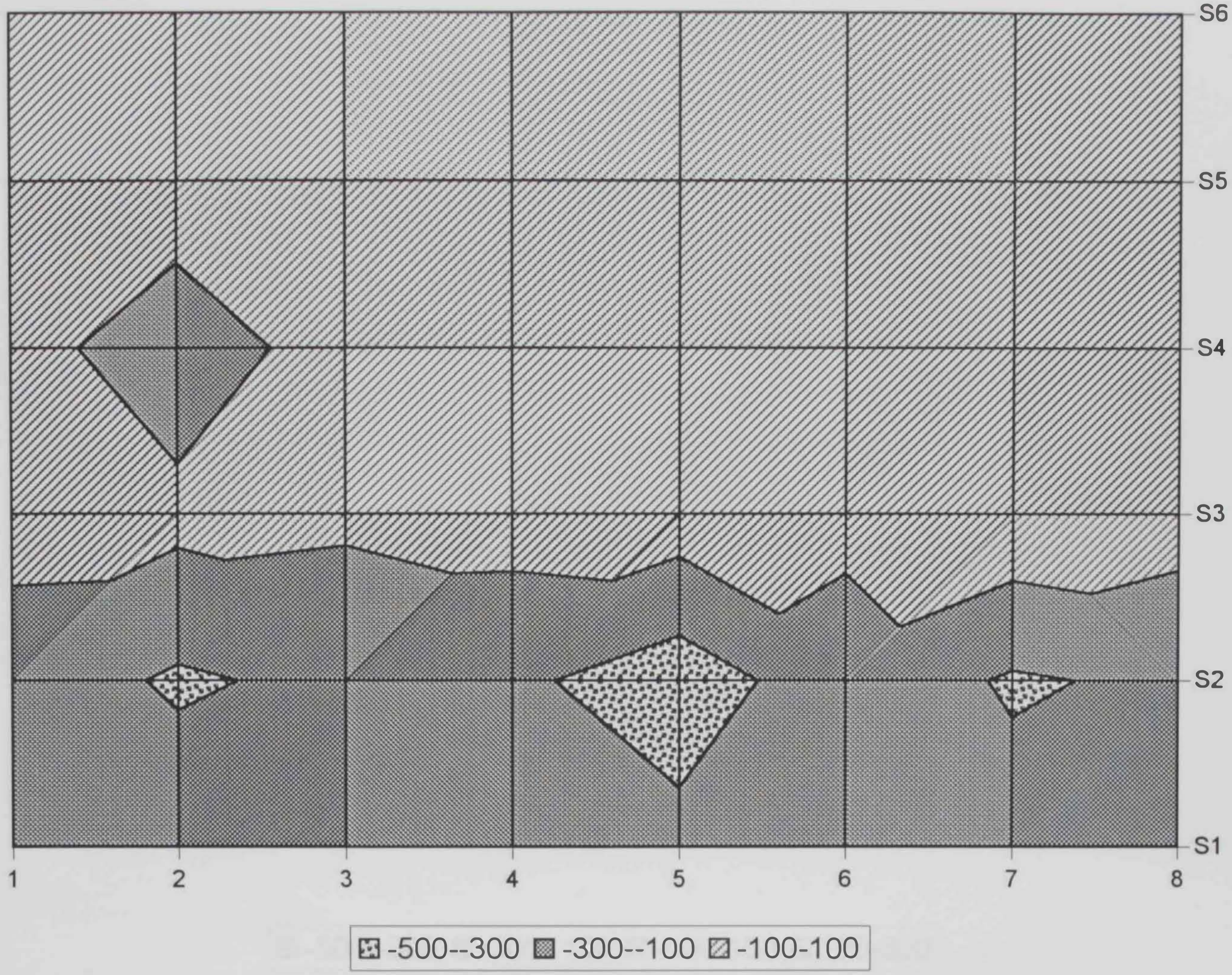

