Performance Evaluation of Concrete Coatings

by

Faiz Mohammed Khan

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

June, 2000

INFORMATION TO USERS

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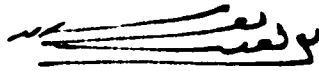
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This thesis, written by **Faiz Mohammed Khan** under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING.**
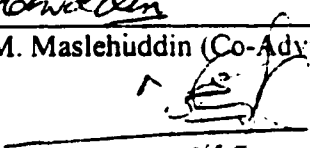
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Dedicated to my beloved parents..

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FAIZ MOHAMMED KHAN

PERFORMANCE EVALUATION OF CONCRETE COATINGS

CIVIL ENGINEERING

17 JUNE, 2000

The use of surface coatings to minimize concrete deterioration, mainly due to reinforcement corrosion, is widespread. However, with the wide range of coatings available in the market it becomes extremely difficult to choose the right type, since coatings of similar generic types may exhibit considerably different properties. Further, the performance of surface coatings under the environmental conditions prevailing in the Arabian Gulf is not very well documented.

This study was conducted to evaluate the performance of concrete surface coatings under conditions simulating those of the Arabian Gulf.

Based on a survey of the concrete coatings available in the market, five generic types of coatings, namely, acrylic coatings, polymer emulsion coatings, epoxy coatings, polyurethane coatings and chlorinated rubber coatings were selected to evaluate their performance under aggressive environmental conditions.

The selected coatings were applied on concrete/mortar specimens of suitable size in accordance with the manufacturer guidelines and tested to evaluate their performance. The results of the experimental program indicated that both epoxy and polyurethane coatings performed better than the other coatings in almost all the exposure conditions evaluated in this study.

Based on the results of this study, guidance for selection of coatings appropriate for the service conditions has been provided. Performance criteria for evaluation of concrete coatings have also been suggested. Further, the experimental data was utilized to calculate the chloride and carbonation diffusion coefficients and a model was suggested to evaluate the useful service life of a reinforced concrete structure coated with the selected coatings.

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خلاصة الرسالة

فايز محمد خان

تقييم أداء أطلية الخرسانة

الهندسة المدنية

١٧ يونيو ٢٠٠٠م

لقد تم إنشاء استخدام الأطلية السطحية للخرسانة المسلحة وذلك لتقليل تدهور أدائها نتيجة صدأ حديد التسليح . ولكن هناك صعوبة في اختيار النوع الأنسب نتيجة زيادة عدد هذه الأطلية في الأسواق ، والتي قد تظهر خصائص مختلفة مع أنها تحمل نفس الصفات . كذلك لم تتم دراسة أداء هذه الأطلية تحت الظروف المناخية السائدة في منطقة الخليج العربي . ولذلك فقد تم إجراء هذه الدراسة لتقييم أداء هذه الأطلية السطحية للخرسانة وذلك بمحاكاة الظروف المناخية في منطقة الخليج العربي .

لقد تم اختيار خمسة أنواع من الأطلية بناءً على استبيان وحصر المتواجد منها في الأسواق ، وهي : طلاء الأكريلك ، طلاء البوليمر المستحلب ، طلاء الإيبوكسي ، طلاء البولي ــ يورثين ، وطلاء المطاط الكلوريـــدي ، وذلك لتقييم أدائها تحت الظروف المناخية السابق ذكرها .

وقد تم اختبار هذه الأنواع الخمسة المختارة لقياس أدائها ، وذلك بطلائها على عينات خرسانية مناســبة الحجم بناءً على توصيات المنتج . وقد دلّت نتائج هذا البحث على أن طلاء الإيبوكسي والبولي ــ يورثين ، أظهرا أداءً أفضل مقارنة بالأنواع الأخرى في معظم حالات التعرض .

بناءً على نتائج هذه الدراسة ، لقد تم إصدار التوصيات وذلك لاختيار النوع الأصلح والمناسب لظـروف الخدمة . ولقد تم اقتراح خصائص الأداء وذلك لتقييم أطلية الخرسانة . كذلك تم حســـاب معـــامل التغلغــل الكلوريدي والكربوني بناءً على نتائج الاختبارات المعملية . ولقد تم اقتراح نموذج لتحديد العمر الخدمي لـــلأداء الجيد للخرسانة والتي قد تم طلاءها بالأنواع المختارة .

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران ـ المملكة العربية السعودية

يونيو ٢٠٠٠

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CHAPTER 1

INTRODUCTION

1.1 CONCRETE DURABILITY IN AGGRESSIVE ENVIRONMENT

Reinforced concrete has proved to be an efficient and durable construction material for structures over a long period of time. Its low-cost, ecologically favorable profile, and excellent strength and stiffness properties coupled with its ease of manufacture at the construction site are important factors that have established it as a major construction material.

Although concrete is the most widely used construction material, it has its own limitations. It has been observed that concrete deteriorates rapidly in conditions where moisture and temperature are high and more so, in the presence of aggressive ions. The reduction in the useful service-life of reinforced concrete construction, mainly due to reinforcement corrosion, in North America, Europe and the arid and semi-arid regions of the world is of concern to the construction

industry. Considerable resources have to be diverted towards the repair and rehabilitation of the deteriorated concrete structures. While reinforcement corrosion, in the temperate climatic conditions, is mainly attributed to the use of deicer salts; in the arid and semi-arid regions, it is attributed to (i) severe climatic and geomorphic conditions, (ii) inappropriate materials specifications, and (iii) inadequate construction practices. In such environments, the construction practices need to be modified to be compatible with the climate. The concrete construction in such environments should be designed for durability in addition to strength. In these regions, concrete quality should be specified in terms of diffusion and permeability indices [1].

Deterioration of concrete components is noted within a short span of 5 to 10 years in the eastern province of Saudi Arabia. This is attributed mainly to chloride-induced corrosion of the reinforcing steel.

1.1.1 Protection of the Steel Reinforcement by the Concrete

Portland cement concrete provides both chemical and physical protection to the reinforcing steel. The chemical protection is provided by the highly alkaline nature of the pore solution (pH > 13). At this high pH, steel is passivated in the presence of oxygen, presumably due to the formation of a submicroscopically thin Gamma-ferric oxide (γ- Fe_2O_3) film [2].

According to Page [3], the lime-rich layer, which is observed at the steel-concrete interface, provides further protection to the steel. This was confirmed by Leek and Poole [4] who reported that the interfacial layer consists of an aggregate

free zone of Portlandite [Ca(OH)$_2$] of variable thickness (5 to 15μm) disrupted by inclusions of calcium-silicate-hydrate (C-S-H) gel. This layer is thought to screen most of the surface of the steel from the aggressive ions and to act as an alkaline buffer to pH reductions resulting from the hydrolysis of corrosion products. According to Sagoe-Crentsil and Glasser [5], both Ca(OH)$_2$ and C-S-H gel form a buffering pair, and a high pH is readily maintained by C-S-H as well as Ca(OH)$_2$. The physical protection to steel is provided by the dense and impermeable structure of concrete, which retards the diffusion of the aggressive species such as chlorides, carbon dioxide, oxygen and moisture to the steel-concrete interface.

1.1.2 Mechanism of reinforcement corrosion

The most common form of reinforcement corrosion in an aqueous medium is electrochemical. It requires an anode (where oxidation takes place), a cathode (where reduction occurs), an electrical conductor (steel reinforcement) and an electrolyte (concrete). At the anode metallic iron goes into solution by oxidation (loss of electrons):

$$Fe \rightarrow Fe^{++} + 2e^- \qquad \text{(Oxidation)} \qquad (1.1)$$

At the cathode, dissolved oxygen in the pore water that has diffused to the steel surface is reduced by electrons supplied by the anodic reaction to form hydroxyl ions:

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \qquad \text{(Reduction)} \qquad (1.2)$$

The OH ions flow back to the anode through the concrete to complete the circuit. The rate of this transfer depends on the temperature, moisture content, ionic concentration and electrical resistivity of concrete.

The OH ions at the anode can then combine with the Fe^{++} cation to form a fairly soluble ferrous hydroxide, Fe $(OH)_2$:

$$Fe^{++} + 2OH^- \rightarrow Fe(OH)_2 \tag{1.3}$$

If sufficient oxygen is available, this product can be further oxidized to form insoluble hydrated red rust. This rust can have a volume 2 to 14 times of the parent iron from which it is formed. The rust product can exert tensile stresses of the order of 4000 psi, which is 10 times the tensile strength of concrete. This excessive pressure causes the concrete cover to crack leading to its eventual spalling off at an advanced stage of the corrosion process leading to a reduction in the cross-sectional area of the structural member.

Hence, it can be noted that oxygen and moisture are the most important ingredients for reinforcement corrosion to occur and the ingress of these elements through the concrete must be controlled to avoid corrosion.

1.1.3 Chloride-induced Reinforcement Corrosion

In fresh concrete, amongst the hydration products of Portland cement are present alkaline hydroxides, which form a thin insoluble film of γ-Fe_2O_3 on the steel bars. This film prevents the Fe^{++} cations from entering into solution and also acts as a barrier to prevent oxygen anions from contacting the steel surface.

Corrosion of steel in concrete proceeds at a far greater rate in the presence of chloride ions. The chloride ion acts as an essential catalyst in the corrosion reaction. Most researchers believe that the chloride ion initiates the corrosion reaction by depassivating the natural oxide film on the steel surface, allowing the iron to dissolve into solution. On reaching the iron substrate, the chloride ion oxidizes the iron to form $FeCl_3$ and draws its unstable ferrous ion into solution, where it reacts with the available hydroxyl ions to form Fe $(OH)_2$. This releases the Cl^- ions back in to the solution and consumes hydroxyl ions, as seen in the following reactions:

$$2Fe + 6Cl^- \rightarrow 2FeCl_3^- + 4Fe^- \qquad (1.4)$$

$$FeCl_3^- + 2OH^- \rightarrow Fe(OH)_2 + 3Cl^- \qquad (1.5)$$
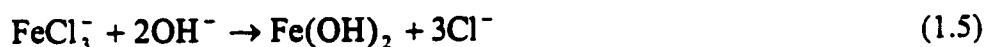
The electrons released in the oxidation reaction, as shown in Equation 1.4, flow through the steel to the cathode. This process results in an increase in the concentration of the chloride ions and a reduction of the pH at the points of corrosion initiation, probably accounting for the process of pitting corrosion. Equation 1.5 indicates that 3 chloride ions are released as a by-product of steel corrosion indicating that once the chloride ion reaches the metal surface no further chloride ions are required and depending on the electrical resistivity of concrete either general or local corrosion proceeds. It can also be noted that even for the chloride-induced reinforcement corrosion to occur, the presence of moisture and oxygen is necessary.

1.1.4 Carbonation of Concrete

Reinforcement corrosion may also be caused by carbonation of concrete. Carbonation involves a reaction of atmospheric carbon dioxide, CO_2, with the Portlandite, $Ca(OH)_2$, in the cement gel to form insoluble $CaCO_3$ and water:

$$CO_2 + Ca(OH)_2 \xrightarrow{\text{moisture}} CaCO_3 \downarrow + H_2O \tag{1.6}$$
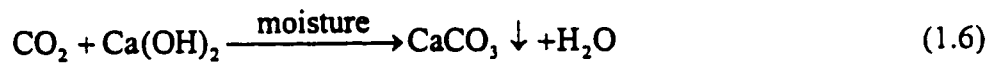
This reaction results in a reduction in the pH of the electrolyte to less than 8.5 due to removal of hydroxyl ions from the pore water. At this low pH, the steel is no longer passive and corrosion can occur. Factors influencing carbonation of concrete and the subsequent corrosion of embedded steel include concrete mix design, depth of reinforcement cover, improper curing, moisture conditions and temperature.

Steel corrosion due to carbonation of the concrete is mainly observed in the old structures and in industrial environments. The environmental conditions in the coastal areas of the Arabian Gulf (Temperature: 35 to 45 $^\circ$C; R.H: 45 to 60%) are conducive for the acceleration of carbonation of concrete and the resulting depassivation of the reinforcing steel. Carbonation depths of more than the concrete cover were measured in reinforced concrete structures located in industrial environment in a survey conducted by King Fahd University of Petroleum and Minerals [6].

1.2 PREVENTION OF CONCRETE DETERIORATION

1.2.1 Improving Concrete Quality

Maslehuddin, et al [7] have reviewed the methods for monitoring the quality of hardened concrete and provided information on the range of values for evaluating the quality of concrete in the Arabian Gulf.

Depassivation of the reinforcing steel occurs by the reduction of the pore solution pH to less than 8.5, due to carbonation or by ingress of chloride ions to the steel–concrete interface. A number of mechanisms by which chlorides break down the passive layer have been proposed, e.g., the chemical dissolution of the film [8], the build-up of pinholes at the film-substrate interface [9] and due to high chloride concentrations at the iron oxide-pore solution interface that leads to local acidification and pitting [10].

The chloride ions play a dominant role in the initiation of reinforcement corrosion. From this perspective, ACI 318-85 limits the water-soluble chlorides to 0.15% by weight of cement. ACI Committee 224, adopting a more conservative approach, has suggested that the acid-soluble chloride content should not be more than 0.2% by weight of cement. The British Standard, BS 8110 allows a maximum chloride content of 0.4%. The Norwegian Code, NS 3474, allows an acid–soluble chloride content of 0.6%. RILEM permits 0.4% and the revised Australian Standard for Concrete Structures, AS 3600, allows an acid-soluble chloride content of 0.8 kg/m^3 of concrete. Rasheeduzzafar et al [11] indicated that the chloride threshold limits for cements with upto 8% C_3A agree very well with the ACI 318 limit of

0.15% water-soluble chlorides. They also reported that the ACI, BS and Australian code limits appeared to be conservative for concrete prepared with high C_3A cements.

Recent research findings have shown that cement alkalinity also significantly influences the chloride binding and hence the volume of free chlorides [12, 13, 14, 15]. Taking into account the concomitant effect of chlorides and alkalinity, Hausmann [16] suggested that the critical Cl^-/OH^- ratio is about 0.6. Gouda [17] indicated that the Cl^-/OH^- ratio was 0.3 based on the pH values of the electrolyte representative of the concrete pore solution.

Mangat and Moloy [18] indicated that a universal threshold Cl^-/OH^- ratio is not applicable to different cement concretes. In their investigations, reinforcing steel corrosion was observed in the control matrix when the pore fluid Cl^-/OH^- was 13. Al-Amoudi et al. [19] reported minimal reinforcement corrosion in silica fume and blast furnace slag cement mortar specimens placed in the aggressive environment of sabkha, even at Cl^-/OH^- ratios of 3.3 and 6.5, respectively.

Chloride ions are often unintentionally inducted into the concrete through the constituent materials like salt contaminated aggregates or water and sometimes intentionally in the form of chemicals to accelerate the setting of concrete. Moreover, they may penetrate the hardened concrete when exposed to aggressive environment. While the chlorides contributed by the constituent materials can be controlled by strict adherence to improved construction practices, the ingress of

chloride ions from the service environment can only be controlled by producing a good quality concrete and /or coating with impermeable membranes.

1.2.2 Use of Preventive Methods

Ordinary Portland cement concrete even at high cement content and low water cement ratio does not constitute an effective barrier against diffusion of aggressive species, such as chloride, oxygen and carbon dioxide and therefore, using surface treatment is a necessary requirement to protect concrete structures exposed to chloride laden environments [20]. The premature deterioration of concrete in severe environmental conditions is attributed to the unrealistic evaluation of the severity of the service-conditions. Once the severity of the service-conditions are realized, the economic superiority of Portland cement concrete can best be utilized by formulating materials specifications and construction practices commensurate with the severity of the service conditions. Various preventive methods have been proposed that include: (i) use of protective concrete surface coatings, (ii) use of metallic, epoxy, and polymeric coatings on the rebar, (iii) use of corrosion inhibitors, (iv) use of cathodic protection and, (v) production of dense and impermeable concrete, using appropriate design and construction practices [1].

Application of surface coatings on concrete is one of the options available to the engineer that can provide long-term effective protection to the concrete as well as to the reinforcing steel, provided the surface coating possesses certain engineering properties. Until recently, most coating manufacturers and users have

emphasized the diffusional, chemical and weathering properties of the surface coatings while ignoring their engineering properties. Because of this, most of the surface coatings available in the market have failed to either fulfill their intended purpose, or have lacked the reasonable durability of 5 to 10 years of fault-free operation expected of them. Extensive studies [1] on the properties of surface coatings for concrete show that their engineering properties are just as important as their diffusional, chemical, and weathering characteristics. It has also been shown that, for the long-term fault-free performance, a surface coating should possess adequate elasticity, thermal stability, crack bridging ability, and adhesion in real or simulated aggressive environmental conditions.

While the performance of concrete coatings in mild weather conditions is adequately documented, its performance under hot weather conditions is not adequately evaluated.

1.3 NEED FOR THIS RESEARCH

As discussed in the previous section, deterioration of concrete structures is a wide spread phenomenon all over the world. Vast resources are directed every year on repair and rehabilitation of structures. Low quality porous concrete significantly increases the ingress of chlorides, oxygen, moisture and carbon dioxide to the steel surface. This situation is ideal for the initiation of reinforcement corrosion, especially if the cover over the reinforcing steel is insufficient.

One method to reduce this problem may be to stop the supply of oxygen, moisture and other aggressive ions and gases to the steel surface, which are essential for reinforcement corrosion to occur. This can be achieved by applying a surface coating on the concrete. It is thus important to investigate the performance and effectiveness of concrete coatings in reducing concrete deterioration, particularly that due to reinforcement corrosion.

Several concrete surface coatings are marketed worldwide. However, with a wide range of coatings available it becomes extremely difficult to choose the right type. The nature and severity of exposure, i.e. environmental conditions, is a major factor determining the performance characteristics of coatings. Furthermore, the performance of coatings, commonly used in the environmental conditions of the Arabian Gulf is not very well documented. Most of the performance data supplied by the manufacturers were developed in the temperate climates, such as Europe and North America. In addition, there is a need to develop guidelines for the selection of coatings for the exposure conditions prevalent in this region.

Thus, there is a need, firstly to conduct a survey of the coatings available in the Saudi market, and, secondly, to evaluate their performance under the environment prevailing in this region. The data developed in this study will be beneficial in enhancing the useful service-life of reinforced concrete structures. The additional protection provided to the concrete structure will further enhance the safety and reliability of the structure, and will result in considerable saving of resources in terms of extended life of the structure and delayed repair and rehabilitation.

1.4 OBJECTIVES

The broad objectives of this research were to evaluate the performance of concrete surface coatings under aggressive environmental conditions.

The specific objectives were:

i. To conduct a survey of the local market to assess the available generic types of coatings,

ii. To evaluate the performance of concrete surface coatings under aggressive environments by subjecting them to various exposures and testing them for specific parameters,

iii. To specify the generic type of coatings suitable for application to concrete under various exposure conditions, and

iv. To develop the performance criteria for selection of surface coatings.

CHAPTER 2

LITERATURE REVIEW

2.1 COATINGS – TERMINOLOGY, AND CLASSIFICATION

Coatings have many uses in industrial situations. They are used for corrosion control, chemical resistance, heat resistance, temperature control, identification, decoration, camouflage, fire retardation, noise control, anti-fouling protection and many other reasons, as shown in Figure 2.1 [21, 22].

Terminology used in the industry can be confusing. The terms paint, coating and lining sometimes are used interchangeably, but there are differences in their meanings. The Paints/Coatings Dictionary [23] defines paint and coating as follows:

- Paint - Any pigmented liquid, liquefiable or mastic composition designed for application to a substrate in a thin layer that is converted to an opaque solid film after application. Used for protection, decoration, or identification, or to
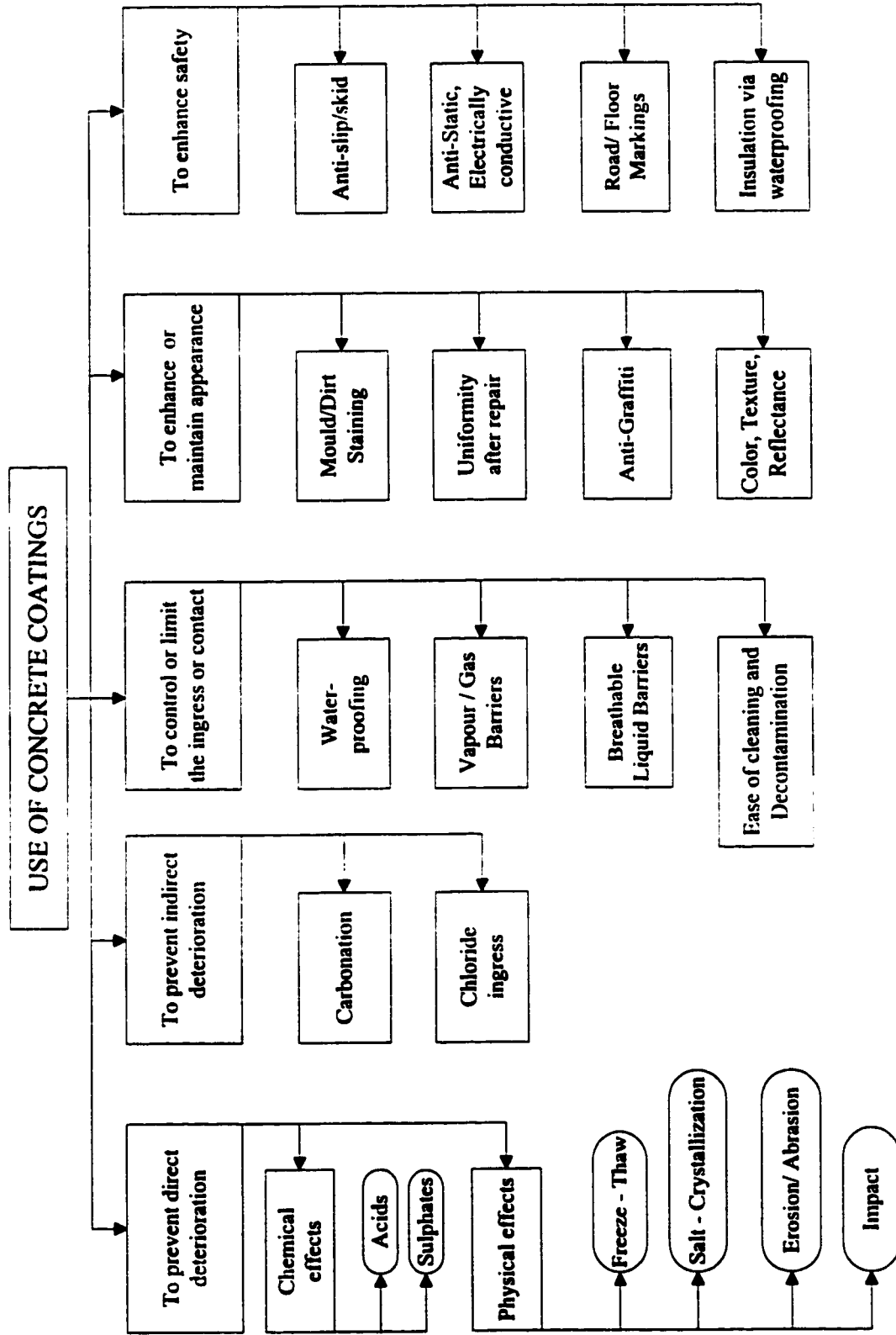
Figure 2.1: Common reasons for applying surface coatings

serve some functional purpose such as the filling or concealing of surface irregularities, the modification of light and heat radiation characteristics, etc.

- Coating – A liquid, liquefiable or mastic composition, which is converted to a solid protective, decorative, or functional adherent film after application as a thin layer.

Based on these definitions, the major difference between paint and coating is that paint is pigmented, while no such requirement is mentioned for coating. They both are liquid, liquefiable or mastic compositions that are converted to a film after application as a thin layer. Therefore, varnishes and clear coats are coatings but not paints. Processes, such as galvanizing and metallizing also meet the definition of coating.

While the distinctions between paint and coating appear to be minor, it is common in the industry to distinguish between them, even though most materials used are pigmented and meet the definition of paint. Coating generally refers to materials used for protective or functional purposes, while paint refers to materials used for aesthetic or decorative purposes. Thus, a structure is coated while a room is painted. This differentiation is further emphasized by some who refer to the materials used in industrial situations as protective coatings.

The definition of lining, from the Industrial Maintenance Coatings Glossary [24], is 'a material used to protect a container against corrosion and/or to protect the contents of a container from contamination by the container shell material.' Liners commonly are thought of as thick, built-up systems containing matting or similar

reinforcing material. However, the definition does not exclude coatings from use as linings.

2.2 COATING COMPONENTS

A coating can contain as few as three or four ingredients or as many as 20 or 30 ingredients, depending on the formulation. The three main components of a coating are the resin, pigment and solvent. Resin and solvent comprise the liquid portion of a coating. Together, they are called the vehicle. Resin and pigment are referred to as the film solids, since they are the materials left after the coating has dried [21, 22].

2.2.1   Resins

Resin is the binder that holds the pigment particles together and provides adhesion of the coating to the surface. Most coatings are named by the generic type of resin (i.e., epoxy, acrylic, polyurethane, etc.). The resin component of most coatings is a mixture or chemical blend of materials. There are different types of epoxy resin, for example, and many combinations of epoxy resin and hardener. Therefore, the resin composition of an epoxy coating may be different for epoxy coatings from different suppliers or even for different products from the same manufacturer. In addition, other resin types can be modified with epoxy resin.

The resin or binder is responsible for most of the coating's physical and chemical properties, including hardness, abrasion resistance, chemical resistance,

weather resistance, adhesion and cohesion. The type of resin system also determines a coating's curing mechanism.

Resins can be classified as thermoplastic and thermoset. Thermoplastic resins can be repeatedly softened by heating and hardened by cooling. They also can be dissolved by the original solvent used in the coating. Coatings based on thermoplastic resins usually are packaged in one container. Thermosetting resins, however, undergo a chemical reaction by the action of heat, catalysts, ultraviolet light, etc., that makes them relatively infusible. They do not harden and soften by heating and cooling or redissolve in solvent. Epoxies are such a resin. Coatings based on thermosetting resins usually are packaged in two or more containers, although thermosetting resins that cure by such methods as heating, ultraviolet light, or reaction with constituents in the atmosphere come in one container.

2.2.2 Pigments

Most pigments are inorganic compounds, although some bright color pigments are insoluble organic compounds. Prime pigments provide opacity, a term for hiding power. They can also provide improved durability, weathering and protection to light-sensitive resins.

Some coating types contain anti-corrosive pigments for corrosion protection. Lead and chromium based compounds historically used for this purpose are being replaced by nontoxic metal compounds such as phosphates, chromates, phosphites, some organic compounds and other compounds. Flat, plate-like pigments, such as mica and aluminum flake are used to decrease moisture permeability. Still another

group of pigments, known as extender or filler pigments, add mechanical strength to the film, control viscosity, reduce settling, reduce gloss and improve film-build.

2.2.3 Solvents

The main function of the solvent is to provide ease of coating application. Solvents dissolve or disperse the resin, provide flow-out and leveling during application, and control adhesion and durability of the dry film.

A coating formulation usually contains a blend of solvents. The resin is dissolved or dispersed in the primary solvent. However, if one of the constituents of the resin is not soluble in the primary solvent, a co-solvent may be needed. Other solvents may be added to control the evaporation rate or to provide adequate flow-out and leveling. The solvent can control the rate of chemical reaction in some coatings. Solvents are not part of the dry film, they evaporate during the drying or curing process.

2.2.4 Additives

In addition to resins, pigments and solvents, many coating formulations contain additives- specialty materials that vary widely depending on the resin type. Oil-based coatings for example, contain dryers to promote curing. Hard, brittle resins, such as vinyls contain plasticizers to produce a more flexible film. Emulsion systems employ a number of additives, including wetting agents, dispersants, freeze-thaw stabilizers, anti-microbial agents and film forming aids. Other additives

may be incorporated into a coating formulation to control consistency and pigment

settling or improve sag resistance.

2.3 CURING MECHANISM OF COATINGS

Cure refers to the length of time before a coating can be put into service.

There are four curing mechanisms for coating: air oxidation, solvent evaporation,

chemical reaction and hydrolysis.

2.3.1 Air Oxidation

Coatings that cure by air oxidation contain drying oils. These include oil-

based coatings and some hybrid coatings. Cross-linking of the resin polymers

occurs by reaction with oxygen in the air. The solvent evaporates when the coating

is applied, but it takes longer for oxygen to permeate the film. Therefore, recoat

times are generally long for some formulations. The slow-drying characteristic of

oil-based primers can be an advantage since the coating can flow into the surface.

Air oxidizing coatings have moderate moisture permeability. Therefore, anti-

corrosive pigments usually are added to the primer formulation for products applied

to steel. Air-oxidizing coatings, generally, are formulated in one component and

have unlimited pot-life. They are easy to apply by brush, roller or spray.

2.3.2 Solvent Evaporation

Coatings that cure by this method only require that the solvent evaporate from

the film. These coatings are made by dissolving the resin in an appropriate solvent.

No cross-linking or chemical reaction occurs during film formation, which involves attraction and entanglement of the resin molecules to the point where their movement is restricted. These types of coatings contain thermoplastic resins. Vinyls, chlorinated rubbers and asphaltics are examples of coatings in this class.

Solvent evaporating coatings have relatively low solids, low moisture permeability and they protect by a barrier mechanism. They have good water and sunlight resistance but poor solvent resistance. They are easy to repair because the topcoat solvent softens the existing film, giving a good bond. These are applied by spray methods only. They become viscous quickly, so they cannot be worked with a brush or roller. The curing mechanism does allow low temperature application, although drying is retarded.

Latex and other water-borne coatings also cure by solvent evaporation. In these cases, the solvent is water. The resin is present as emulsified particles, which coalesce to form a film when the water evaporates. The coalescing reaction is temperature-dependant and there is a proper temperature range in which they can be applied. Application methods include brush, roller or spray.

2.3.3   Chemical Reaction

Coatings that cure by chemical reaction are packaged in two or more containers. One can contains the resin, while the other can contains the cross-linking agent, referred to as the hardener or curing agent. The resin, after mixing, becomes thermosetting, which means the components form a film by a chemical

cross-linking reaction. Epoxies, polyurethanes and polyesters are common coatings that cure by this mechanism.

Chemically cured coatings have a pot life and may have an induction time. The chemical reactions are temperature dependent and the materials can be applied and cured above the minimum application temperature. The cross-linking reaction that occurs usually results in a smooth, hard film, which is likely to have a maximum recoat time. Most chemically cured coatings can be applied by brush, roller or spray equipment.

These films have low permeability and protect by barrier formation. The properties of the barrier film provide these coatings with good chemical and solvent resistance.

2.3.4 Hydrolysis

Hydrolysis means reaction with water. Coatings that cure by hydrolysis require a sufficient amount of moisture in the air to react with the chemical groups to form the film. Self-curing, solvent-borne inorganic zinc-rich primers and moisture-curing polyurethanes are the two main coating types that cure by this mechanism.

Humidity is as important as temperature in the cure of these coatings. Moisture-cure coatings have a pot life. When they are exposed to air during mixing and application, moisture in the air reacts with the resin, causing it to polymerize.

2.4 PROTECTION MECHANISMS OF COATINGS

The three mechanisms by which coatings can protect a substrate are barrier protection, inhibitive pigment protection, and sacrificial protection.

2.4.1 Barrier Protection

All coatings protect partially or solely by barrier protection. They separate the substrate from the environment, especially sunlight and moisture. One indicator of a coating's ability to act as a barrier is its moisture vapor transmission rate, which is the rate at which moisture vapor permeates a coating and reaches the substrate. Good barrier coatings have very low moisture vapor transmission rates.

2.4.2 Inhibitive Pigment Protection

Coatings with high moisture vapor transmission rates incorporate anti-corrosive pigments for application to steel substrates. These pigments are slightly-soluble and a small amount dissolves as moisture permeates the film. They are carried to the substrate where they passivate the steel.

2.4.3 Sacrificial Protection

Corrosion theory states that when two dissimilar metals are in contact and corrosion conditions exist, the more active metal will corrode to protect the less active metal. Zinc metal is more active than steel, therefore, sacrificial coatings contain zinc in electrical continuity with the steel.

2.5 GENERIC COATING TYPES

Thousands of coatings are sold worldwide for industrial use, making it impossible to memorize the names, attributes, properties, and limitations of all of them. Therefore, a method is needed to classify coatings based on some similarity so that the selection process is manageable. The most common method of classification for coatings is generic type, which refers to the chemical attribute - most often the resin type - that is unique to a group of coatings.

Generic type is the most useful classification principle because coatings of the same generic type have similar handling and performance properties.

The name for most generic types of coatings is based on the resin (binder) in the formulation, as shown in Figure 2.2. A secondary generic classification of coatings is by curing mechanism or some other compositional element. Vinyl and epoxy, for example, are generic coating types with names based on the resin. Polyurethanes as a generic resin type are subdivided very distinctly by curing mechanism, so there are moisture-curing (commonly one-component) polyurethanes and chemical-curing (two-component) polyurethanes. Latex coatings are a generic type in which the classification is made solely by curing mechanism. In latex emulsions, the resin is suspended as microscopic particles in water. The coating cures by coalescence, which means that after the coating is applied and the water starts to evaporate, the resin particles come together and eventually fuse. Many different resins can be used in latex coatings. Other generic coating types are classified using systems designed to indicate even broader classifications. Inorganic
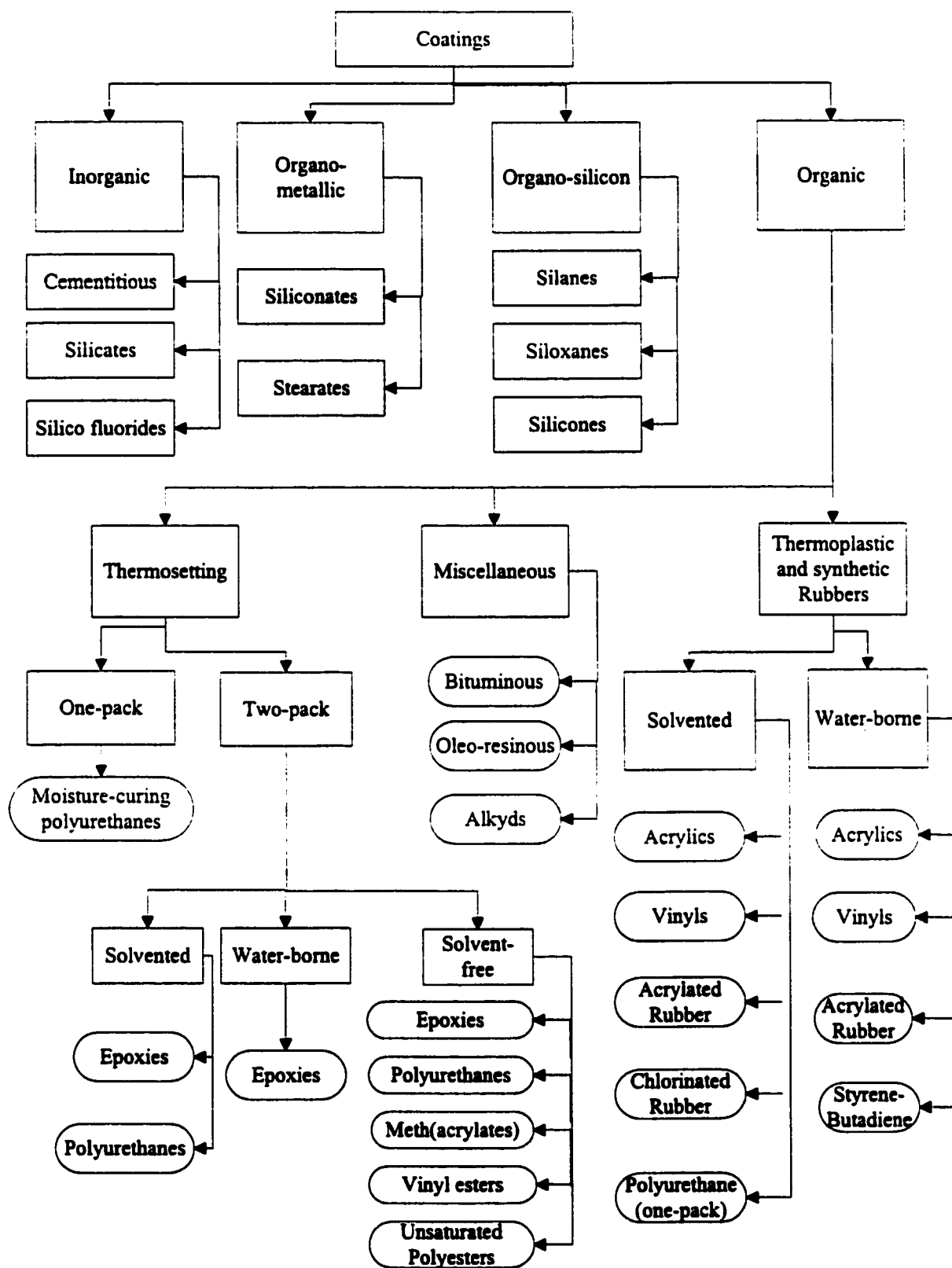
Figure 2.2: Classification of surface coatings and treatments

zinc-rich and organic zinc-rich coatings are examples. Zinc-rich indicates that high loadings of zinc dust are part of the formulation, while the resin component is only broadly classified by its general chemistry - inorganic or organic. (Organic resins are based primarily on carbon in the polymer backbone; inorganic resins do not contain carbon.).

Some of the most widely used generic types of coatings that are utilized to protect concrete have been described in detail in the following paragraphs.

2.5.1   Water-borne Acrylic Coatings

Water-borne acrylic or acrylic latex coatings are materials where the resin is dispersed in water to form an emulsion. While latex coatings can be made with a number of organic resins, acrylic is the major resin type used. Latex coatings are used as both protective and architectural coatings in the form of primers, intermediate coats, and topcoats [25, 26].

Water-borne acrylic coatings have high moisture vapor transmission rates. In coatings that protect wood or concrete, where moisture in the structure must be allowed to pass through the coating, this is an asset. However, in primers for steel, it is a liability that requires the use of anti-corrosive pigments as compensation.

Water-borne acrylic coatings are one-component materials that cure by solvent evaporation followed by coalescence of the resin particles. These coatings are used to protect steel in mild or moderate environments. They also are used as

overcoats for oil based or alkyd coatings, because they have low shrinkage when they cure and therefore, apply very little stress to the existing system.

2.5.2   Polymer Emulsion Coatings

Emulsion paints are generally air-drying and can be applied on almost all conventional paints. The thinner for emulsion paints is water, hence they are easy to apply and dry quickly. The wet adhesion of polymer emulsions is not very good and peeling may occur when applied on glossy, fully hardened alkyd paint.

Polymer emulsions can be formulated to give very flexible films but excessive film thickness may cause cracking and peeling. These paints are not particularly resistant to chemicals and strong solvents [27].

2.5.3   Epoxy Resin Coatings

The organic resin of epoxy coatings contains a specific chemical group known as an epoxide. Epoxy coatings cure by chemical reaction when a hardener is added to the resin, usually a nitrogen-containing entity such as an amine or polyamide. Epoxy coatings are packaged in two containers, one each for the hardener and the resin. They are mixed just prior to application.

Epoxy coatings are similar to epoxy adhesives. They offer excellent adhesion to most substrates and yield tough, durable films. Epoxies are known for good resistance to solvents, water, and chemicals, as well as resistance to abrasion. However, they are known to break down on reaction with sunlight in a process

called chalking. This tendency limits their use outdoors to primers and intermediate coats.

The tough, slick film of an epoxy coating can be either an advantage or a disadvantage. It is an advantage if cleaning or decontaminating the surface is important but a disadvantage if another coat of material must be applied, because there may be a maximum recoat time, a period of time after which the coating becomes too hard to overcoat.

The most commonly used epoxies are polyamide-cured and amine-cured. Polyamide-cured epoxies have better water resistance; amine-cured epoxies have better chemical resistance. Other related curing agents are used in formulations, such as epoxy mastics. The latest development in epoxy coatings has been thin film formulations used as sealers for coating over existing oil based and alkyd coating systems.

There are a number of different epoxy resins and hardeners that can be used to formulate coatings. Epoxy resins also can be used to modify other resin types. However, the coating must cure by chemical reaction through the epoxide group to be included in the generic class of epoxies [27, 28].

2.5.4   Two-component Polyurethane Coatings

Coatings in this generic class use an iso-cyanate functional group (-N=C=O) to cross-link the resin. Thus, the classification is by curing agent and not by resin. In fact, many different resins, such as acrylics, epoxies, polyesters, and vinyl can be

used to formulate polyurethanes. Two-component polyurethanes are packaged in two containers, and like other chemical curing materials, have a limited pot life after mixing.

A number of different performance properties can be achieved with this type of coating, depending on the resin and the type of isocyanate-containing molecule used. In general, two-component polyurethanes have good water and chemical resistance. Aliphatic polyurethanes are known for gloss and color retention, while aromatic polyurethanes yellow in sunlight but are less expensive. Two-component polyurethanes form a smooth, slick film. The surface can be easily cleaned or decontaminated [29, 30].

2.5.5   Chlorinated Rubber and Vinyl Coatings

Chlorinated rubber and vinyl, which are organic resins, are grouped together because they dry by solvent evaporation. Film formation is essentially by precipitation, which is solidification of the binder with no changes occurring to the resin due to any type of chemical reaction. True vinyl and chlorinated rubber coatings, as opposed to modified versions, must be applied by spray because of their curing mechanism. They dry quickly and are easy to topcoat or repair.

Chlorinated rubber and vinyl coatings have very low moisture vapor transmission rates. They form very good barrier coats with good chemical resistance. They also perform well when they are immersed in water. They have poor solvent and heat resistance, however. Because they are solvent-borne, they usually are high in volatile organic compounds (VOC). Many state and local

regulations limit the VOC content allowed in paint. As a result, it is difficult formulating coatings that are based on vinyl or chlorinated rubber resins and that comply with VOC content limits.

Good gloss retention is possible with these coatings, so they can be used as topcoats. Chlorinated rubber formulations are the material of choice for coating swimming pools. Unmodified chlorinated rubber and vinyl resin do not adhere well to steel; the resin must be modified to use these materials as primers [31, 32].

2.6 STRENGTHS AND LIMITS OF GENERIC CLASSIFICATION OF COATINGS

Classifying by generic type establishes groups of coatings with similar chemical and performance properties. The person who must select coatings can, therefore, more readily sort among the thousands of products available to find the most appropriate one. For instance, when a coating is to be exposed to splash and spillage of harsh acids in an exterior environment, the specifier of the coating can exclude alkyds because of their limited resistance to acids; additionally, the specifier can exclude epoxies as topcoat candidates because of their weakness in sunlight. Two-component polyurethane, on the other hand, with strong resistance to both acids and sunlight, is an appropriate candidate; the search is narrowed in this way to consideration of only those products classified as two-component polyurethanes.

Generic coating classifications, while useful, have their own limitations. The classifications are general and broad. Within each generic type are many variations.

For instance, the generic type epoxy includes different resins and hardeners with a broad range of specific properties. Oil-based and alkyd coatings, likewise, include many different resins of varying quality. In addition, most generic types can be subdivided into narrower, more descriptive classes. For example, two-component polyurethanes can incorporate many different resins with the resultant film having different performance properties. Using the example above, which requires a coating with resistance to sunlight and to chemical spills, the specifier can choose between acrylic polyurethanes, which have better resistance to sunlight, and polyester polyurethanes, which have better acid resistance. The choice between them will depend on which of the two performance properties is more important.

Another weakness of the generic type classification system, indeed of any coating classification system, is that it does not give any indication about the quality of the product. There are many constituents, both major and minor, that are incorporated into a coating's formulation. In fact, formulation has as much of an influence on performance as does the generic type. Any classification system indicates only generalities about the coatings in each class and assumes that the material is properly formulated. Choice of a specific product from a manufacturer is best made, based on performance testing.

Classification by generic type is one of the most useful methods of categorizing coatings. Some generic types have specific uses, such as resistance to certain exposure environments, or specific strengths, such as color and gloss retention. Some generic types have more general uses, and the user must select the types of coating based on factors, such as the severity of the exposure environment,

level of surface preparation, and expected life. Compatibility of primers and topcoats is also often expressed in terms of generic type [21].

Referencing coatings by their generic type usually indicates a use, special attribute, or level of performance.

2.7 CONCRETE COATINGS

Surface coatings are now more commonly used for the protection of concrete structures. Coating and linings are defined as protectants for concrete. This protectant function is primarily one of a physical barrier rather than chemical conditioner [33].

2.7.1 Protective Coatings

The majority of concrete structures, particularly those in coastal environments, often suffer from both chloride and atmospheric carbonation attacks. Application of polymer-based concrete surface coating is one of the solutions available for the long-term protection of the reinforcement steel from corrosion.

Swamy et al. [34] evaluated the performance of concrete slabs coated with acrylic-based coating against chloride and atmospheric carbon dioxide attacks. For this purpose, fully and partially surface-coated slabs were exposed to repeated cyclic wetting by sodium chloride solution followed by drying. After completion of the cyclic exposure regime, the slabs were exposed to laboratory drying environment and then subjected to experimental investigations.

The experimental results showed practically no chloride penetration into the concrete beneath the acrylic-based surface coating even after long-term exposure. On the other hand, for the uncoated concrete, the amount of chlorides and their depth of penetration into the concrete were found to be dependent on the water-cement ratio of the concrete. The amount of chlorides penetrating laterally, and the distance they penetrate from the uncoated concrete into the adjoining concrete below the acrylic-based surface coating is also a function of the w/c ratio of concrete. Further, both X-ray diffraction studies and phenolphthalein spray tests showed the acrylic-based coating to be very effective in controlling the carbonation of the concrete below it, especially when the coating was applied by spraying. The coating maintained good adhesion with the substrate concrete even after the long-term repetitive wetting and drying cycles [34].

Surface coatings on concrete can provide an effective and efficient protection for both concrete and the steel embedded in it, and can enhance the long-term durability of concrete materials and concrete structures exposed to aggressive environments. In practice, concrete is often cracked, and the crack-bridging ability of coatings is an important factor to be considered in evaluating their performance characteristics.

Swamy and Tanikawa [35] evaluated four different coatings for their crack-bridging ability by tests of exposure to ozone and ultraviolet light, and for their ability to control chloride penetration and steel protection by accelerated wet-dry or continuous salt spray tests. From these results, a highly elastic acrylic rubber coating was chosen for further long-term stability tests. The data presented show

conclusively that the acrylic rubber coating can prevent penetration of water, air and chloride ions, and ensure the long-term durability of steel embedded in concrete both when the concrete is free of chlorides and when it is contaminated with sodium chloride up to 1% of the mortar matrix. At high levels of chloride in the concrete, a high cover is also essential if the benefits of the surface coating are to be fully realized, and long-term serviceability of the concrete structure is to be ensured.

The effect of organic coatings on water and chloride transport in reinforced concrete was studied by Fluckiger et al. [36]. They concluded that the surface coatings strongly reduced the water and chloride uptake of concrete.

A wide range of organic polymers are used as coatings, while the most widely used penetrating materials tend to be siliceous which line the pores of concrete forming silicone resins providing protection through their water repellant properties. There is another class of penetrating material, whose action is to block the pores of concrete, such as epoxy resins [37]. Although significant variation in their performance exists, there are certain specific formulations of different chemical materials, which exhibit very good to excellent properties. These materials are able to reduce the intrusion of chloride by 80 to 99% when compared to uncoated concrete [38].

Kamal and Salama [39] investigated the potentiality of using polymers as protective coatings for reinforced concrete elements exposed to ammonium nitrate salts. Tests were performed on hinged concrete beams, bond test specimens and

mild steel bars. The main variables taken into consideration were the concentration of the salt in the surrounding medium, the concrete cover and the method of protection. Polymer coatings showed to be of great efficiency in protecting reinforced concrete structures against deterioration of concrete and corrosion of reinforcing steel.

2.7.2   Surface Treatments

Ibrahim [40] investigated the effect of concrete surface treatments on the compressive strength, water absorption, initiation of reinforcement corrosion, cracking due to reinforcement corrosion and depth of carbonation. Silane/Siloxane sealants with a topcoat and an acrylic coating were the most effective in reducing reinforcement corrosion, carbonation, permeability and water absorption.

Treatment compounds used to protect concrete against chloride penetration were tested by Pfeiffer and Scali [41] by immersing treated concrete cubes in 15% NaCl solution for 21 days. Their results indicated that epoxies. methyl methacrylates, urethanes and silane provide an excellent barrier against the ingress of chloride ions into concrete.

Cleland and Basheer [42] tested a number of coatings and found that the application of surface treatments had delayed the chloride induced corrosion of reinforcement and the time to initiation of corrosion of steel bars with a 25-mm cover depth were reported to have doubled with the application of surface treatments.

Vassie [43] determined the effectiveness of surface treatments in reducing the on-going corrosion by embedding steel bars at different depths from the surface and, then ponding the surface of these test samples with salt water. Once the top bars started corroding, protective systems were applied on the specimen surface and salt-water ponding continued. Half-cell potentials and chloride contents were measured in order to assess the effectiveness of the treatments. It was observed that alkyl-alkoxy silane reduced the on-going corrosion by 37perecent however it failed to stop the corrosion completely.

Katawaki proposed the use of urethanes in Japan because of their reportedly excellent resistance to water, weathering and cracking [44].

According to Harwood [45], acrylic/methacrylic pigmented coatings provide a very effective physical barrier to carbon dioxide and other acidic gases. In addition, they have excellent UV resistance, color stability and a minimum life expectancy of 15 years. The most effective method of ensuring long-term protection to a reinforced concrete structure is to use a combination system, which consists of a siloxane/acrylic blend primer and a pigmented acrylic topcoat. This system acts synergistically to produce the equivalent of an extra 500-mm of concrete cover over the reinforcement and, in addition, enhances the appearance of the structure.