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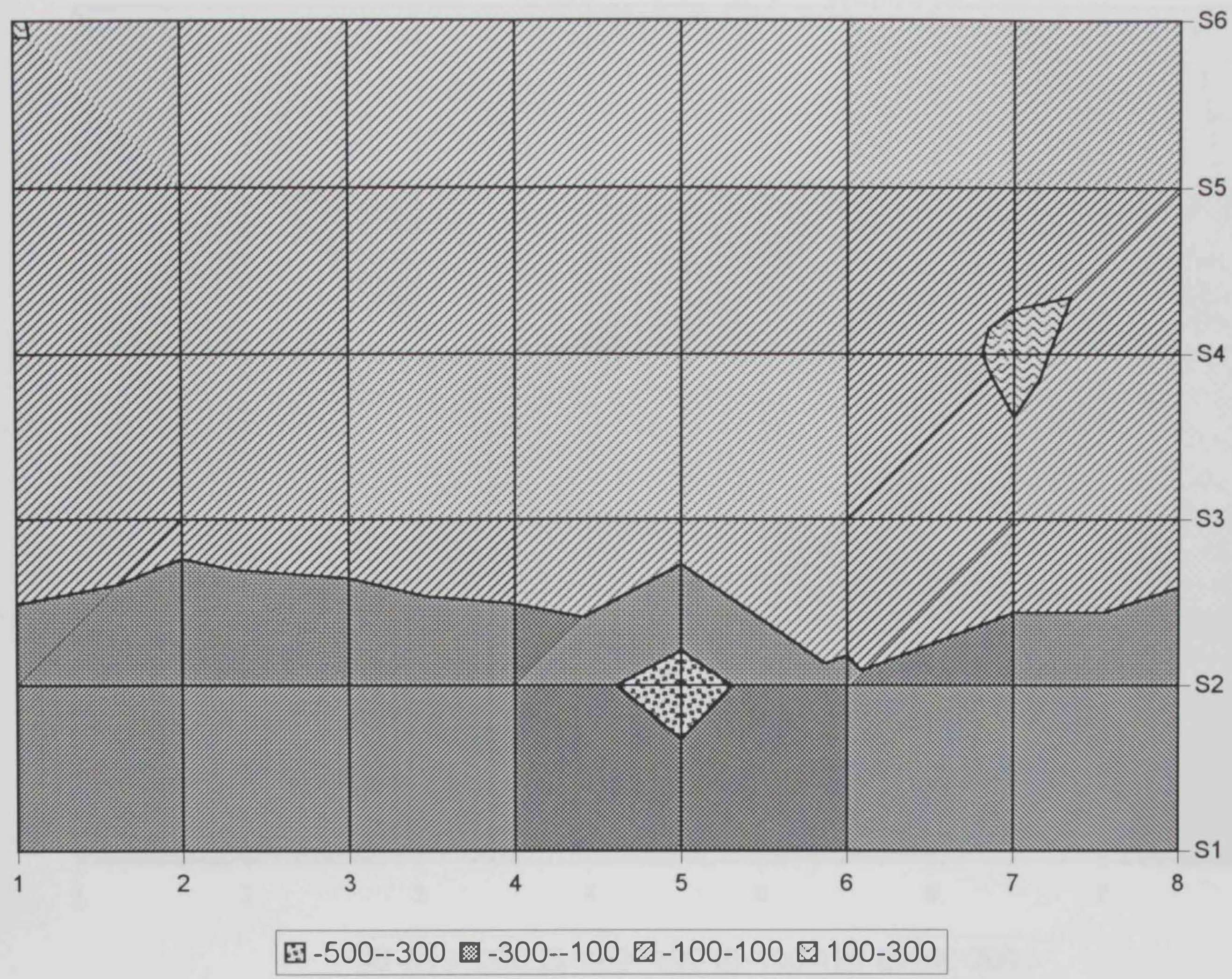