Thompson and Leeming [46] evaluated 21 different surface treatments. They used a spray of 10% sodium chloride solution for 10 days for some samples and placed some treated samples with their treated face down on a capillary matting

saturated with 15% rock salt solution for a total of 3 weeks in order to determine the water penetration resistance of the treated substrate. A large variation in the performance of the treatments was observed, but there was a reduction of up to 90% in the chloride uptake of the treated specimen.

Nielsen [47] studied the behavior of concrete substrate treated with 20% silane on immersion in water. A reduction of 87.5% was obtained in the water absorption

McCurrich et al. [48] used a silane-acrylic two-coat system for concrete and subjected it to water absorption tests. They concluded that 75 to 95% reduction in water absorption was possible with a silane-acrylic system.

O'Donoghue et al. [49] studied the penetration, wetting and adhesion properties of different coatings on various porous substrates, such as concrete, rust etc. Scanning electron microscopy, optical microscopy and various physical tests showed that low viscosity, thin film, 100% solids epoxies and methacrylate have generally superior penetration capabilities compared to thinned high build epoxies, moisture cured urethane and polysiloxane penetrating sealers.

According to Cabrera and Hassan [50], the use of an 'effective treatment' not only protects the concrete against penetration of harmful substances, but also improves the performance properties of badly cured concrete by allowing the redistribution of internal moisture. The authors [50] also utilized the ponding test to determine the chloride diffusion coefficients. Treated and untreated specimens were immersed in 15% NaCl solution for a year. Chloride profiles were drawn and

diffusion coefficients were calculated. The effectiveness of the surface treatments was studied by monitoring the water absorption upto one year of immersion.

Robinson [51,52] tested the carbonation resistance of silane and siloxane treatment compounds and found that all the specimen carbonated to the same depth and there was no difference with the control untreated concrete.

Basheer et al. [53] evaluated the performance of several surface treatments in resisting accelerated carbonation by exposing coated samples to an enriched carbon dioxide environment. The depth of carbonation was determined by splitting the samples and spraying the freshly fractured surfaces with a phenolphthalein indicator solution. They observed that only acrylic based coatings reduced the diffusion of carbon dioxide.

Garcia et al. [54] used six different materials for the accelerated carbonation test and concluded that epoxy resin and ethylene polymer resin were the best in resisting carbonation of the concrete substrate.

2.7.3 Engineering Properties of coatings

Surface coatings have a significant role to play in protecting and preserving new and existing structures, and particularly those that are damaged and deteriorating by controlling the ingress of aggressive agents into concrete. In evaluating the performance characteristics of such coatings, it has been shown that certain basic engineering requirements, such as crack bridging ability, elasticity,

strain capacity, adhesion strength and fatigue resistance are also essential for the successful protection of concrete [55].

A highly elastic acrylic rubber type coating (Aron Wall) with an overall thickness of about 1000 μm is reported to exhibit excellent performance characteristics and is reliable in resisting the intrusion into concrete of a wide range of aggressive agents [55].

Saraswathy and Rangaswamy [56] investigated the influence of various characteristics of the concrete substrate on coating adhesion and have shown that the adhesion strength of a coating on a concrete substrate depends on the substrate strength itself and it was found that the adhesion strength of an acrylic coating was slightly higher than the surface strength of the substrate.

Swamy and Tanikawa [57] also reported the development of an acrylic rubber coating possessing excellent elasticity, thermal stability and crack-bridging properties. They presented field data to show the coatings outstanding diffusion properties in preventing, almost totally, penetration of chloride ions and carbonation. With time, coated concrete could cause realkalisation of the carbonated concrete.

2.7.4 Considerations for coating selection

The random selection of surface coatings, chosen for initial cost or appearance considerations alone, is very likely to result in early failures. Care is needed to consider precisely the individual requirements of the given structure,

taking into account the local conditions of exposure. All parties involved in the specification or use of the surface coating protection of a given structure must consider the foregoing, to avoid quite preventable failures [58].

There are no codes or standards at present other than that produced by The British Board of Agre'ment - MOAT. 33: 1986 that can provide any guidance in the selection of suitable surface coatings for concrete. The claims made by suppliers for their products need to be sifted carefully and quoted test results need to be closely examined for their relevance to performance on concrete [58].

The lack of satisfactory methods for monitoring application parameters suggests the use of reliable applicators who are experienced in applying the chosen system. Good surface preparation is essential before application to avoid early deterioration of the paint film.

While surface treatment materials are expensive in themselves they are very thin, so a little material goes a long way. However, getting access to the surface of the concrete, with scaffolding for instance, is a large proportion of the cost of any surface treatment. Surface preparation and the labor of application are required by all surface treatments; hence, small differences in material costs represent a much smaller percentage of the overall cost. It is cost effective in the end to concentrate on good workmanship and materials that have a good record of accomplishment.

Shields et al. [59] developed flowcharts for the selection of a coating system for both new and a deteriorating substrate, as shown in Figure 2.3. However, in
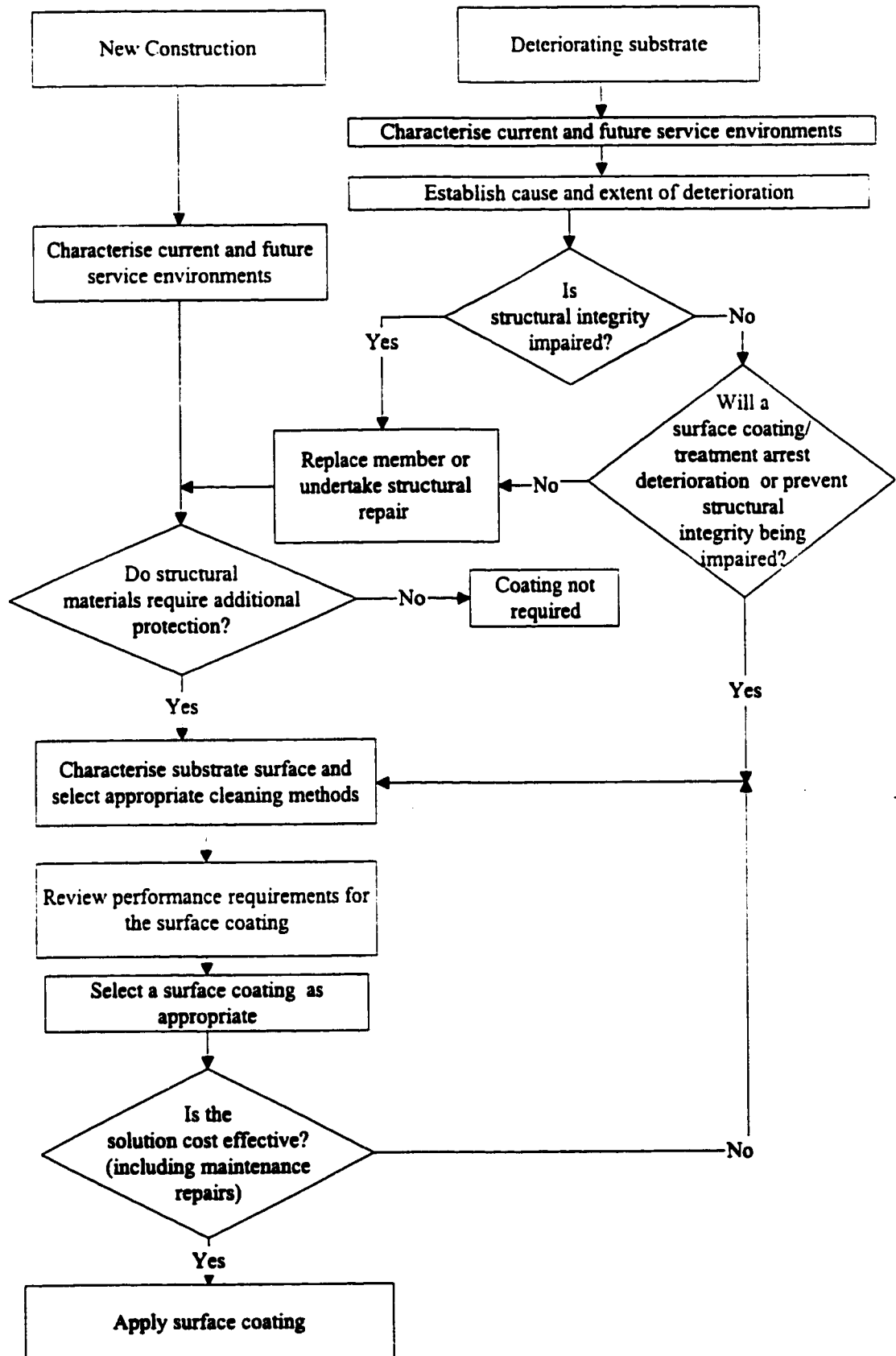
Figure 2.3: Guide for the selection of concrete surface coating

order to make use of this flowchart, there is a need to understand the relationship between the performance and durability of the surface treatments.

The reasons why the concrete is deteriorating needs to be carefully examined and an appropriate surface treatment chosen to deal with the problem. A surface treatment can protect only from external deteriorating influences on concrete. If the concrete is already heavily contaminated, there is little a surface coating can do to help.

Surface treatments can be both decorative and protective, and research has shown that most coatings, of adequate thickness, are a considerable improvement on bare concrete [58].

CHAPTER 3

METHODOLOGY FOR COATING EVALUATION

3.1 SELECTION OF COATINGS

The work in this task involved an initial screening of the concrete coatings available in the local market. Based on this survey, a range of concrete coatings, based on the available generic type, was selected.

The concrete coatings were selected to represent the following five generic types:

    i.   Acrylic coatings,

    ii.   Polymer emulsion coatings,

    iii.   Epoxy resin coatings,

    iv.   Polyurethane coatings, and

v.   Chlorinated rubber coatings.

Each generic type was represented in the study by two coatings procured from different manufacturers, making it a total of ten coatings to be evaluated.

3.2 SPECIMEN PREPARATION

Concrete and mortar specimens were cast for the application of selected surface coatings to determine their physical, chemical and weathering properties. Table 3.1 lists the types of specimens that were utilized to evaluate the performance of selected coatings.

3.2.1   Concrete Mix Specifications

A concrete mix with a cement content of 370 kg/m^3 and effective water to cement ratio of 0.45 was utilized for the concrete specimens. Coarse aggregate constituted 62 percent of the total aggregate and the rest was sand. The physical properties of the coarse aggregate utilized for preparing the concrete specimens are summarized in Table 3.2. The gradation of the coarse aggregate based on ASTM C33 is shown in Table 3.3. Table 3.4 summarizes the physical properties of the fine aggregate utilized in the mortar and concrete specimens. The composition of the ASTM C150 Type V cement used for casting the mortar and concrete specimens is given in Table 3.5.

Table 3.1: Details of mortar and concrete specimen utilized to evaluate the performance of coatings.

Property	Specimen material	Size of the specimen
Adhesion	Concrete	100mm × 62.5mm × 300mm
Crack bridging	Mortar	25mm× 25mm× 250mm
Thermal variation resistance	Mortar	50mm× 50mm×50mm
Moisture variation resistance	Mortar	50mm× 50mm×50mm
Chemical resistance	Mortar	25mm× 25mm×25mm
Moisture vapor resistance	Mortar	50mm Φ × 75mm height
Carbonation resistance	Mortar	50mm Φ × 75mm height
Chloride permeability	Concrete	75mm Φ × 50mm height
Chloride diffusion	Concrete	75mm Φ × 150mm height
Reinforcement corrosion	Concrete	75mm Φ × 150mm height

Table 3.2: Properties of coarse aggregates utilized in preparing concrete specimens.

Absorption, ASTM C 127	2.5%
Specific gravity, ASTM C 127	2.42

Table 3.3: Grading of the coarse aggregates used in the concrete specimens.

Sieve Opening, mm	Percent passing
12.5	60
9.5	20
4.75	15
2.36	5

Table 3.4: Properties of fine aggregate used in the concrete and mortar specimens.

Absorption, ASTM C 128	0.5%
Specific Gravity, ASTM C 128	2.64

3.2.2 Mortar Mix Specifications

The cement mortar specimens were prepared with cement to sand ratio of 2.5 with an effective water to cement ratio of 0.45. Table 3.4 and Table 3.5 show the properties of the fine aggregate and cement used in the cement mortar specimens, respectively.

3.3 TEST TECHNIQUES

The selected coatings were applied on concrete/mortar specimens, detailed in Table 3.1, in accordance with the manufacturers recommendations and tested for the following:

i. Adhesion with concrete,

ii. Crack bridging,

iii. Chloride permeability,

iv. Moisture vapor resistance,

v. Chemical resistance,

vi. Resistance to thermal variations,

vii. Resistance to moisture variation,

viii. Carbonation resistance,

ix. Chloride diffusion, and

Table 3.5: Chemical composition of the ASTM C150 Type V cement used in the concrete and mortar specimens.

Constituent	Weight, %
SiO_2	25.0
Al_2O_3	3.4
Fe_2O_3	2.8
CaO	64.4
MgO	1.9
SO_3	1.6

x. Resistance to reinforcement corrosion.

The above tests have been described in detail in the following pages.

3.3.1 Adhesion with Concrete

The selected coatings were applied on 100 mm x 62.5 mm x 300 mm prismatic concrete specimens. Three aluminum dollies were fixed on the coated surface of the specimen, as schematically shown in Figure 3.1, with strong epoxy glue to ensure that the strength of the bond between the dolly and surface coating was much higher than the adhesive strength of the coating with concrete. Figure 3.2 shows the dollies fixed on a coated concrete specimen. Upon drying, the dollies were pulled off the coated surface using a pull-off tester, as per the procedure outlined in ASTM D 4541, and the pull-off load recorded. Figure 3.3 shows a concrete specimen with the dollies and pull-off tester. A cross-sectional view of the pull-off tester is shown in Figure 3.4. The average of three pull-off readings was recorded as the adhesive strength of the surface coating with the concrete substrate.

3.3.2 Crack Bridging Ability

The notched 25 mm x 25 mm x 250 mm mortar specimens were coated with the selected coating and two steel plates were fixed on the coated surface using epoxy glue, as schematically represented in Figure 3.5. A similar setup was utilized by Dulaijan et al. [60, 61] to evaluate the crack bridging ability of epoxy resin coatings. A tensile load was applied on the mortar specimen through the steel plates using MTS loading machine. A very low rate of loading was utilized to

Coated surface

300 mm

100 mm

62.5 mm

Metal Dollies
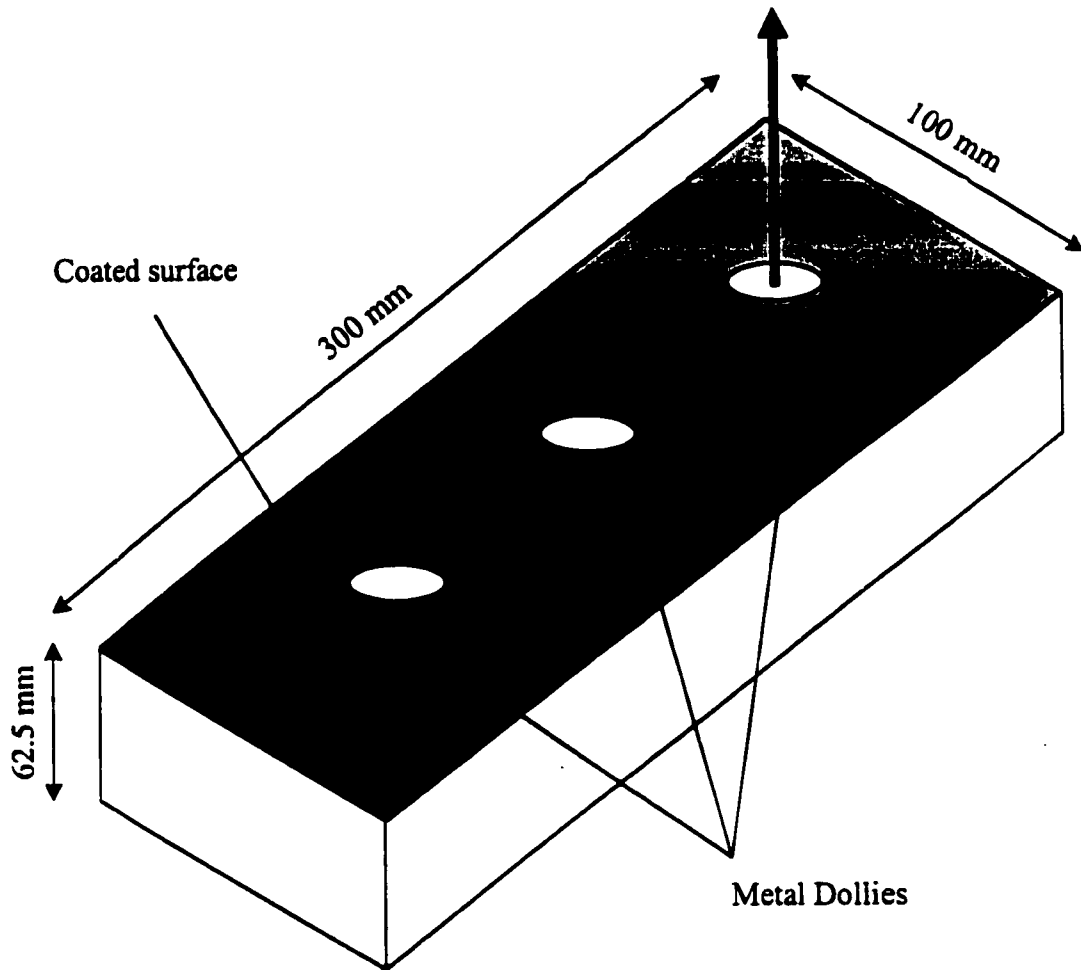
Not to Scale

Figure 3.1: Concrete specimen to be utilized to
evaluate the Adhesion of Concrete Coatings
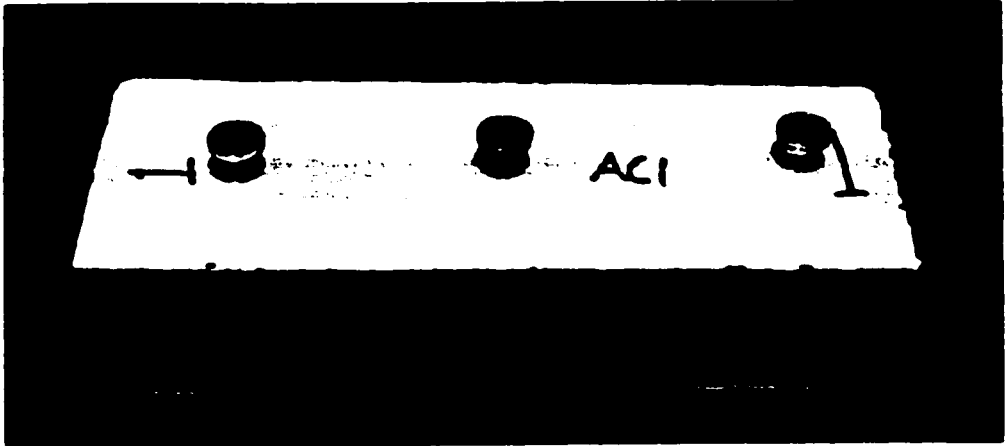
Figure 3.2: Concrete specimen tested for coating adhesion.
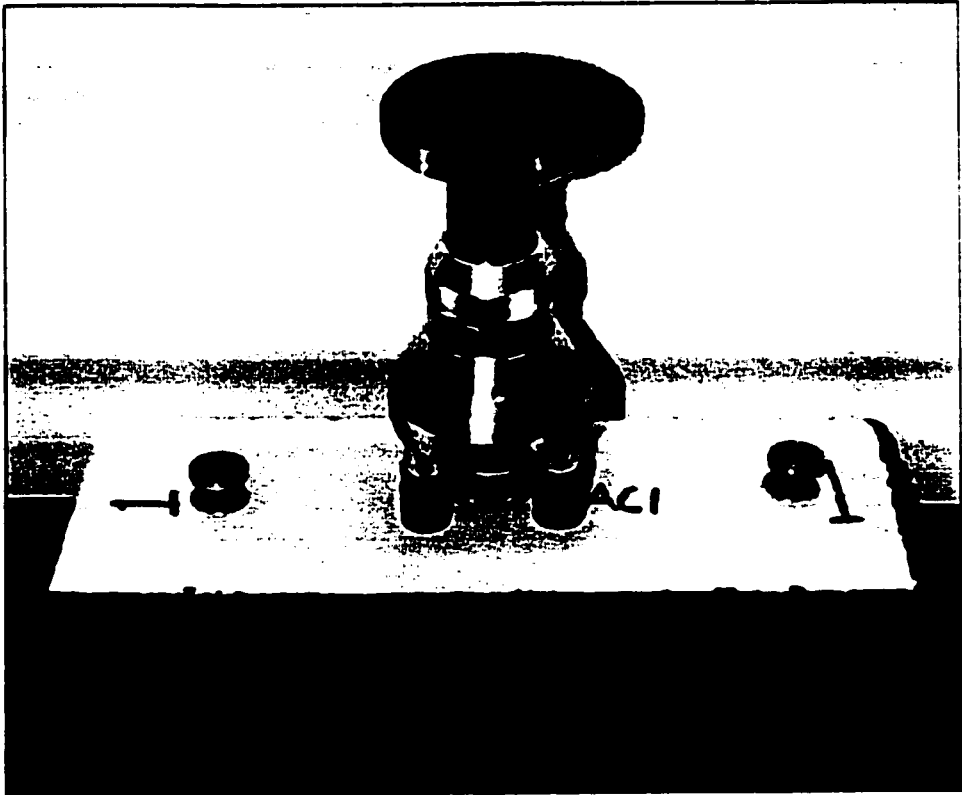
Figure 3.3: Adhesion testing apparatus.
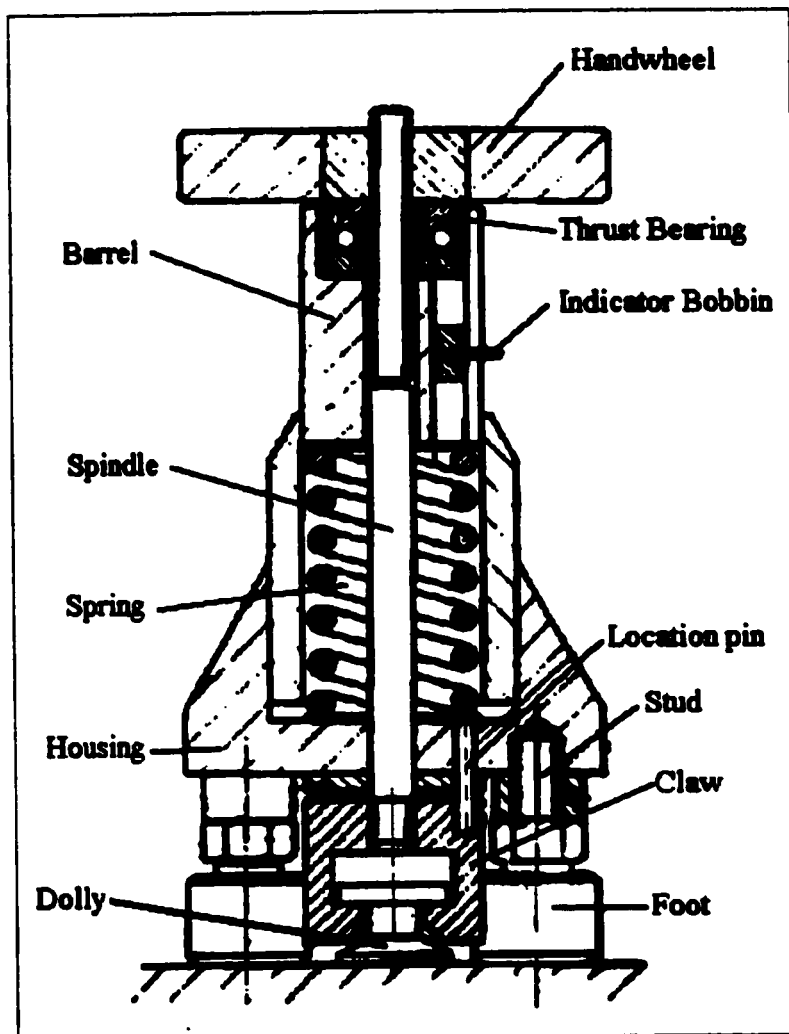
Figure 3.4: Cross- sectional view of the adhesion tester.
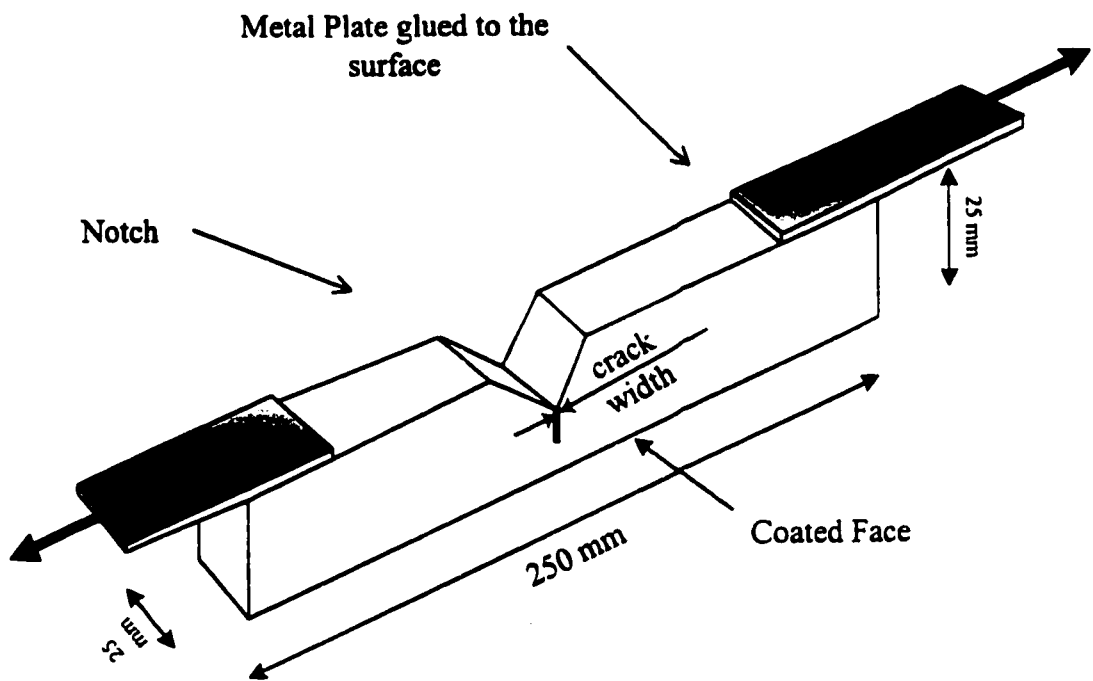
Figure 3.5:   Geometry of Test Specimen used to evaluate the Crack
Bridging Ability of Concrete Coating.

ensure that the specimen failure was gradual. As the load was applied, a crack initiated at the notch and propagated towards the coated surface. The width of the crack was carefully observed and the width at which a crack appeared in the coating was recorded as the crack bridging ability of the surface coating. Three specimens were tested and the average crack width reported.

3.3.3   Chloride Permeability

The selected surface coatings were applied on the two faces of 75 mm ϕ x 50 mm concrete discs. A rapid set epoxy coating was applied on the curved surfaces of the discs to make them impermeable. The samples were, then, saturated with water, under vacuum as per the procedures outlined in ASTM C 1202. The specimen was then clamped between the two halves of a chloride permeability cell, schematically shown in Figure 3.6. Figures 3.7 and 3.8 show the actual setup for the chloride permeability test. One half portion of the cell contained a reservoir, filled with 3% sodium chloride solution. This portion was connected to the positive terminal of a DC power source. The second half of the cell was filled with 0.3 molar sodium hydroxide solution, and was connected to the negative terminal of the DC power source. One copper mesh was provided on each side of the cell for impressing the current on the specimen and rubber shims were used to prevent leakage.

A D.C. power source was utilized to apply a potential of 60 V. The intensity of current flowing across the sample was calculated by determining the potential drop over the two terminals of a resistor connected as part of the power line. The
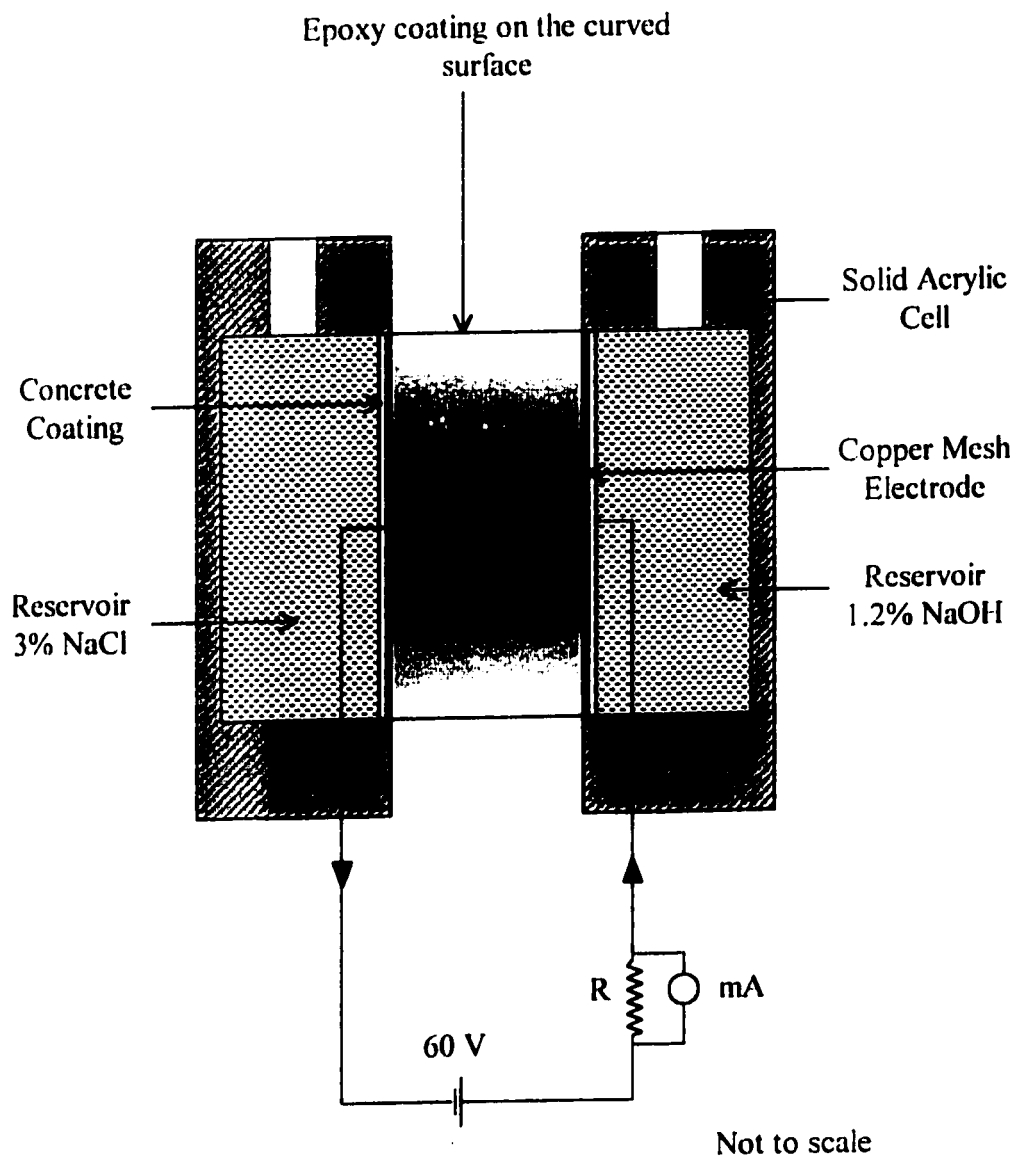
Figure 3.6: Chloride Permeability Test Setup.

Figure 3.7: Chloride permeability test set-up.
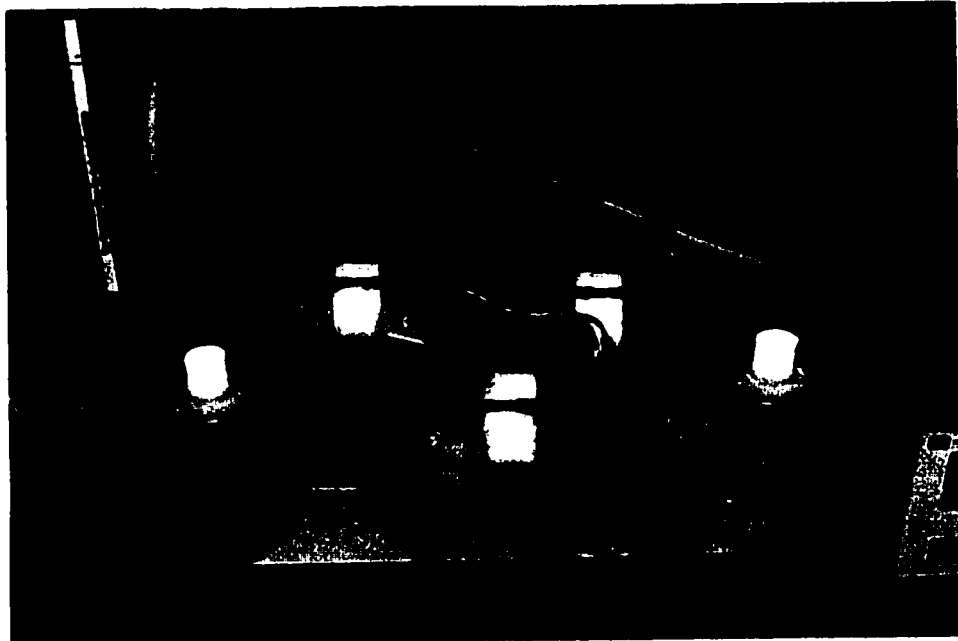
Figure 3.8: A close view of the chloride permeability test cells.

current was recorded for 6 hours at intervals of 15 minutes and plotted against time. The area under the curve provides the total charge passed in Coulombs (ampere-seconds). Higher values of total charge passed indicate lower electrical resistivity of concrete and greater chances of reinforcement corrosion.

Maslehuddin et al [62] have recommended the upper limits of chloride permeability for various plain and blended cement concrete's in the Gulf conditions.

3.3.4　Moisture Vapor Resistance

The selected coatings were applied on all the faces of 50 mm ϕ x 75 mm cement mortar specimens. The specimens were weighed after the coating dried and then placed in a water tank on a wire mesh such that only the bottom face was always in contact with water, as shown in Figure 3.9. The increase in weight of the sample, due to absorption of water, was recorded at periodic intervals and plotted against time to evaluate the moisture vapor transmission resistance of the coating.

3.3.5　Chemical Resistance

The 25 x 25 x 25 mm cement mortar specimens were coated on all the faces with the selected coating and then immersed in a 2% sulfuric acid solution. The coated specimens were visually inspected at regular intervals for signs of deterioration. The extent of deterioration was evaluated on a qualitative rating varying from 1 to 5. A rating of 1 would indicate no deterioration while a rating of 5 would indicate complete deterioration of the coating.
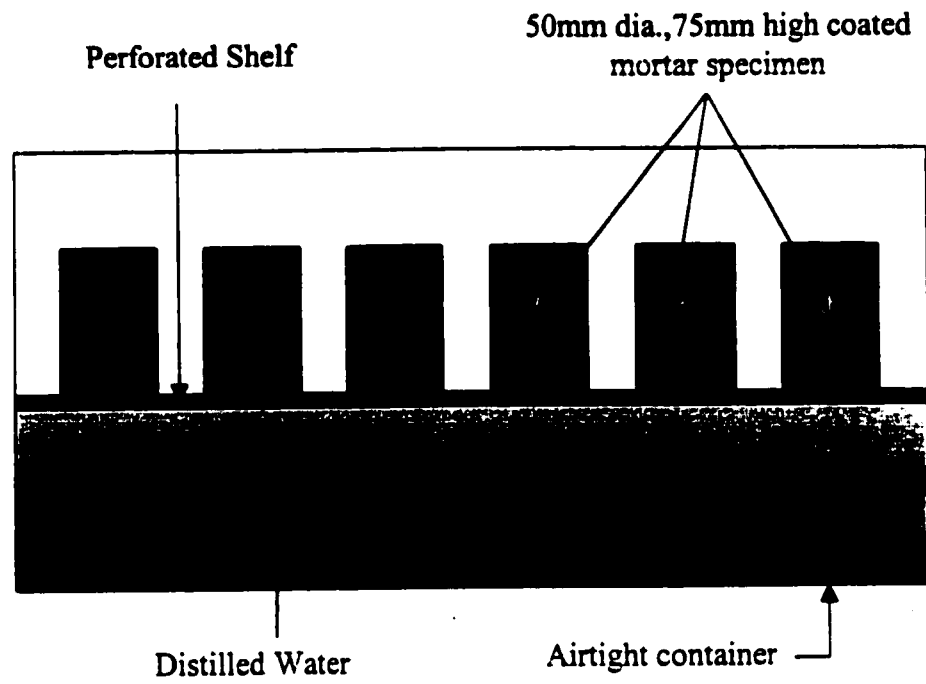
Figure 3.9: Setup for the moisture vapor resistance testing

Dulaijan et al [60] evaluated the chemical resistance of epoxy resin coatings by immersing them in 2% sulfuric acid for 56 days and performing a similar visual coating deterioration rating.

3.3.6 Resistance to Thermal Variations

The selected coatings were applied on all the faces of 50 x 50 x 50 mm cement mortar specimens. These cubes, upon drying, were placed in an oven where they were exposed to 70 °C for 8 hours and 25 °C for 16 hours. This completed one thermal cycle. The performance of the coating was evaluated after 30, 60, 90 thermal cycles by qualitative and quantitative testing as follows: -

Quantitative test: water absorption according to ASTM C 642.

Qualitative test: visual inspection for cracking and blistering of coating.

3.3.7 Resistance to Moisture Variation

The selected coatings were applied on all the faces of the 50 x 50 x 50 mm cement mortar specimens. These specimen, after being oven-dried at 70 °C for 3 days, were weighed and then exposed to wet and dry cycles. They were submerged in water for 4 hours and dried in air for 8 hours. After 60, 120 and 180 wet-dry cycles, the specimens were examined for coating deterioration and weight loss.

3.3.8 Carbonation Resistance

The 50 mm ϕ x 75 mm mortar specimens were coated on all the faces with the selected coating. These specimens were then exposed to an accelerated

carbonation environment by placing them in a chamber through which carbon dioxide (3% CO_2) gas was passed for three months. The setup is shown in Figure 3.10. The specimens were taken out at the end of one, two and three months of exposure and then cut into two halves perpendicular to the cylindrical axis and the cut surfaces were sprayed with phenolphthalein. The uncarbonated portion turned pink and the carbonated area remained unchanged, clearly specifying the depth of carbonation. The depth of carbonation was determined at several locations and the average value reported.

3.3.9   Chloride Diffusion

The selected surface coating was applied on one face of 75 mm ϕ x 150 mm cylinders. Wax was applied on the curved surface and the uncoated face of the cylinder to ensure unidirectional flow of chloride ions and then they were immersed in 5% sodium chloride (NaCl) solution for three months. The setup is shown in Figure 3.11. After this period, the specimens were removed and cleaned and concrete discs of 5 mm thickness were obtained at depths of 5, 20, 50, 75 and 100 mm. These discs were crushed to obtain concrete powder passing ASTM # 100 sieve. Five grams of this sample was placed in a beaker to which 50 ml of hot distilled water was added. The beaker was covered and the contents were allowed to cool for 24 hours. The mixture was then filtered into a flask and the filtrate was made up to 150 ml by adding more distilled water. 0.2 ml of this solution was added to 9.8 ml of distilled water using a pipette tip. Then, 2 ml of 0.25 M ferric ammonium sulfate and 2 ml of mercuric thiocyanate were added to it. This solution was then poured into a test tube and the test tube was placed in spectrophotometer
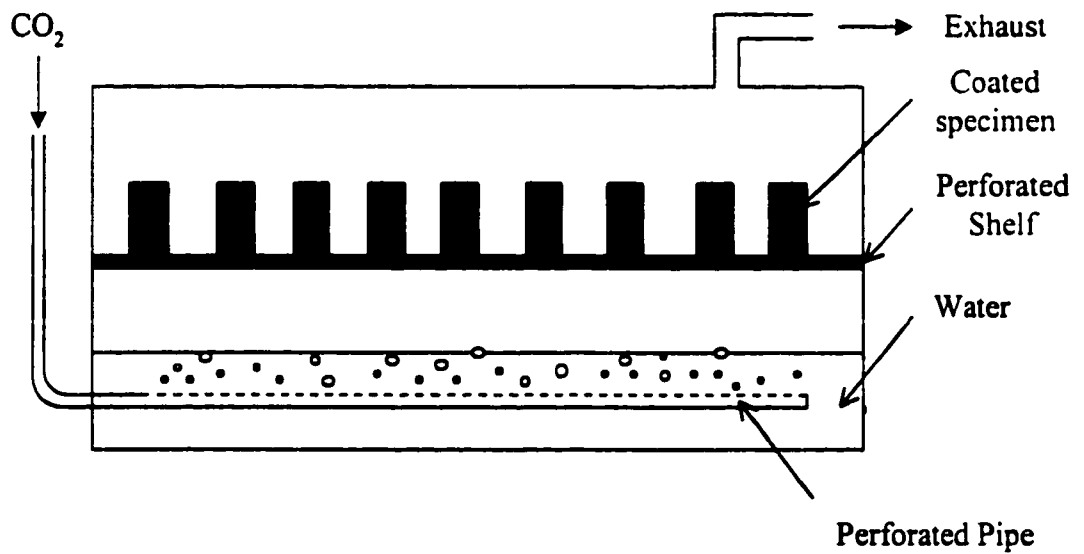
Accelerated carbonation tank
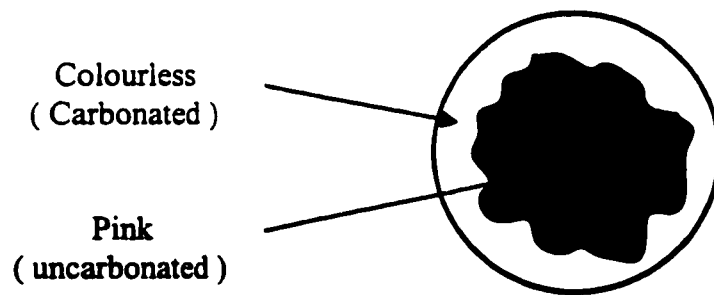
Section through Specimen after three
months of exposure to CO_2

Figure 3.10: Experimental setup to measure carbonation

75mm dia., 150mm high concrete
specimen coated on the top face

Wax coating on all
other surface

15% Sodium Chloride
solution
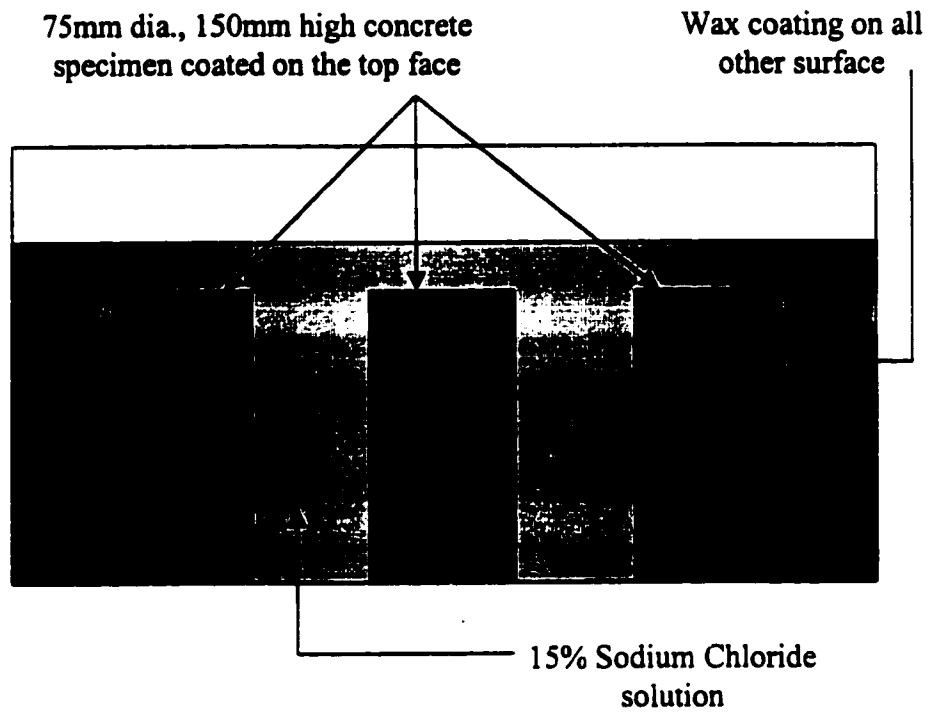
Figure 3.11: Setup to evaluate Chloride Diffusion in the coated
concrete specimens.

to measure the absorbance. A blank solution was prepared and its absorbance was also measured. The chloride concentration was calculated using the chloride calibration curve prepared earlier utilizing a chloride solution of known concentration.

The chloride concentration was then plotted against depth. The coefficient of chloride diffusion in each of the selected coating was determined from the chloride profile by solving Fick's second law of diffusion [63, 64], as shown below.

$$\frac{C_x}{C_s} = 1 - erf\left\{\frac{x}{2\sqrt{D_c t}}\right\} \qquad (3.1)$$

where, C_x is the chloride concentration at depth x,

Cs is the chloride concentration at the concrete surface,

x is the depth from concrete surface,

t is the time in seconds, and

D_c is the effective chloride difusion coefficient.

3.3.10   Reinforcement Corrosion

Cylindrical concrete specimens measuring 75 mm ϕ x 150 mm with an embedded bar were cast, as shown in Figure 3.12. Epoxy paint was applied to the bar at the specified regions to avoid the initiation of corrosion at those critical locations. These specimens were then exposed to an accelerated corrosion environment by impressing an anodic potential of 4 Volts. For this purpose, the bars in the concrete specimens were connected to the positive terminal of a DC power supply, while a stainless steel plate was connected to its negative terminal.
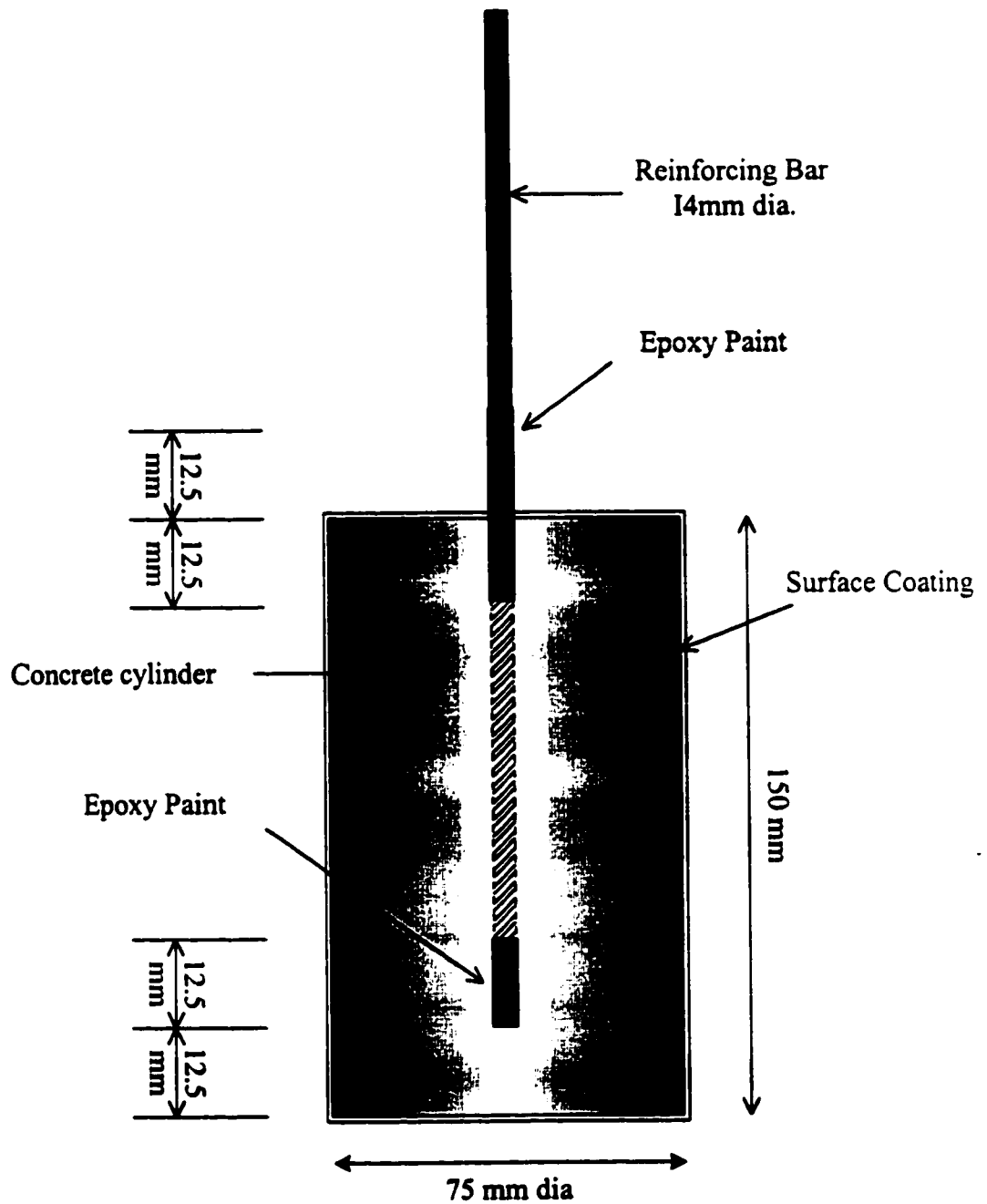
Figure 3.12: Concrete Specimen to be utilized to evaluate Reinforcement Corrosion in the coated specimens.