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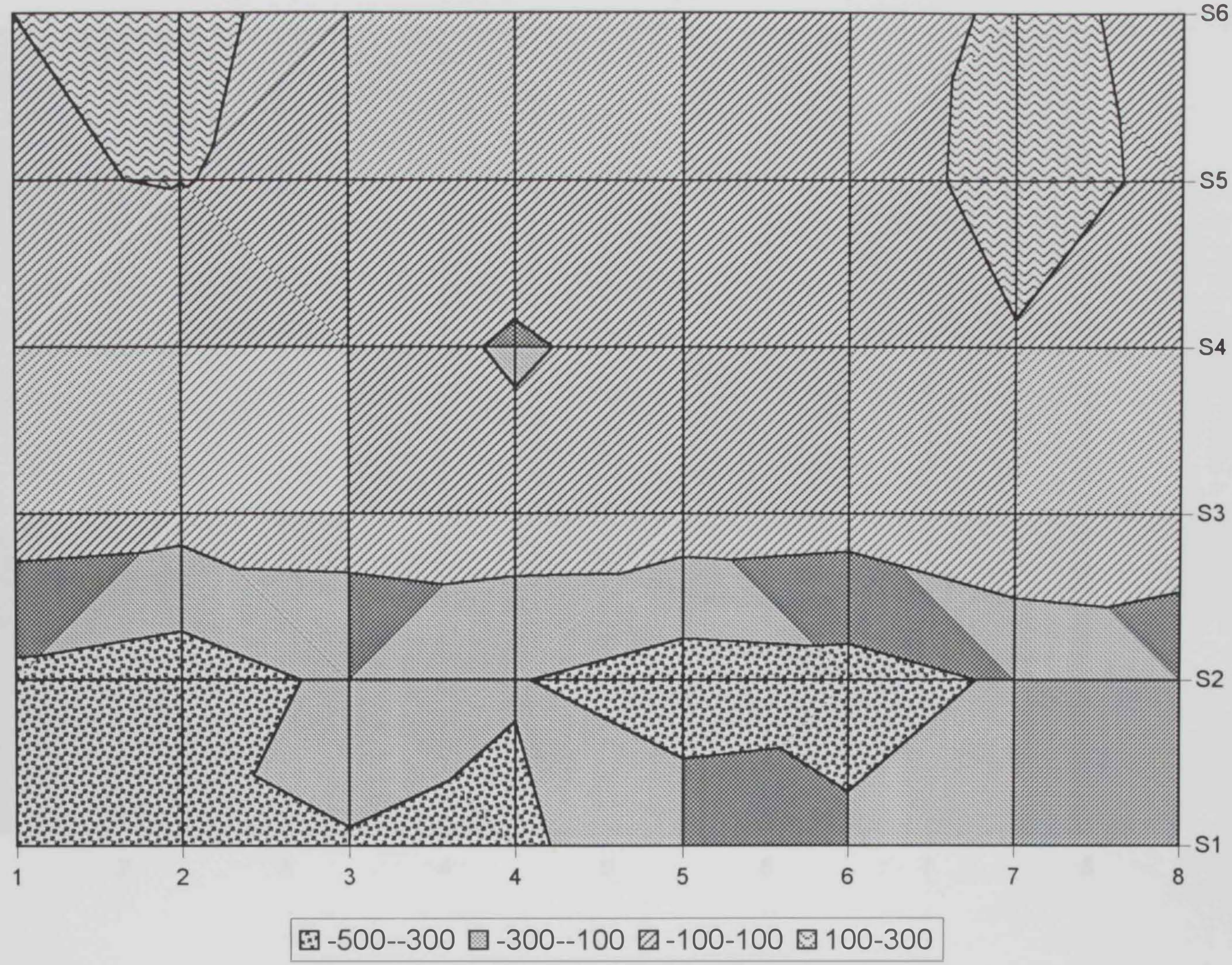