The current supplied to each of the specimen, due to the application of a potential difference of +4V, was monitored at 4 hours interval by measuring the potential drop over a 1 Ohm resistor. The two leads of the resistor were connected to a data acquisition system for monitoring the current. Figure 3.13 is a schematic representation of the experimental setup utilized to evaluate corrosion resistance of coated and uncoated concrete specimens. The current supplied to each specimen was plotted against time and the time – current curves were utilized to evaluate the time to cracking of concrete due to reinforcement corrosion [40].

4 V
Impressed Potential

Current passing
through to the
electrode

(4V)

(mA)

Coated Sample

Stainless Steel
Electrode

5 % NaCl Electrolyte
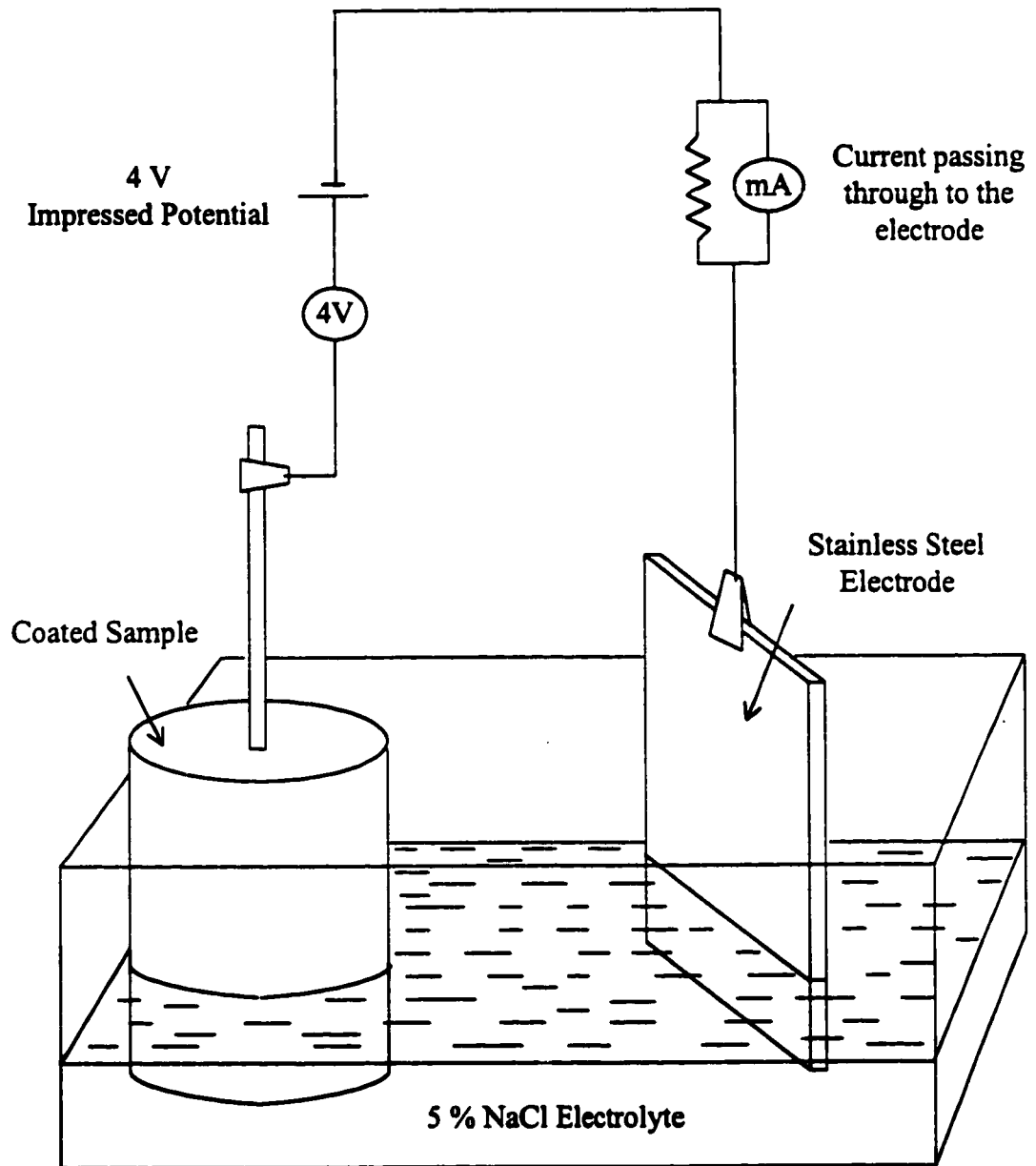
Figure 3.13: Accelerated corrosion test setup.

CHAPTER 4

RESULTS AND DISCUSSIONS

The selected coatings were tested, after application on cement mortar/ concrete specimens, for their performance as elaborated in the previous Chapter. Results from the experimental program were analyzed to ascertain the performance of each coating under the aggressive environmental conditions. The results of tests conducted on the selected coatings are presented with a discussion thereon.

4.1 ADHESION TO CONCRETE

The coatings were tested for adhesion with concrete by applying them on prismatic concrete specimens. Three aluminum dollies were fixed on the coated surface of the specimen with a strong epoxy glue. After 48 hours of application of the glue, the dollies were pulled off the coated surface using a pull-off tester as per the procedure outlined in ASTM D 4541, and the pull-off load recorded. The

average of three pull-off readings was recorded as the adhesive strength of the surface coating with the concrete.

Four types of adhesion failure were noted:

i. Coating failure: In most cases, at failure, the coating adhered fully to the dolly and the concrete surface exposed was smooth and circular in shape, as shown in Figure 4.1. Such a failure gave reliable results.

ii. Concrete failure: In certain instances, the coating adhered to the dolly as well as to the concrete leaving behind a depression in the concrete surface. This meant that the coating adhesion was stronger than the tensile strength of the concrete causing the concrete to breakaway, as shown in Figure 4.2.

iii. Partial Failure: This occurred when the coating was not completely attached to the dolly. The concrete surface exposed was irregular and the dolly was not covered fully with the coating, as shown in Figure 4.3. This implied that the bond between the dolly and the coating had failed before the coating failure, due to improper application of the glue. Such results were discarded, as the validity was questionable.

iv. Inter-layer failure: In some cases, the failure was observed between the topcoat and the primer. The topcoat came off and the primer was exposed, as shown in Figure 4.4.

The readings on the pull-off tester were in the range of 0.5 to 3.5 MPa. Table 4.1 summarizes the adhesive strength of the selected coatings and the results have
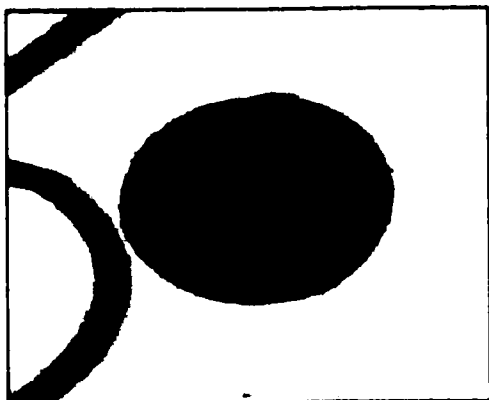
Figure 4.1: Failure in coating.
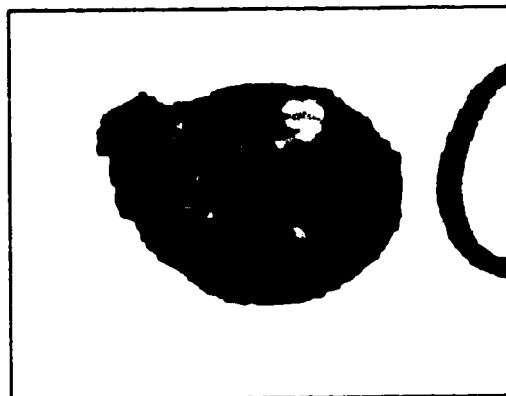
Figure 4.2: Failure in concrete.
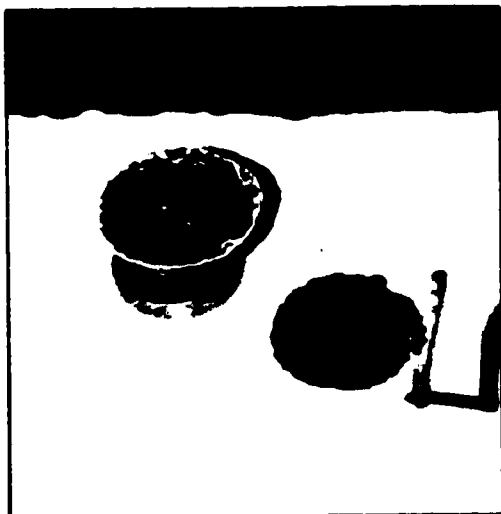
Figure 4.3: Partial failure.

Figure 4.4: Coating inter-layer failure.

Table 4.1: Adhesion of the coatings with concrete.

Coating	Adhesion strength, MPa
Acrylic coating AC1	1.2
Acrylic coating AC2	1.5
Polymer emulsion coating PE1	0.9
Polymer emulsion coating PE2	0.9
Epoxy coating EP1	3.3
Epoxy coating EP2	1.8
Polyurethane coating PU1	1.8
Polyurethane coating PU2	1.5
Chlorinated rubber coating CR1	1.0
Chlorinated rubber coating CR2	2.2

been plotted in Figure 4.5. The highest value of adhesive strength. 3.3 MPa, was noted in the epoxy coating, EP1. Further, failure was noted in the concrete indicating that the adhesion strength of coating was higher than the tensile strength of concrete. The chlorinated rubber coating, CR2 was the next best in adhesion as it failed at 2.2 MPa, but CR1 gave low readings due to inter-layer failure of the coating. The polyurethane coatings also performed well with coating failures occurring between 1.5 to 1.8 MPa. The adhesive strength of the acrylic coatings was in the range of 1.2 to 1.5 MPa while it was 0.9 MPa for the polymer emulsion coatings.

The results in Table 4.1 and Figure 4.5 indicate that the adhesion of the epoxy resin coatings was better than that of the other coatings. This was followed by chlorinated rubber and polyurethane coatings. The superior performance of these coatings in adhesion with concrete could be attributed to their chemical formulation. Based on the results, a threshold adhesive strength of 1.5 MPa can be specified for concrete coatings. Polymer emulsion and acrylic coatings should not be used where the substrate is very smooth because of their low adhesive strength.

Swamy and Tanikawa [57] performed adhesion tests on an acrylic rubber coating and reported maximum adhesive strength of 2.7 MPa. Dulaijan et al. [60] reported a maximum adhesive strength of 2 MPa for epoxy resin coatings.

The performance of the selected coatings in adhesion with concrete can be rated in the following descending order:

    i)   Epoxy resin coating, EP1
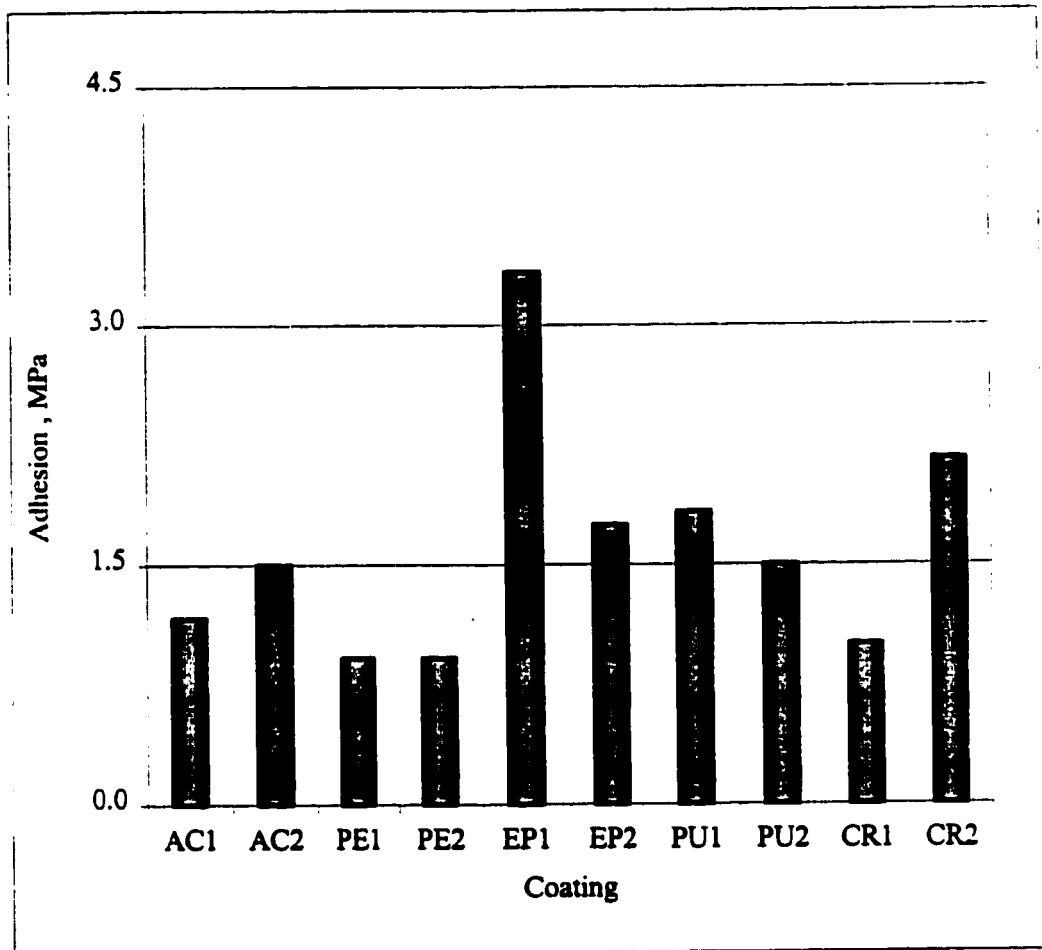
Figure 4.5: Adhesion of the selected coatings with concrete.

ii)   Chlorinated rubber coating, CR2

iii) Polyurethane coating, PU1

iv)   Epoxy resin coating, EP2

v)   Polyurethane coating, PU2

vi)   Acrylic coating, AC2

vii) Acrylic coating, AC1

viii) Chlorinated rubber coating, CR1

ix)   Polymer emulsion coating, PE1

x)   Polymer emulsion coating, PE2

4.2   CRACK BRIDGING ABILITY

Two types of failures were observed in the crack-bridging test, sudden failure due to improper alignment of the sample in the grips of the machine and the gradual type of failure, where a gap appeared in the cracked sample and the coating was stretched over this gap until the failure of the coating occurred. The crack width could not be measured in the former type of failure due to the sudden nature of the failure. The latter readings were recorded as the crack width, which the coating was able to bridge, thus determining the crack bridging ability of the coating.

Table 4.2 and Figure 4.6 show the crack bridging ability, i.e. the crack width at coating failure, of the selected coatings. The higher the width of crack at coating failure better would be the crack bridging ability of the coating. The crack bridging ability of the epoxy coatings was more than that of the other coatings, being in the range of 0.64 to 0.77 mm. The chlorinated rubber coatings failed at average crack widths of 0.43 to 0.63 mm, followed by the polyurethane coatings, which failed at a width of 0.32 to 0.48 mm. The crack bridging ability of the acrylic coatings was in the range of 0.24 to 0.33 mm, while it was in the range of 0.33 to 0.48 mm in the polymer emulsion coatings.

The above results are in conformance with the data presented by Dulaijan et al. [60] where the epoxy resin coatings failed at crack widths of 0.2 to 0.55 mm. Swamy and Tanikawa [35] used a different method to evaluate the crack bridging ability of an acrylic rubber coating and observed that the coating bridged cracks from 5 to 14 mm in width before failure.

The crack bridging ability of any coating depends primarily on its flexibility, adhesion and cohesiveness. The crack widths at failure for all the coatings tested were found to be less than 0.5 mm and cracks of this size are very common in structures. These could be shrinkage cracks, structural cracks or thermal expansion cracks. Therefore, concrete surface treatments would be more effective in bridging such cracks. The epoxy and chlorinated rubber coatings were able to bridge cracks wider than 0.5 mm, hence they can be utilized on substrates that are prone to cracking but the polymer emulsion and acrylic coatings should be used only in situations where cracks are not expected.

Table 4.2: Crack width in the coated specimens at coating failure.

Coating	Crack width, mm
Acrylic coating AC1	0.237
Acrylic coating AC2	0.325
Polymer emulsion coating PE1	0.285
Polymer emulsion coating PE2	0.38
Epoxy coating EP1	0.64
Epoxy coating EP2	0.77
Polyurethane coating PU1	0.483
Polyurethane coating PU2	0.325
Chlorinated rubber coating CR1	0.62
Chlorinated rubber coating CR2	0.43
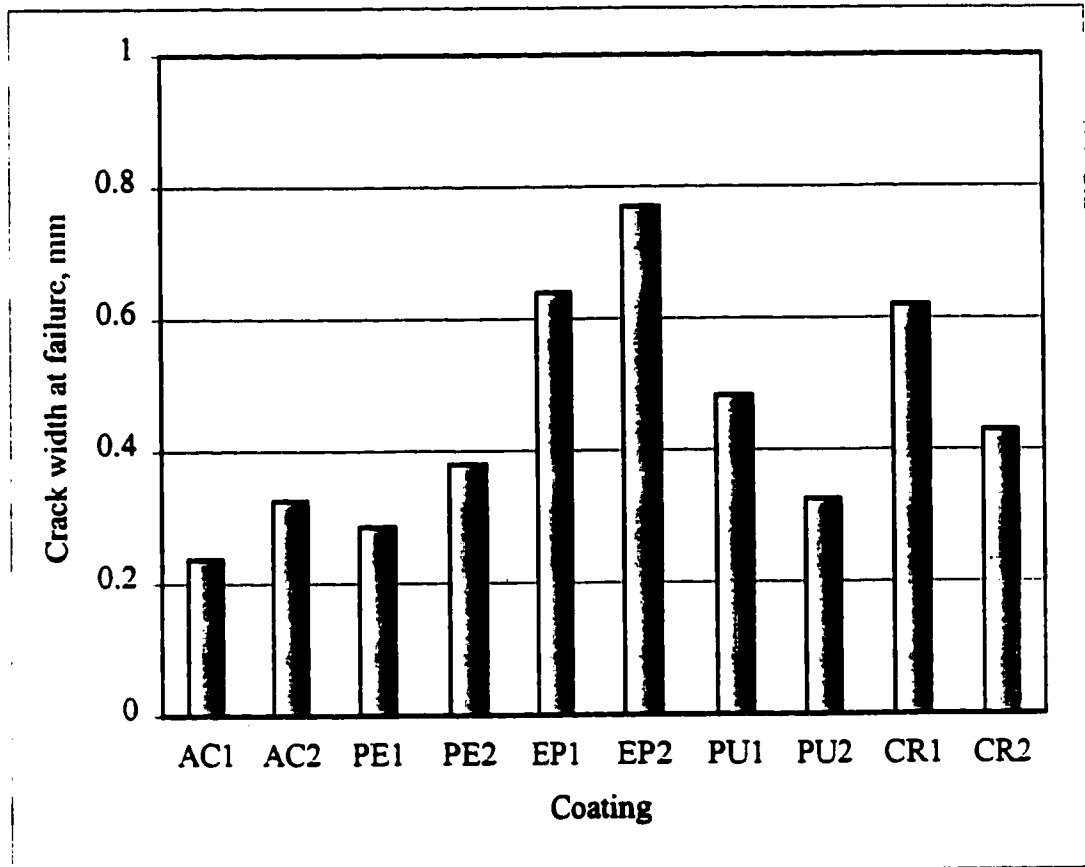
Figure 4.6: Crack bridging ability of the selected coatings

The performance of the selected coatings in crack bridging can be rated in the following descending order:

i)   Epoxy resin coating, EP2

ii)   Epoxy resin coating, EP1

iii) Chlorinated rubber coating, CR1

iv)   Polyurethane coating, PU1

v)   Chlorinated rubber coating, CR2

vi)   Polymer emulsion coating, PE2

vii) Polyurethane coating, PU2

viii) Acrylic coating, AC2

ix)   Polymer emulsion coating, PE1

x)   Acrylic coating, AC1

4.3 CHLORIDE PERMEABILITY

The selected surface coatings were applied on concrete specimens and they were tested for chloride permeability as per the procedures outlined in ASTM C 1202.

The intensity of the current flowing across the sample was determined by measuring the potential drop between the two leads of a resistor connected in the

power line. The current data was recorded for six hours at intervals of 15 minutes and this was plotted against time as shown in Figure 4.7. The area under the curve is the total charge passed in Coulombs (ampere-seconds). Higher values of the total charge passed provide an indication of the electrical resistivity of concrete coated with the selected coating.

Table 4.3 and Figure 4.8 show the total charge passed through the concrete specimens coated with the selected coatings. Table 4.3 also shows the ASTM C 1202 classification for concrete based on the total charge passed. The chloride permeability of the concrete specimens coated with the chlorinated rubber coatings was in the range of 39 to 50 coulombs, while it was in the range of 6 to 40 coulombs in the polyurethane coatings. In the epoxy coated concrete specimens, the total charge passed varied from 7 to 160 coulombs, whereas in the concrete specimens coated with acrylic coatings the total charge passed varied from 70 to 164 coulombs. The total charge passed in the concrete specimens coated with the polymer emulsion coatings was in the range of 515 to 713 coulombs, whereas the total charge passed in the uncoated concrete specimens was 975 coulombs.

According to ASTM C1202 classification the chloride permeability of all the coated concrete specimens was 'negligible' except in those coated with coatings AC1, PE1, PE2 and EP2, which showed 'very low' chloride permeability. The chloride permeability in the uncoated concrete specimens was 'low'.

The chloride permeability of the concrete specimens coated with polyurethane, chlorinated rubber, epoxy and acrylic coatings was almost one-tenth
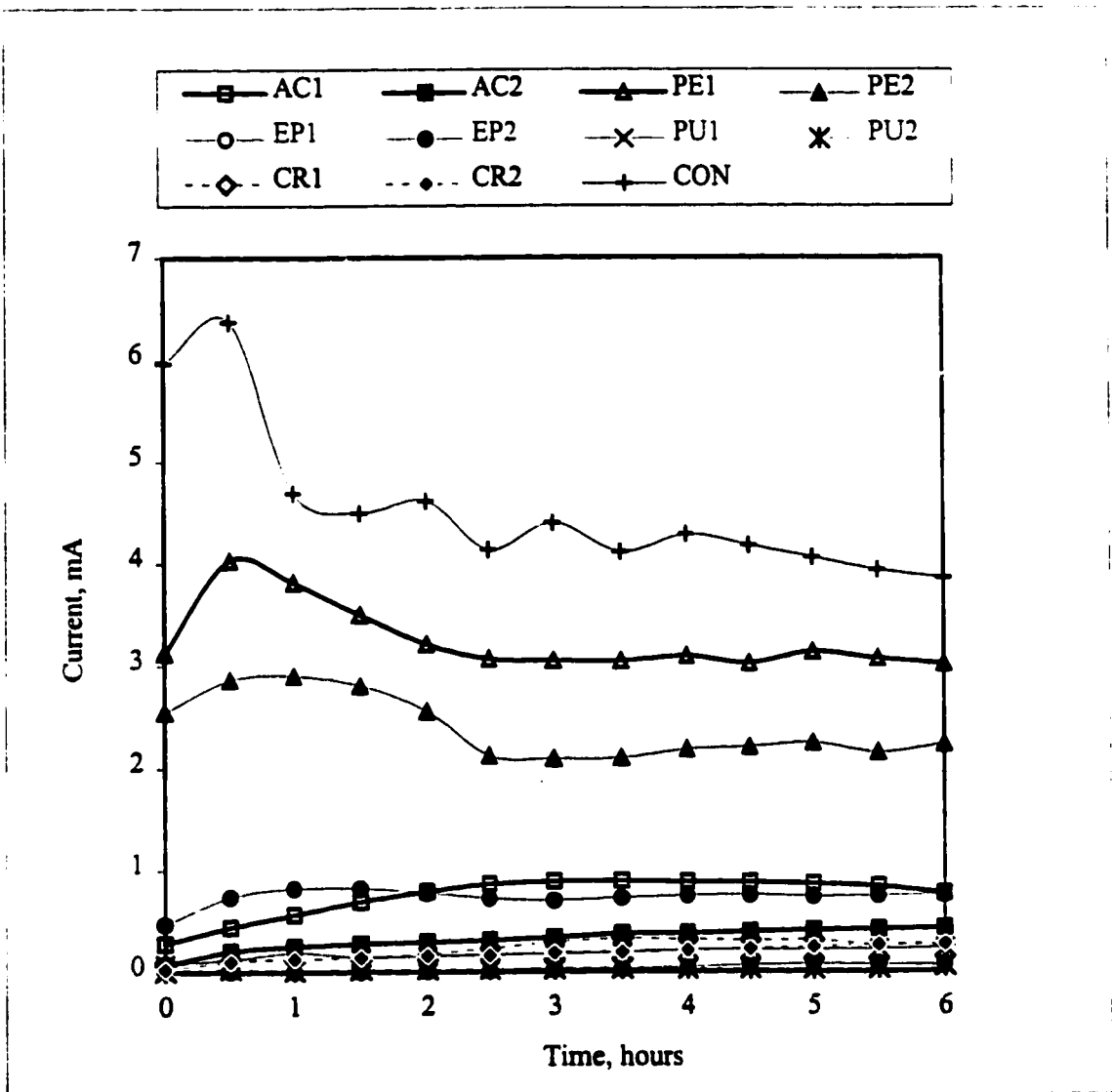
Figure 4.7: Time-current curves for the concrete specimens coated with the selected coatings.

Table 4.3: Charge passed through the coated specimens in the chloride permeability test.

Coating	Charge passed, Coulombs	ASTM C1202 classification
Acrylic coating AC1	163.67	Very low
Acrylic coating AC2	69.71	Negligible
Polymer emulsion coating PE1	703.4	Very low
Polymer emulsion coating PE2	514.67	Very low
Epoxy coating EP1	7.32	Negligible
Epoxy coating EP2	159.93	Very low
Polyurethane coating PU1	39.09	Negligible
Polyurethane coating PU2	6.36	Negligible
Chlorinated rubber coating CR1	49.83	Negligible
Chlorinated rubber coating CR2	38.7	Negligible
None	975.47	Low
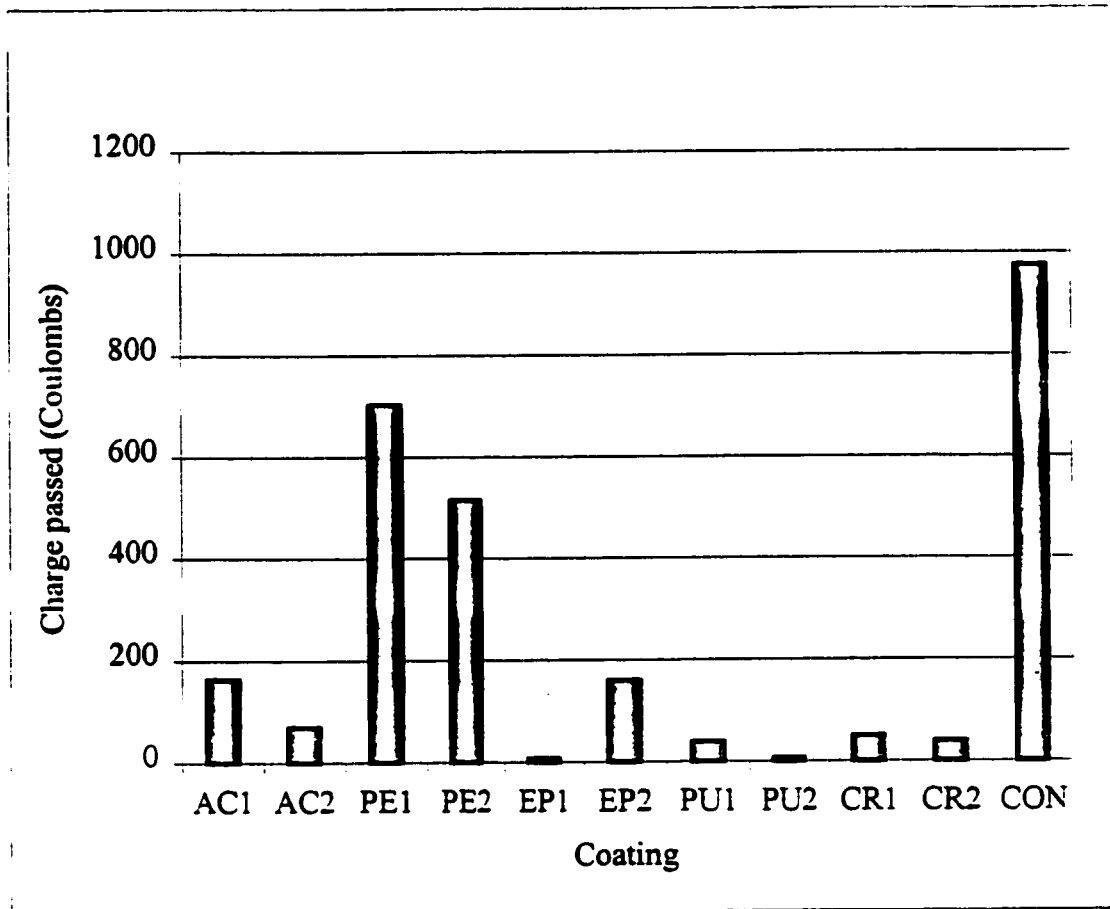
Figure 4.8: Performance of the selected coatings in chloride permeability resistance.

of that of uncoated concrete and one-fifth of the concrete specimens coated with polymer emulsion coatings. All the coatings lay under the 'very low' permeability rating.

The chloride permeability of a coated concrete specimen depends primarily on the porosity of the coating film. Lower the porosity of the film, lower will be the charge passing through the film. The porosity, in turn, depends on the volume of solids, dry film thickness and the type of binder used in the coating. The polyurethane and epoxy coatings are impregnable to the ingress of aggressive ions because they are solvent-based and as the coating cures, it leaves behind a tough film with low porosity.

The chloride permeability of resin-based coatings and cement-based coatings was evaluated by Dulaijan et al. [60] in accordance with ASTM C1202. It was observed that chloride permeability was 'negligible' in epoxy coated specimens and it was 'very low' in samples coated with cement based coatings.

The performance of the selected coatings in resisting chloride permeability is in the following descending order:

i) Polyurethane coating, PU2

ii) Epoxy resin coating, EP1

iii) Chlorinated rubber coating, CR2

iv) Polyurethane coating, PU1

v)   Chlorinated rubber coating, CR1

vi)   Acrylic coating, AC2

vii) Epoxy resin coating, EP2

viii) Acrylic coating, AC1

ix)   Polymer emulsion coating, PE2

x)   Polymer emulsion coating, PE1

4.4 WATER ABSORPTION

The selected coatings were applied on all the faces of 50 mm ϕ x 75 mm mortar specimens. The specimens were weighed oven-dry after the coating dried and then placed in a water tank on a wire mesh such that only the bottom face was always in contact with water. The increase in weight of the samples due to absorption of water was recorded at periodic intervals up to 56 hours and plotted against time to evaluate the moisture vapor transmission resistance of the coated and uncoated samples, as shown in Figure 4.9.

The total weight gained by the samples at the end of 56 hours is shown in Table 4.4 and the results are plotted in Figure 4.10. Uncoated cement mortar specimens absorbed water at a very rapid rate and after 56 hours the total absorption was about 5% by weight. The water absorption in the cement mortar specimens coated with polymer emulsion coatings was in the range of 3.3 to 3.4%, which was more than the water absorption noted in the specimens coated with other
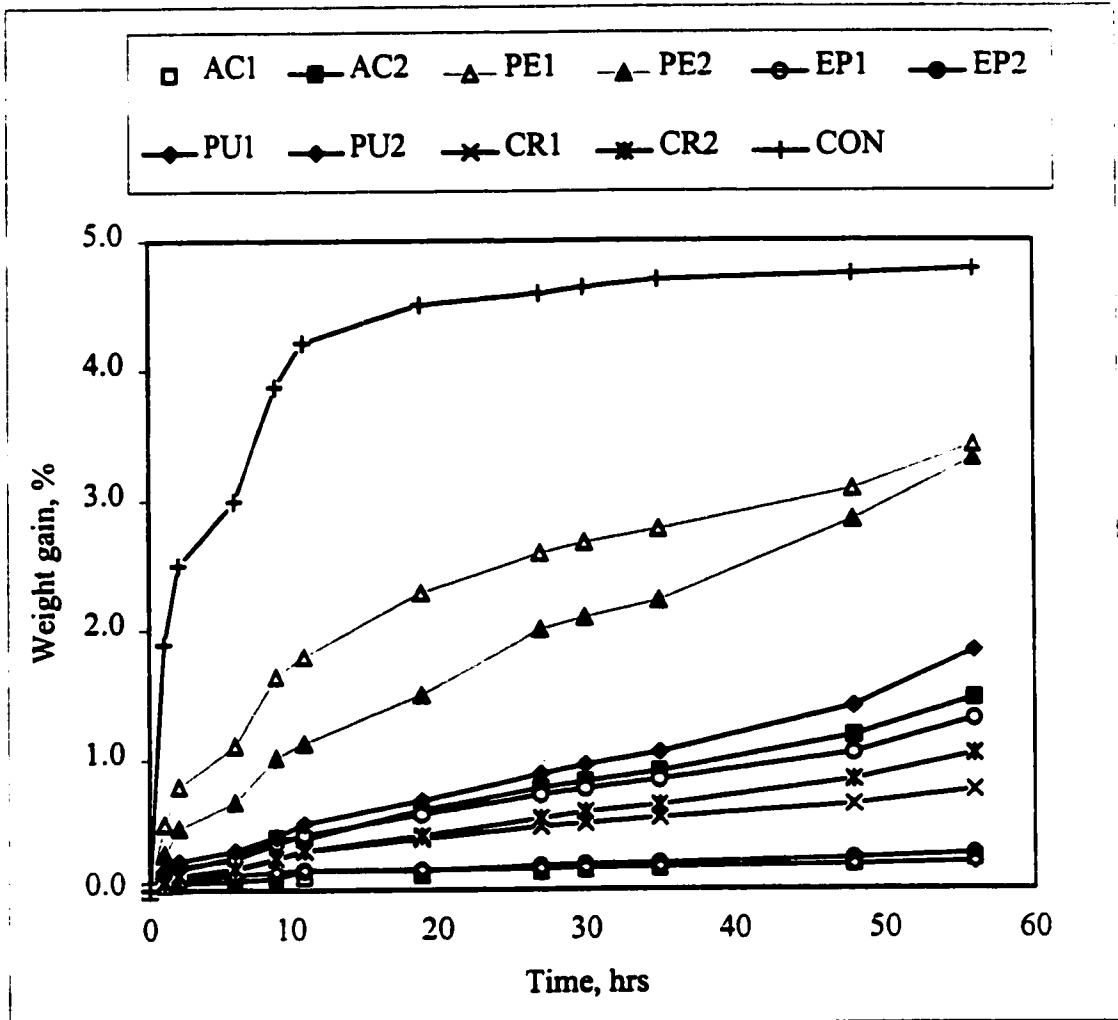
Figure 4.9: Variation of the weight gained by the coated and uncoated mortar specimens due to water absorption.

Table 4.4: Weight gain in the coated and uncoated cement mortar specimens after 56 hours of immersion in water.

Coatings	Weight gain, %
Acrylic coating AC1	0.23
Acrylic coating AC2	1.46
Polymer emulsion coating PE1	3.42
Polymer emulsion coating PE2	3.32
Epoxy coating EP1	1.30
Epoxy coating EP2	0.27
Polyurethane coating PU1	0.21
Polyurethane coating PU2	1.83
Chlorinated rubber coating CR1	0.76
Chlorinated rubber coating CR2	1.04
None	4.78
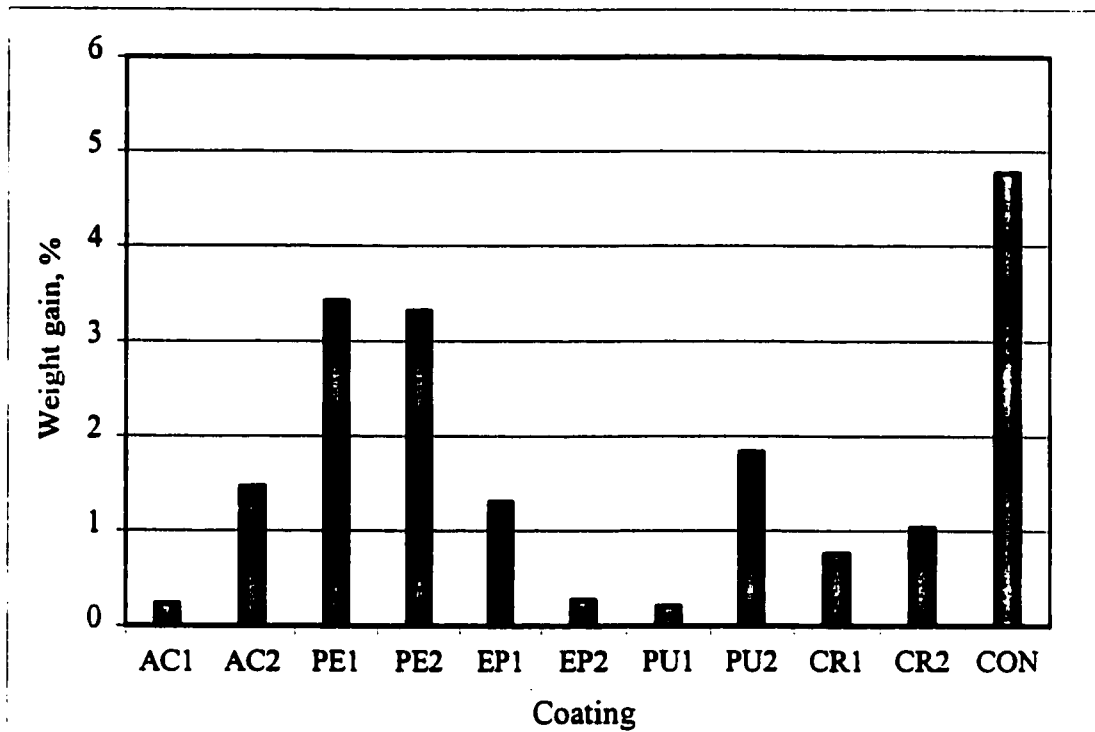
Figure 4.10: Weight gain in the coated and uncoated mortar specimens after 56 hours of immersion.

coatings. The specimens coated with acrylic coatings absorbed 0.23 to 1.46% water while those coated with chlorinated rubber absorbed water in the range of 0.76 to 1.04%. The water absorption in the samples coated with polyurethane coatings was about 0.21 to 1.83% and in the epoxy coated specimens it was in the range of 0.27 to 1.3%.

Minimum weight gain was noted in the cement mortar specimens coated with epoxy and polyurethane coatings. However, a large variation in the performance of the coatings of the same generic type procured from different manufacturers was observed. Hence, it is advised that when selecting a coating for moisture vapor resistance, each coating should be tested individually before use and the generic type should not be the sole criterion for selecting a coating.

The data in Figure 4.9 were utilized to calculate the rate of water absorption and sorptivity of the coated and uncoated mortar specimens using equations 4.1 and 4.2.

$$\text{Rate of water absorption} = W_w/(A_c \cdot t) \tag{4.1}$$

$$\text{Sorptivity} = V_w/(A_c \sqrt{t}) \tag{4.2}$$

where, W_w = weight gained by the specimens,

A_c = cross-sectional area of each specimen,

t = time of exposure, and

V_w = volume of water adsorbed by the specimen.

These data are presented in Table 4.5. The rate of water absorption in the cement mortar specimens coated with polymer emulsion coatings was in the range of 56 to 60 $g/m^2/hr$, whereas in the uncoated mortar specimens it was 63.4 $g/m^2/hr$. The mortar specimens coated with acrylic coatings absorbed water at a rate of 5 to 30 $g/m^2/hr$ and those coated with polyurethane coatings absorbed water at a rate of 4 to 37 $g/m^2/hr$. The rate of water absorption in the mortar specimens coated with chlorinated rubber coatings was in the range of 16 to 22 $g/m^2/hr$, whereas, the water absorption in the epoxy-coated specimens was the lowest, as expected, and it was in the range of 4 to 27 $g/m^2/hr$ due to a dense film formed on the specimens coated with these coatings.

Research [46] on the water absorption of specimens coated with acrylic and polyurethane coatings using the modified ISAT has shown that the rate of water absorption in the treated samples was about 40 $g/m^2/hr$, whereas in the untreated samples it was 350 $g/m^2/hr$. Dulaijan et al. [60] immersed the coated and uncoated mortar specimens for 672 hours in water and observed that the gain in weight of the uncoated specimens was 3% as compared to 0.6 to 2.6% in the specimens coated with epoxy resin-based coatings.

The performance of the selected coatings in absorbing water can be rated in the following descending order:

i)   Polyurethane coating, PU1

ii)   Acrylic coating, AC1

Table 4.5: Rate of absorption and Sorptivity for the coated and uncoated cement mortar specimens.

Coatings	Absorption rate, g/ m^2/hr	Sorptivity, mm / $\sqrt{hr}$
Acrylic coating AC1	4.4	0.03
Acrylic coating AC2	30.6	0.23
Polymer emulsion coating PE1	55.6	0.40
Polymer emulsion coating PE2	59.7	0.45
Epoxy coating EP1	26.9	0.20
Epoxy coating EP2	4.9	0.04
Polyurethane coating PU1	3.4	0.03
Polyurethane coating PU2	36.6	0.27
Chlorinated rubber coating CR1	16.1	0.12
Chlorinated rubber coating CR2	22.6	0.17
None	63.4	0.47

iii) Epoxy resin coating, EP2

iv) Chlorinated rubber coating, CR1

v) Chlorinated rubber coating, CR2

vi) Epoxy resin coating, EP1

vii) Acrylic coating, AC2

viii) Polyurethane coating, PU2

ix) Polymer emulsion coating, PE2

x) Polymer emulsion coating, PE1

4.5 CHEMICAL RESISTANCE

The chemical resistance of the selected coatings was evaluated by immersing the coated cement mortar specimens in a 2.5% sulfuric acid solution. The specimens were visually inspected at regular intervals for signs of deterioration and a qualitative rating, as detailed in Table 4.6, was assigned to the specimens depending on the extent of coating deterioration [39].

The specimens were inspected for deterioration after 3, 7, 21, 30 and 60 days of exposure to the sulfuric acid solution. Figures 4.11 through 4.21 show the coated and uncoated cement mortar specimens placed in the sulfuric acid solution. Figure 4.22 shows the coated and uncoated cement mortar specimens after 60 days of exposure to 2.5% sulfuric acid. Table 4.7 gives the ratings for the coatings after

Table 4.6: Qualitative rating for coating deterioration in specimens exposed to 2.5% H_2SO_4.

Rating	Description
1	Coating intact
2	Corners damaged
3	Corners and edges deteriorated
4	Corners, edges and some surface damage
5	Coating delamination and/or Dissolution

Table 4.7: Deterioration ratings for the coated and uncoated mortar specimens exposed to 2.5% H_2SO_4.

Coating	Deterioration rating, after				
	3 days	7 days	21 days	30 days	60 days
Acrylic coating AC1	1	2	2	3	3
Acrylic coating AC2	2	3	3	3	3
Polymer emulsion coating PE1	3	3	4	5	5
Polymer emulsion coating PE2	3	3	4	4	5
Epoxy coating EP1	1	1	1	1	2
Epoxy coating EP2	1	1	2	2	2
Polyurethane coating PU1	1	1	1	2	2
Polyurethane coating PU2	1	1	1	1	2
Chlorinated rubber coating CR1	2	2	3	4	5
Chlorinated rubber coating CR2	2	2	3	4	4
None	5	5	5	5	5
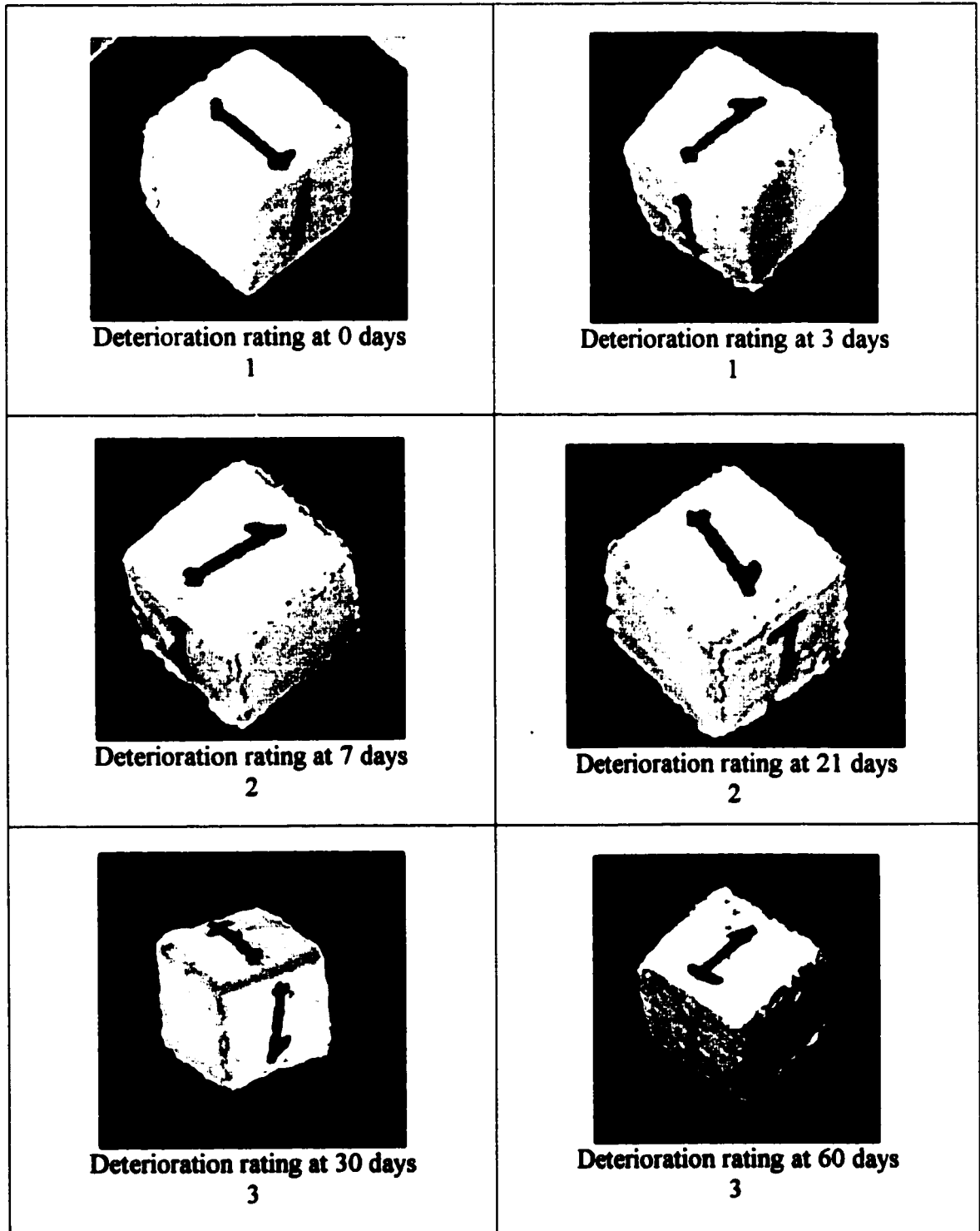
Figure 4.11: Cement mortar specimens coated with acrylic coating, AC1 and exposed to 2.5% sulfuric acid.