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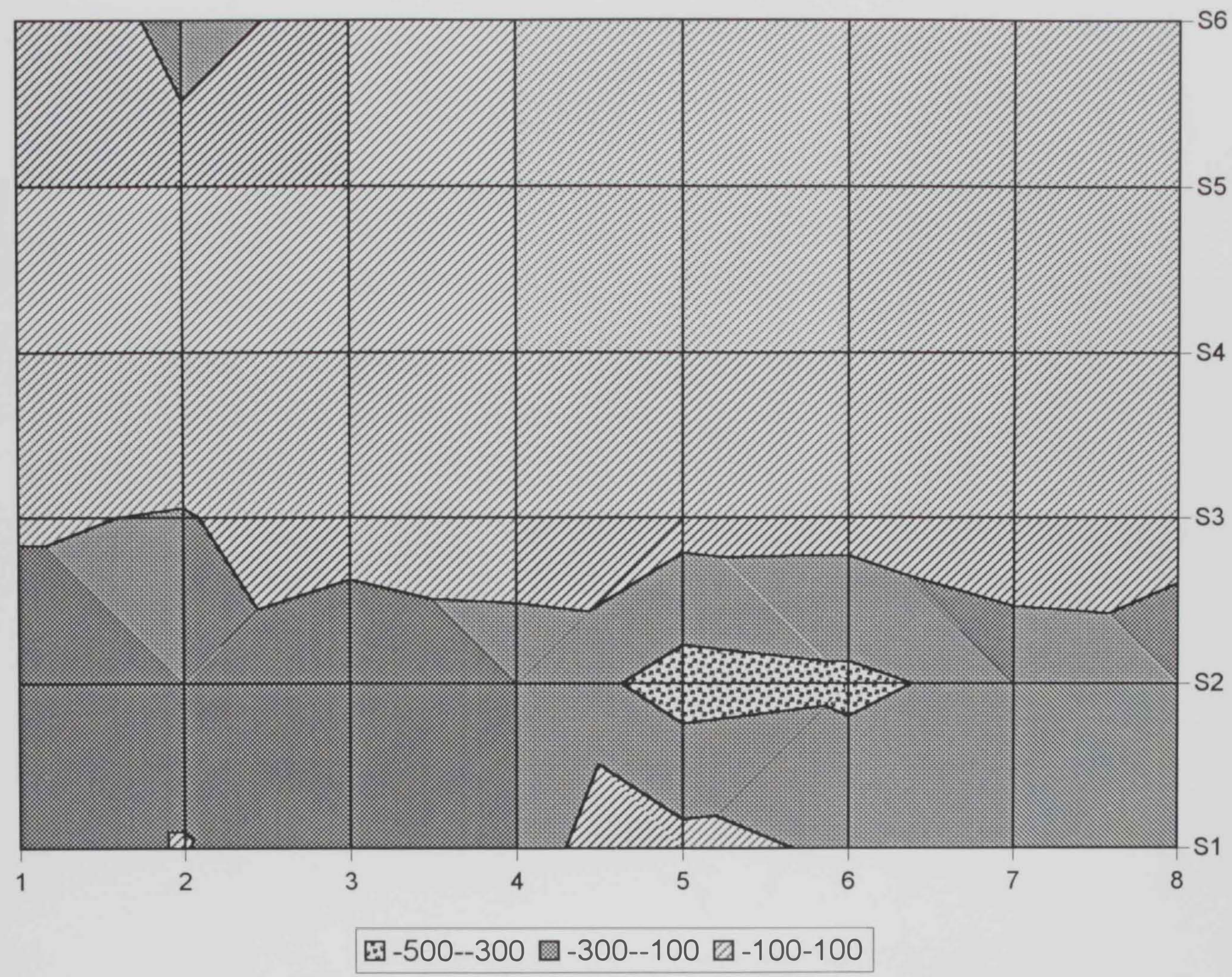

الخلاصة

- تعتبر منطقة الخليج العربي واحدة من أكثر البيئات صعوبة على الخرسانة المسلحة في العالم الطرق التقليدية للحماية من التآكل ليست كافية لتوفير المستوى المطلوب من التحكم في التآكل خلال فترة العمر التصميمي للمنشآت الخرسانية في مثل هذه البيئات .

- الحماية الكاثودية أثبتت أنها تقنية فعالة لمنع تآكل حديد التسليح في الخرسانة والناتج عن الأملاح . وكبديل للحماية الكاثودية بإستخدام التيار المنبعث حصل تطور حديث ملحوظ في تطبيق الحماية الكاثودية بإستخدام القطب المضحي كوسيلة لتحسين أداء الإصلاح الموضعي وعليه كان الهدف الأساسي من هذا البحث وهو دراسة مدى تأثير تطبيق تقنية الحماية الكاثودية بإستخدام القطب المضحي لمنع أو تقليل التآكل في حديد التسليح في الخرسانة المسلحة في البيئات الصعبة .

- عدة تجارب تم إعدادها لدراسة مدة فعالية الأقطاب المضحية داخل وخارج منطقة الإصلاح ، فوق وتحت مستوى الأرض ، في الإصلاحات الموضعية الكبيرة والصغيرة نسبياً ، وفي الإنشاء الجديد حيث تم تقسيم التجارب إلى قسمين موقعي ومختبري : في البرنامج الموقعي تم إختيار ، تقييم إصلاح ومراقبة ثلاثة أعمدة تظهر تآكل واضح وذلك لمدة عام تقريباً حيث تم إستخدام أقطاب مضحية داخل وخارج منطقة الإصلاح . في القسم المختبري تم صب ستة بلاطات صممت لتمثل خرسانة قديمة ذات منطقة إصلاح صغيرة نسبياً وأخرى ذات منطقة إصلاح كبيرة نسبياً وأخرى إنشاء جديد .

- من خلال فترة الإختبارات أظهرت الأقطاب المضحية وخاصة في الأعمدة أكثر عنها في البلاطات أنها طريقة فعالة للتحكم في مشاكل تكون الأنود الناشئ والإخفاق الحاصل في المناطق المحيطة بالإصلاحات في الخرسانة والتي تعاني من التآكل الناتج عن الأملاح .

TO MY PARENTS

يا من علماني معنى الفضيلــة والوعــي وإدراك الذات
يا من زرعا في نفسي الأمل للغد المشرق والحياة الحلوة
إليكما يا من أقف عاجزاً عن شكري وإمتنانــي لهمـــا
إليكما يا من كنتما نبراساً يضيء لي دروب الحيـــاة
إليكما يا مــن كنتمــا لكــل شــيء حققتــه وأحققــه
فــي حياتــي العلميـــة والعمليـــة
إليكمــا أهــدي هــذا الإنجـاز المتواضـــع

TO MY WIFE

إلى نفحة الأمل ... إلى من أنارت دربي بحنانهـــا
إلى من كانت لي سنداً ونبراساً مضيئاً في حياتـــي
إلى منبــع الاحســـاس الصــادق والوفـــاء
إليكِ يا زوجتي الغالية أهدي هذا العمل المتواضع المثمر

جامعـــة الإمـــارات العربيـــة المتحـــــدة

عمـــادة الدراســـات العليـــا

برنامــج علــوم وهندســة المـــــواد

مدى فعالية الحماية الكاثودية بإستخدام الأنود المضحي في التحكم في تآكل حديد التسليح فى الخرسانة فى البيئات الصعبة

إعـــداد

حسن علي أبوبكر الجفري

رسالـــة مقدمـــة لعمـــادة الدراســـات العليـــا

ضمن متطلبات الحصول على درجة الماجستيــر

فـــي علـــوم وهندســـة المـــواد

اد. عبدالله محمد الشامسي

قسم الهندسة المدنية

جامعة الإمارات العربية المتحدة

د. أحمد سعيد الشامســـي

قـســم الكيـميـاء

جامعـــة الإمارات العربية المتحدة

يونيو ٢٠٠٣