Deterioration rating at 0 days
1

Deterioration rating at 3 days
2

Deterioration rating at 7 days
3

Deterioration rating at 21 days
3

Deterioration rating at 30 days
3

Deterioration rating at 60 day
3
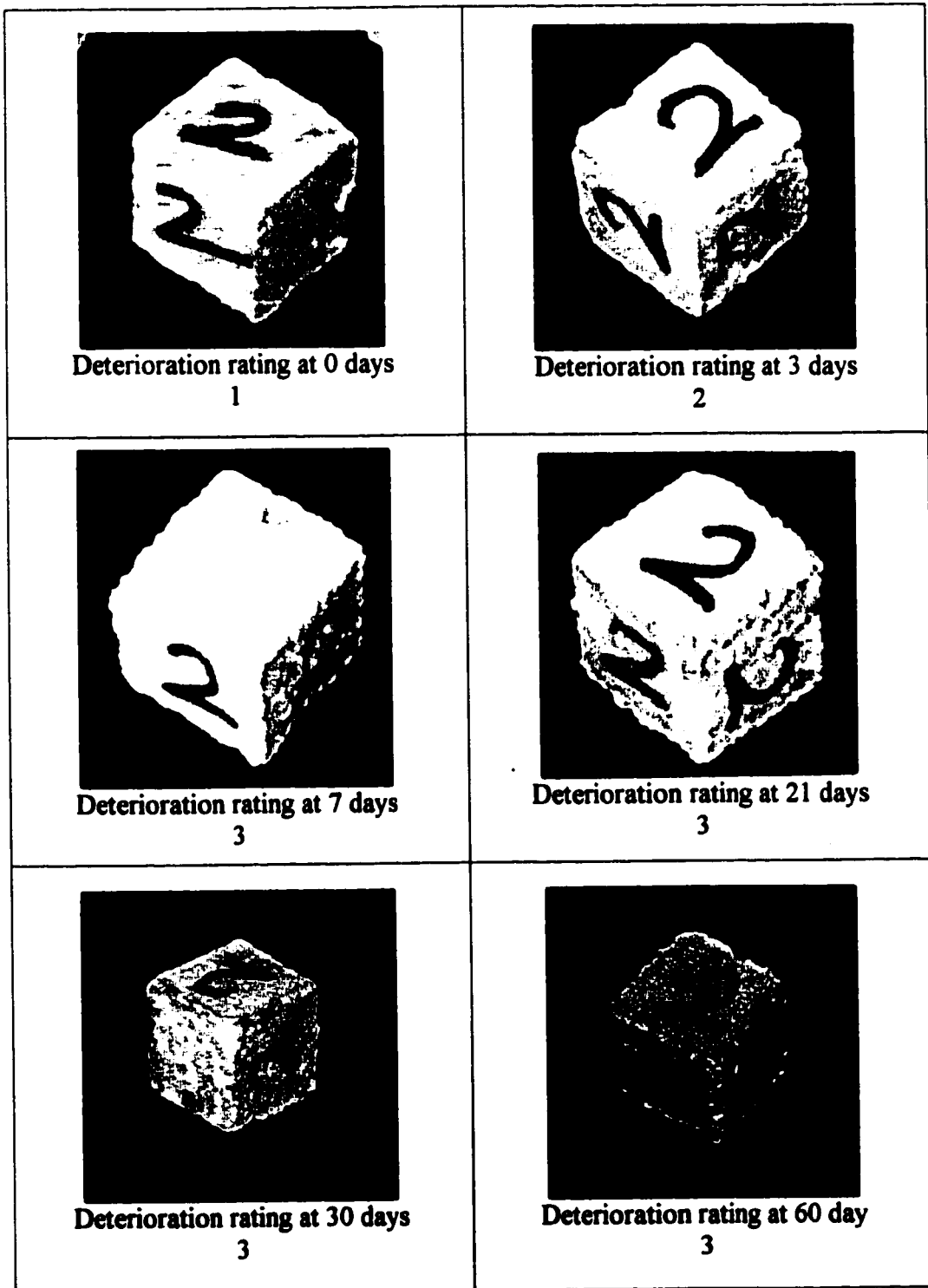
Figure 4.12: Cement mortar specimens coated with acrylic coating, AC2 and exposed to 2.5% sulfuric acid.
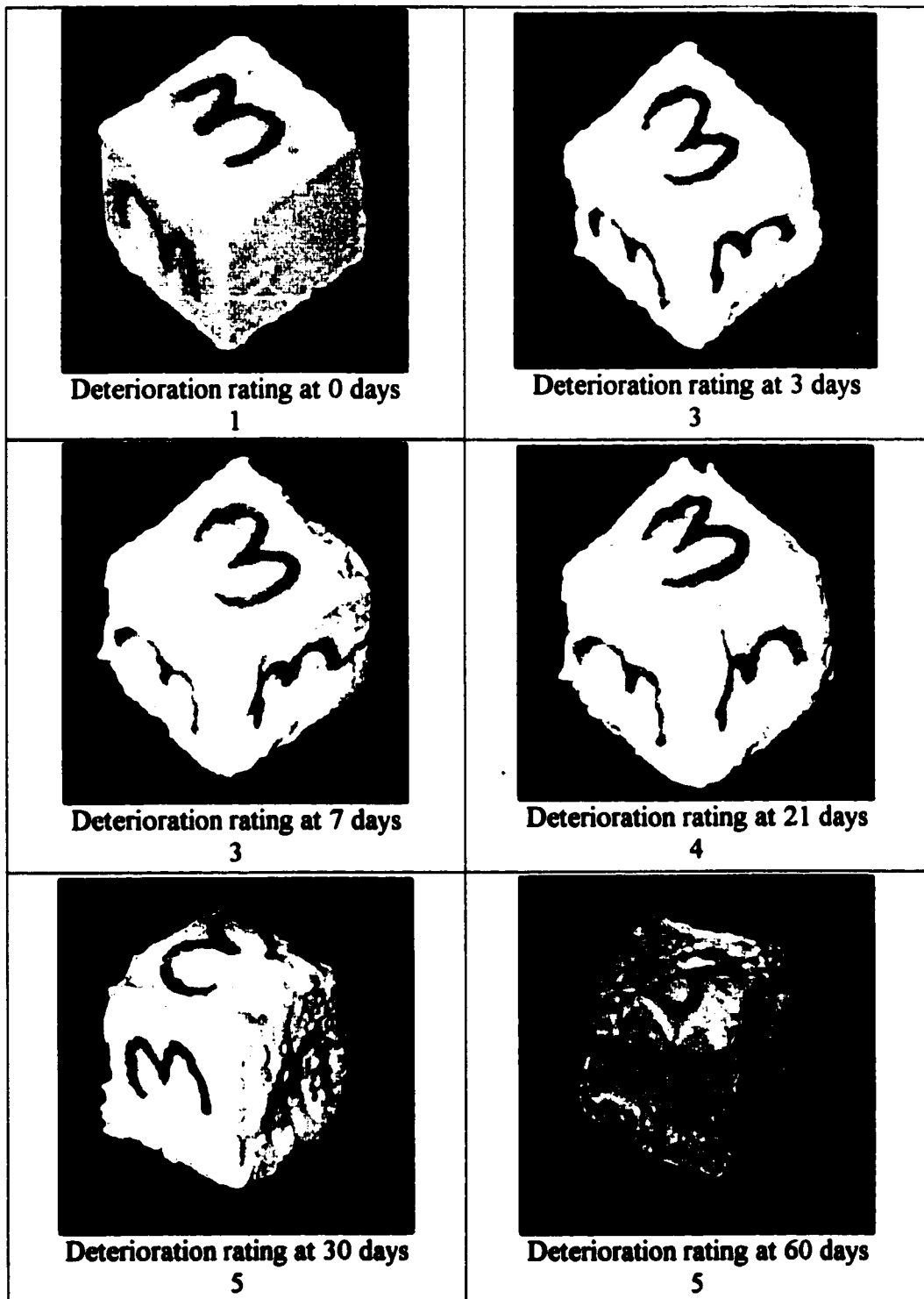
Figure 4.13: Cement mortar specimens coated with polymer emulsion coating, PE1 and exposed to 2.5% sulfuric acid.
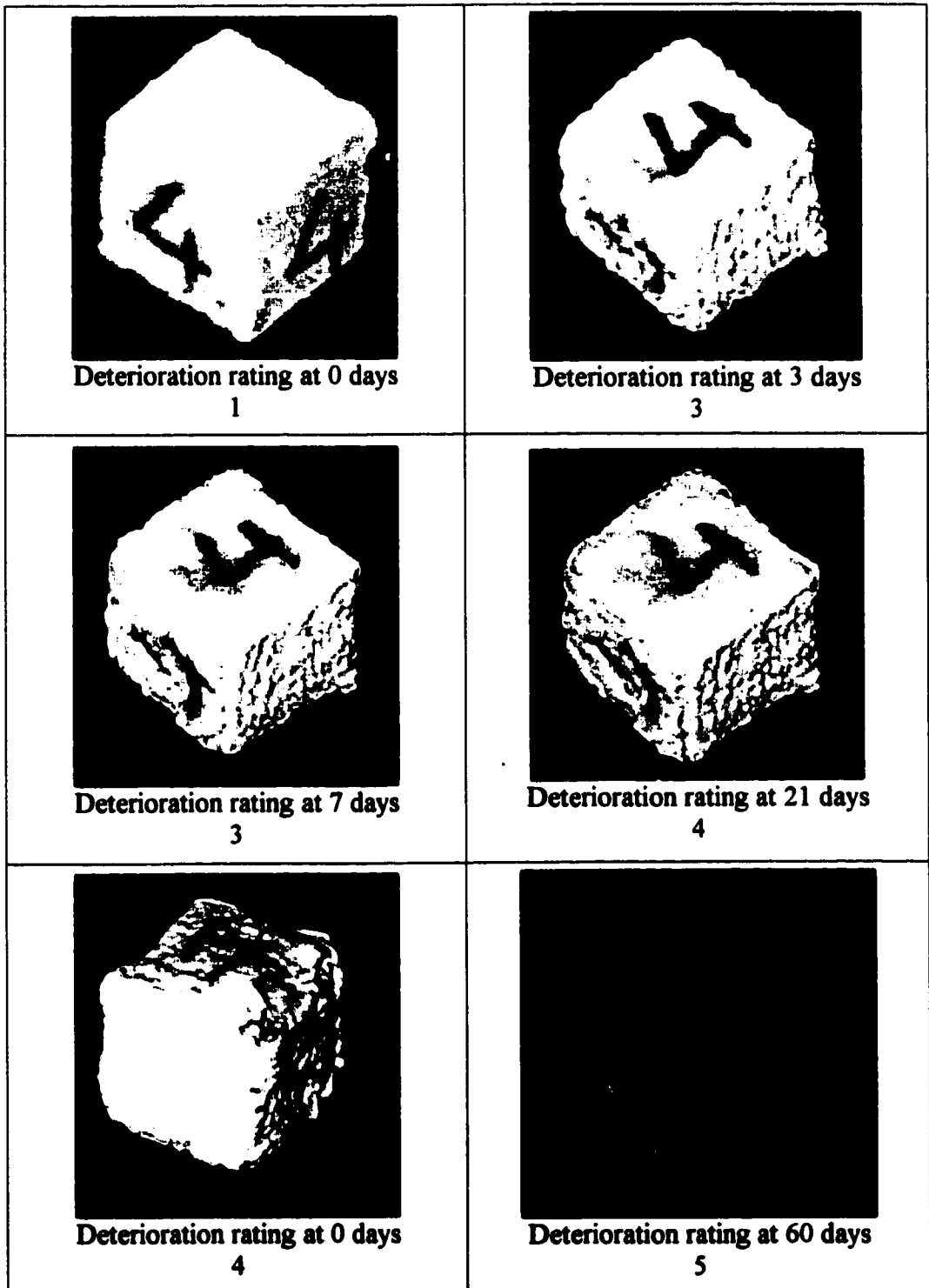
Figure 4.14 Cement mortar specimens coated with polymer emulsion coating, PE2 and exposed to 2.5% sulfuric acid.
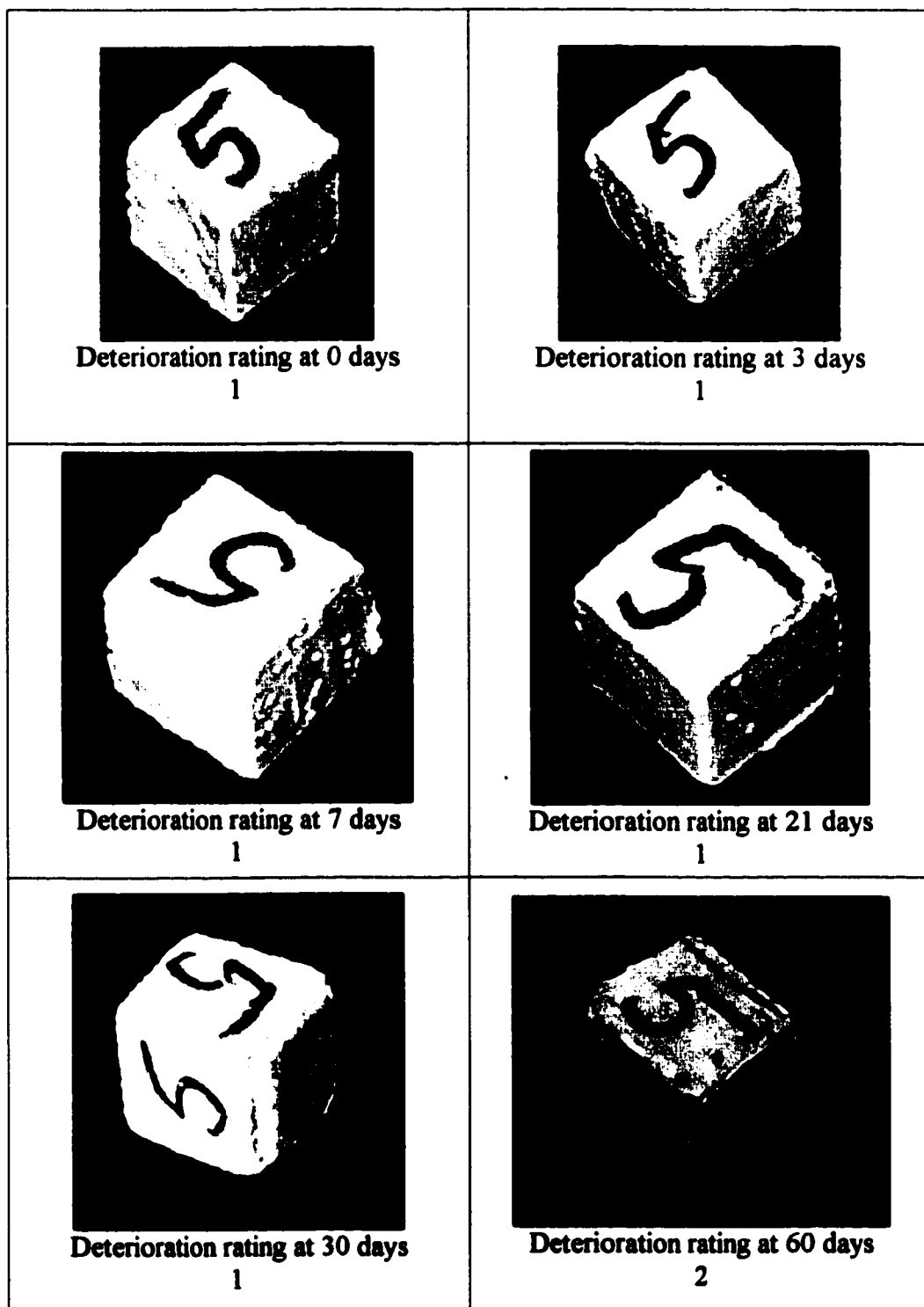
Figure 4.15: Cement mortar specimens coated with epoxy coating, EP1 and exposed to 2.5% sulfuric acid.

Deterioration rating at 0 days
1

Deterioration rating at 3 days
1

Deterioration rating at 7 days
2

Deterioration rating at 21 days
2

Deterioration rating at 30 days
2

Deterioration rating at 60 days
2
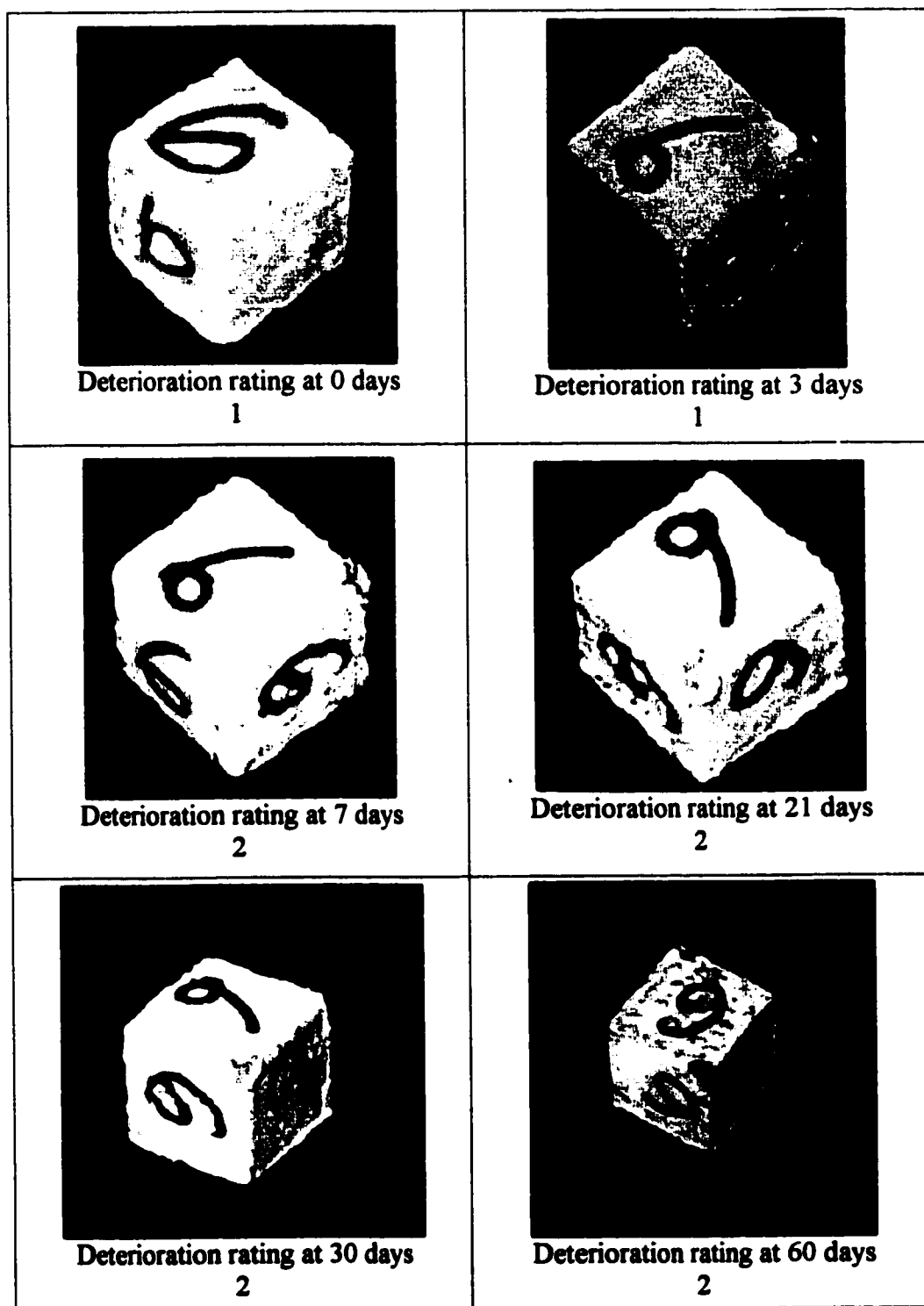
Figure 4.16: Cement mortar specimens coated with epoxy coating, EP2 and exposed to 2.5% sulfuric acid.
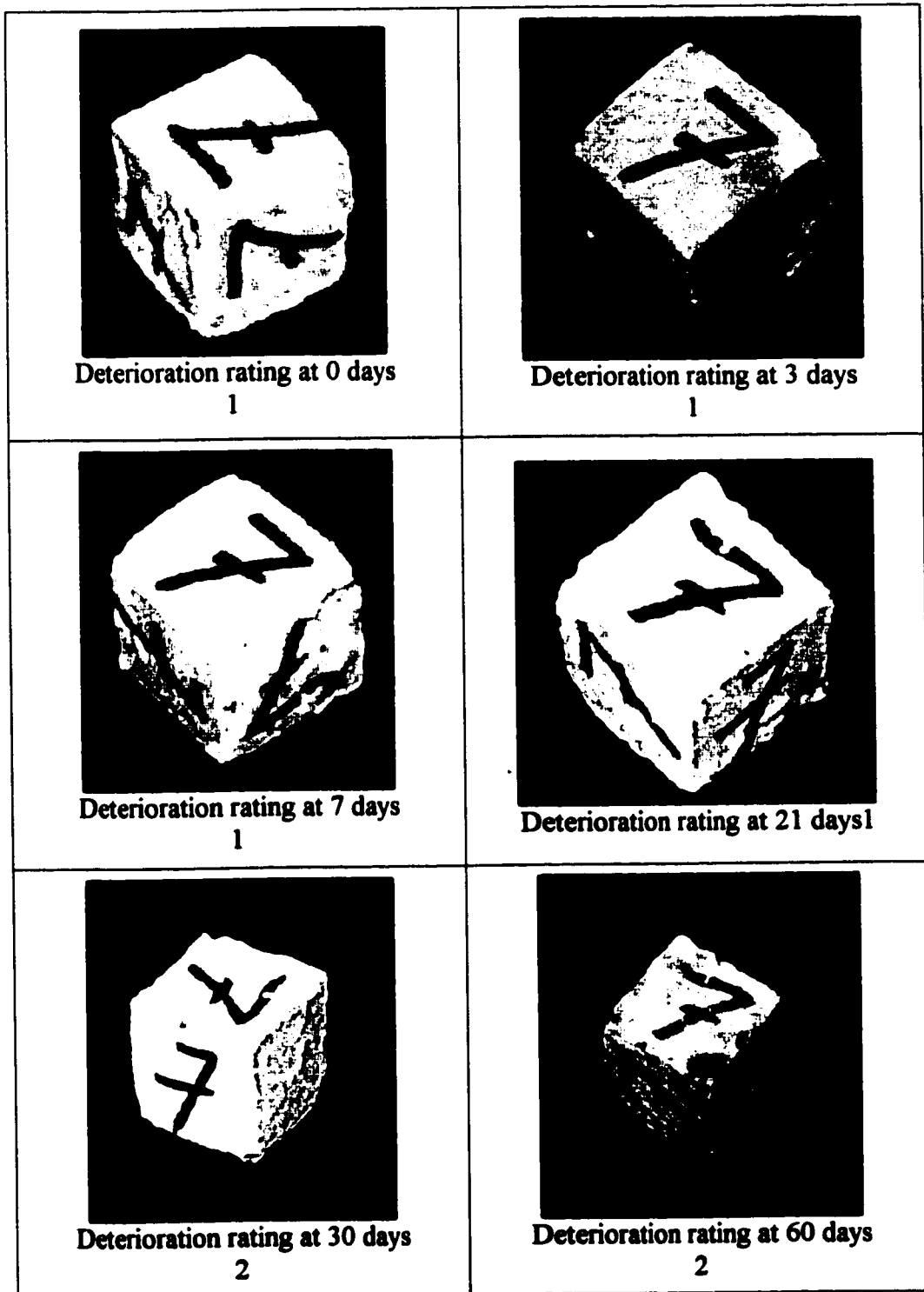
Figure 4.17: Cement mortar specimens coated with polyurethane coating, PU1 and exposed to 2.5% sulfuric acid.

Deterioration rating at 0 days
1

Deterioration rating at 3 days
1

Deterioration rating at 7 days
1

Deterioration rating at 21 days
1

Deterioration rating at 30 days
1

Deterioration rating at 60 days
2
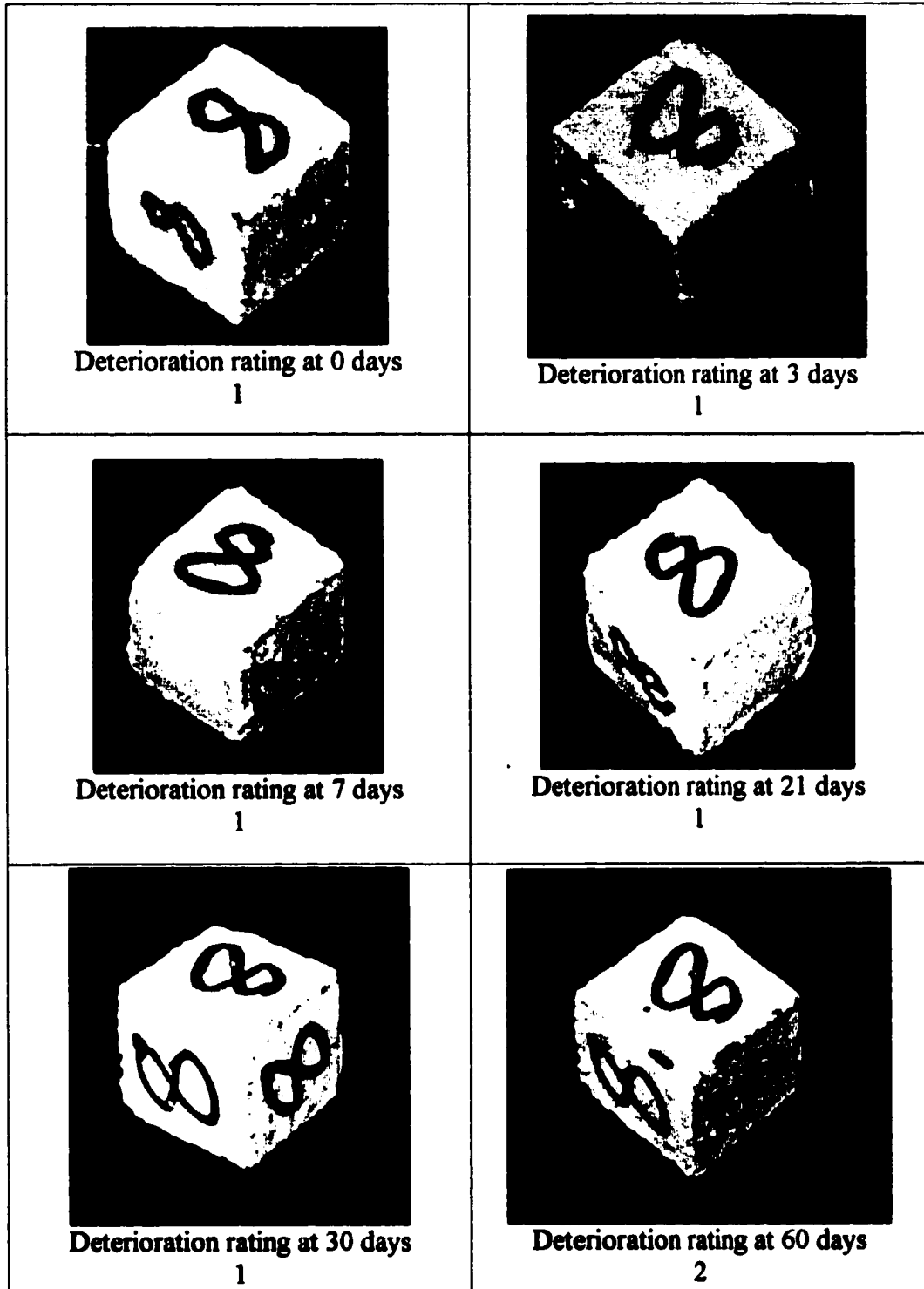
Figure 4.18: Cement mortar specimens coated with polyurethane coating, PU2 and exposed to 2.5% sulfuric acid.

Deterioration rating at 0 days 1	Deterioration rating at 3 days 2
Deterioration rating at 7 days 2	Deterioration rating at 21 days 3
Deterioration rating at 30 days 4	Deterioration rating at 60 days 5
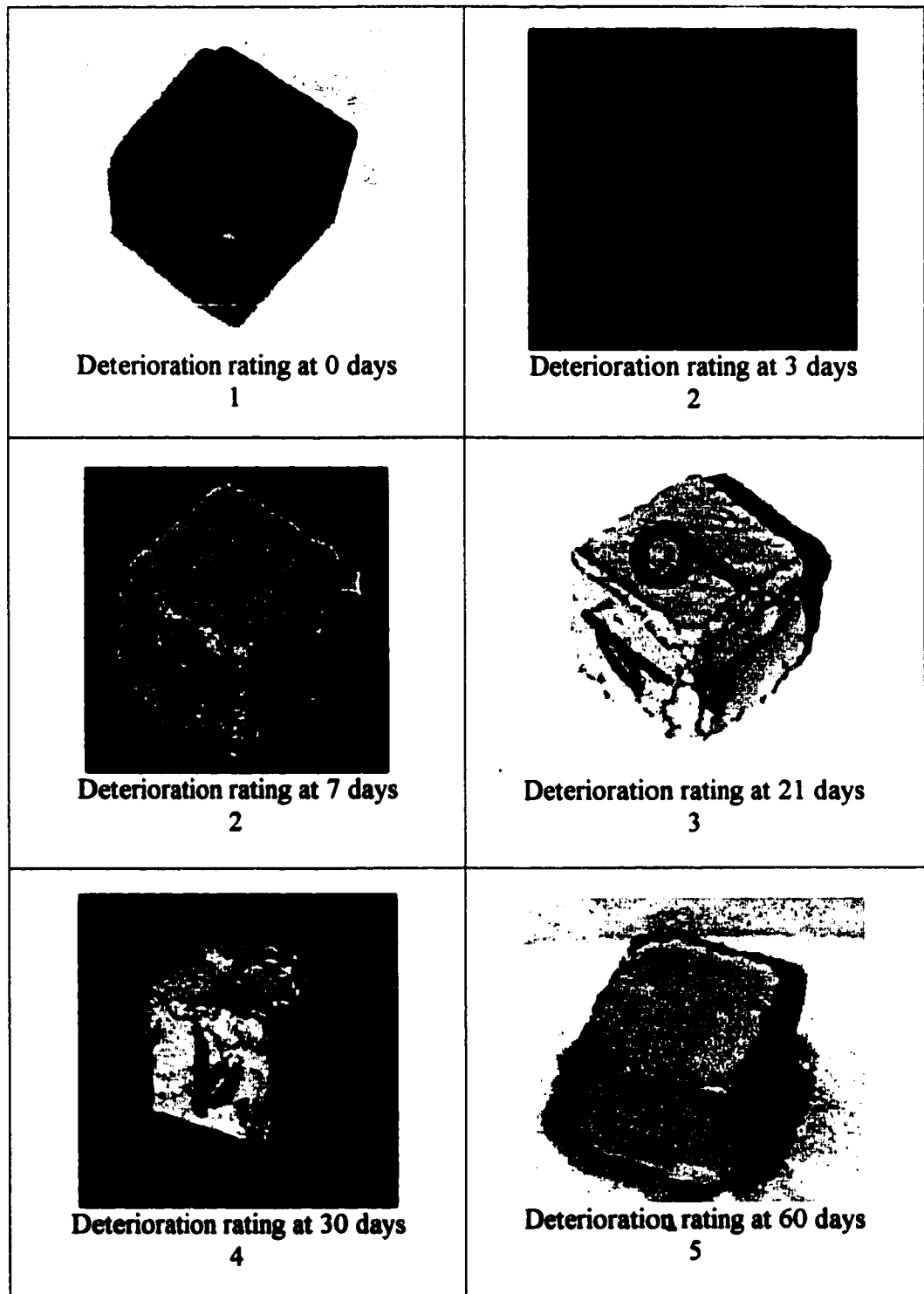
Figure 4.19: Cement mortar specimens coated with chlorinated rubber coating, CR1 and exposed to 2.5% sulfuric acid.

Deterioration rating at 0 days 1	Deterioration rating at 3 days 2
Deterioration rating at 7 days 2	Deterioration rating at 21 days 3
Deterioration rating at 30 days 4	Deterioration rating at 60 days 4
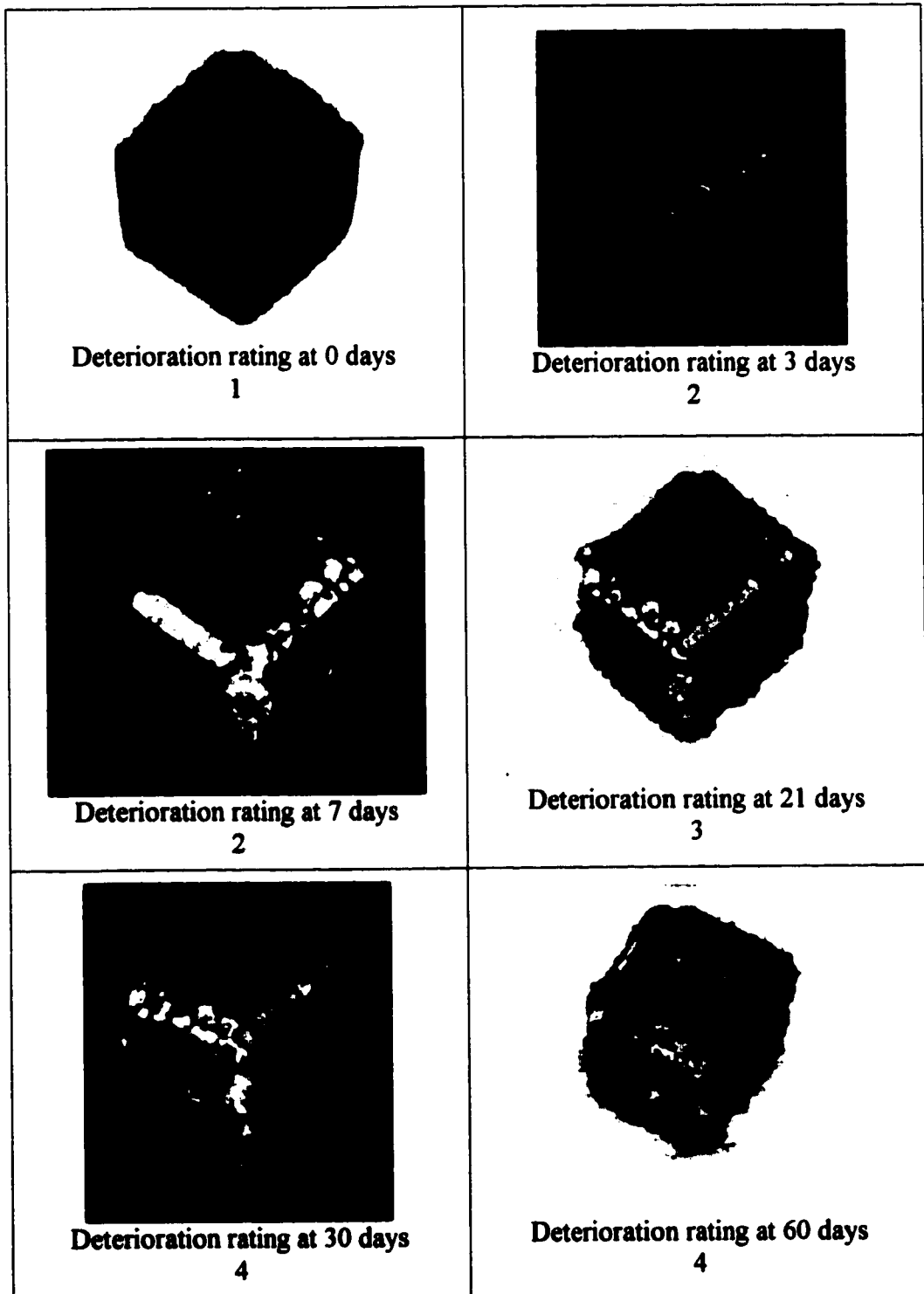
Figure 4.20: Cement mortar specimens coated with chlorinated rubber coating, CR2 and exposed to 2.5% sulfuric acid.
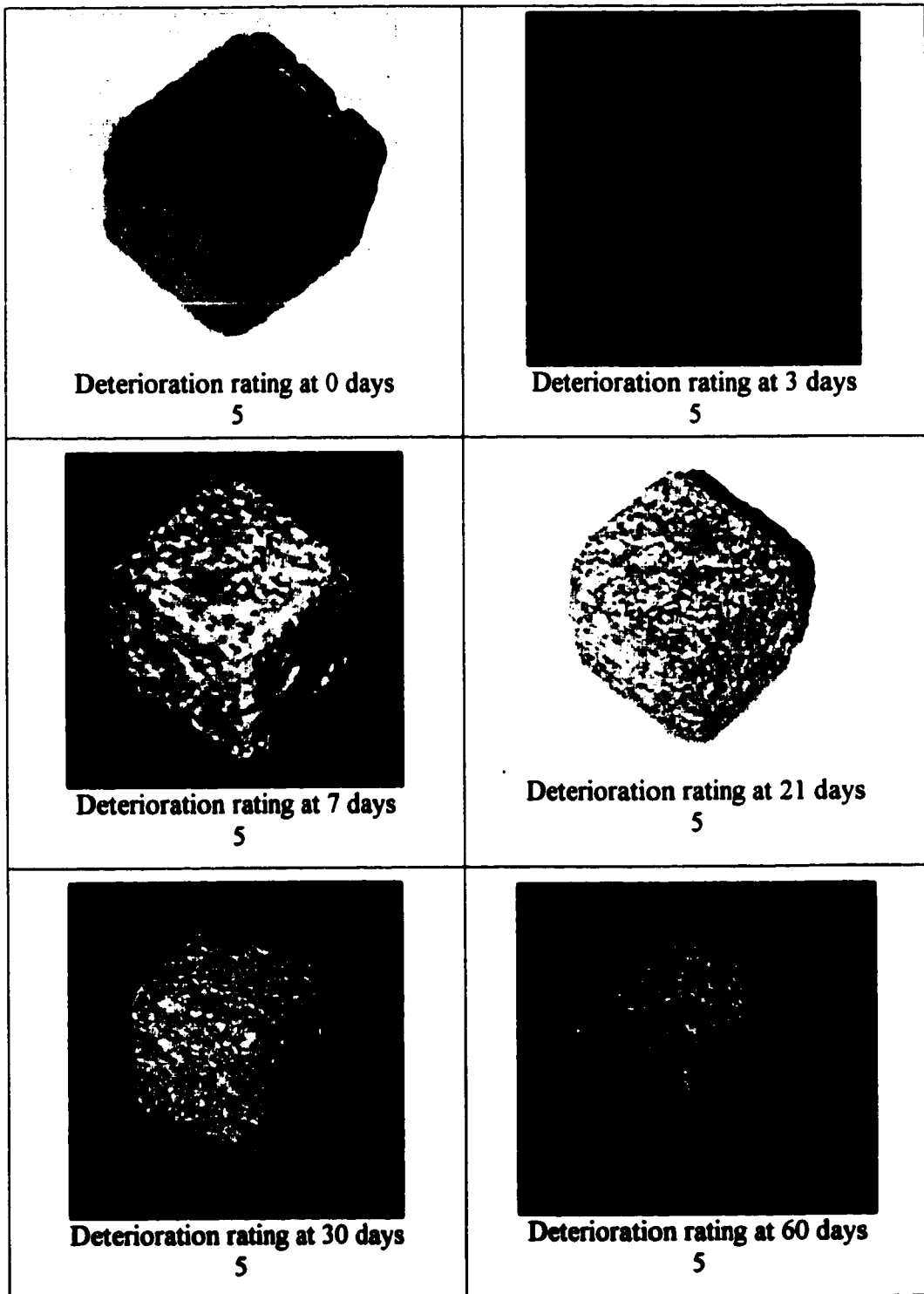
Figure 4.21: Uncoated cement mortar specimens exposed to 2.5% sulfuric acid.

Acrylic coating 1, rating-3	Acrylic coating 2, rating-3	Polymer emulsion 1,rating-5
Polymer emulsion 2,rating- 5	Epoxy coating 1, rating-1	Epoxy coating 2, rating-2
Polyurethane coating 1, rating-2	Polyurethane coating 2, rating- 1	Chlorinated rubber, rating 4
Chlorinated rubber 2, rating-4	Uncoated, Rating- 5	
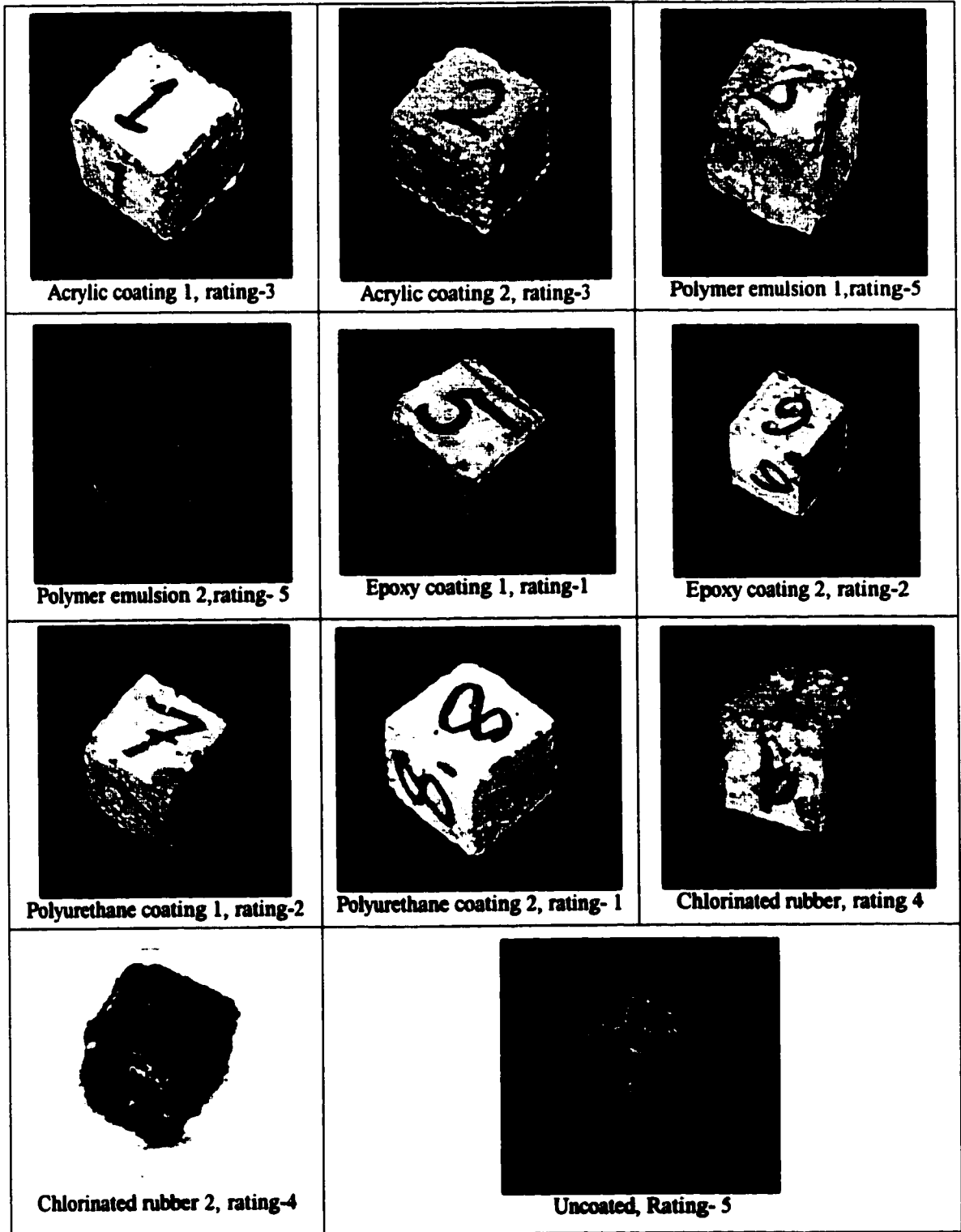
Figure 4.22: Deterioration of the coated mortar specimens after 60 days of exposure to 2.5% H_2SO_4.

3, 7, 21, 30 and 60 days and the ratings after 60 days are plotted in Figure 4.23. After 3 days of exposure, most of the coatings were intact, except the polymer emulsion coatings, which had reacted with the chemical solution making the coating soft and powdery. After 7 days of exposure, chlorinated rubber coatings were seen to be failing by peeling off or delamination and acrylic coatings also started to exhibit signs of deterioration at the corners. After 21 days of exposure, the polymer emulsion coatings had failed completely while the acrylic coatings had failed at edges and the chlorinated rubber coatings continued to peel off. The first signs of distress in the specimens coated with polyurethane and epoxy coatings were noted after 30 days, and then, too, the deterioration was restricted to the corners of the samples. Most of the white colored coatings had turned yellow, except the polyurethane coatings. Even after 60 days, the deterioration in epoxy and polyurethane coatings was limited to the corners, whereas the specimens coated with other coatings were severely damaged.

It was seen that the polymer emulsion coatings deteriorated very rapidly and after only 30 days they were as bad as the uncoated concrete specimens. The chlorinated rubber coatings also began to peel off the surface of the specimens as early as 7 days. The specimens coated with acrylic coatings exhibited failure at the edges in a short time. It was evident that these coatings had reacted with the sulfuric acid to form a pervious, soft film on the substrate. The polyurethane and epoxy coatings were found relatively intact, with just the corners of the specimens damaged, even after 60 days. This could be due to their chemical formulation and
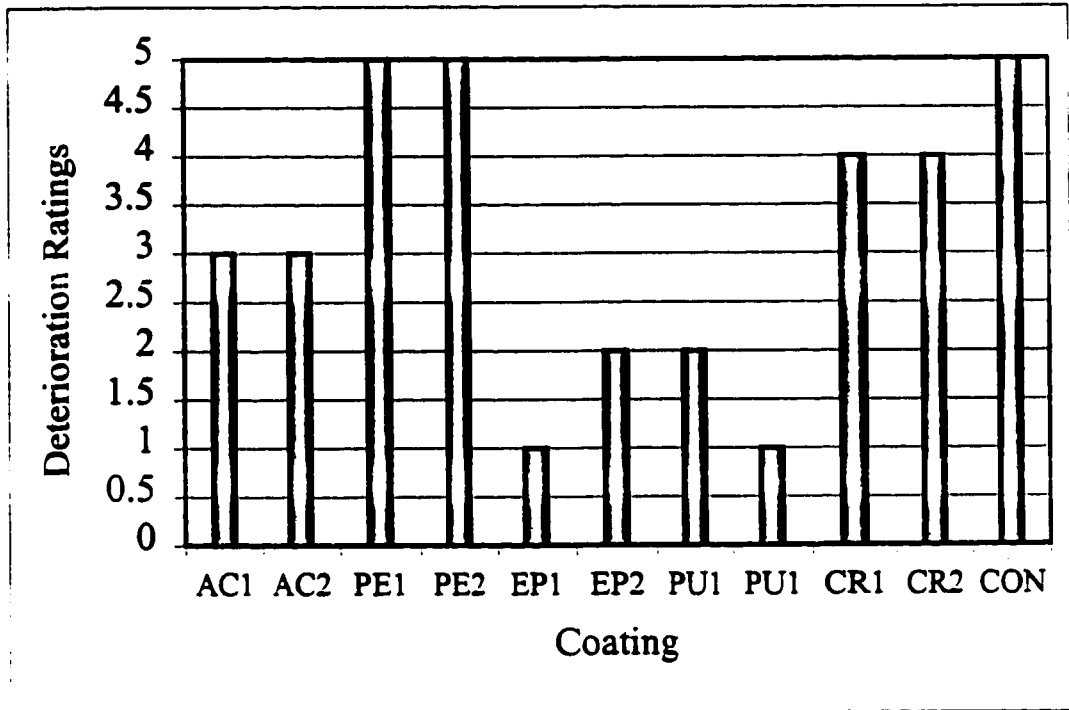
Figure 4.23: Deterioration rating for the selected coatings after 60 days of exposure to 2.5% H_2SO_4.

hence, these generic types should be specified for structures exposed to sulfuric acid.

McGill and Humpage [44] evaluated the chemical resistance of concrete coatings and observed that epoxies have excellent chemical resistance. Dulaijan et al. [60, 61] also utilized a similar deterioration rating system as the one used in this study for evaluating the chemical resistance evaluation of cement-based and resin-based coatings in 2% sulfuric acid solution. They observed that all coatings except epoxy resin coatings deteriorated completely within the first 14 days of exposure.

The performance of the selected coatings in chemical resistance is in the following descending order:

i)   Epoxy resin coating, EP1

ii)   Epoxy resin coating, EP2

iii) Polyurethane coating, PU1

iv)   Polyurethane coating, PU2

v)   Acrylic coating, AC1

vi)   Acrylic coating, AC2

vii) Chlorinated rubber coating, CR2

viii) Chlorinated rubber coating, CR1

ix)   Polymer emulsion coating, PE1

x)   Polymer emulsion coating, PE2

4.6 THERMAL VARIATION

The selected coatings were evaluated for their resistance to thermal variations by exposing 50 x 50 x 50 mm cement mortar specimens, coated with the selected coatings to thermal cycles. Each thermal cycle consisted of exposing the coated mortar specimens at 70 °C for 4 hours and at 25 °C for 8 hours. After 30, 60 and 90 thermal cycles, the specimens were recovered from the oven and immersed in water for 48 hours, after which the specimens were surface dried and weighed to obtain the water absorption of the coated and uncoated specimen. Table 4.8 shows the water absorption in the coated specimens after 0, 30, 60 and 90 thermal cycles.

The change in the water absorption of the coated and uncoated mortar specimens after exposure to 30, 60, and 90 heat-cool cycles is plotted in Figure 4.24. Figure 4.25 shows the increase in water absorption in all the samples after 90 heat-cool cycles. No visible signs of deterioration were noted in any of the coated specimens after 90 heat-cool cycles.

The water absorption in both the coated and uncoated mortar specimens increased with the number of thermal cycles. The increase in water absorption in the uncoated concrete specimens may be attributed to the formation of microcracks in the concrete. In the coated concrete specimens the increase in water absorption may be attributed to the conjoint effect of coating damage and concrete microcracking. After 90 thermal cycles the water absorption in the concrete

Table 4.8: Absorption in the coated and uncoated specimen exposed to heat-cool cycles.

Coatings	Water Absorption, % after			
	0 cycles	30 cycles	60 cycles	90 cycles
Acrylic coating AC1	0.78	0.88	1.17	1.77
Acrylic coating AC2	3.53	3.58	3.77	4.09
Polymer emulsion coating PE1	5.10	5.18	5.40	5.82
Polymer emulsion coating PE2	3.20	3.38	3.65	3.94
Epoxy coating EP1	0.63	0.75	0.91	1.08
Epoxy coating EP2	0.54	0.67	0.88	1.14
Polyurethane coating PU1	1.46	1.68	2.20	3.42
Polyurethane coating PU2	2.78	3.00	3.39	3.72
Chlorinated rubber coating CR1	1.00	1.17	1.85	2.82
Chlorinated rubber coating CR2	2.58	2.74	2.99	3.31
None	5.64	5.75	6.06	6.54
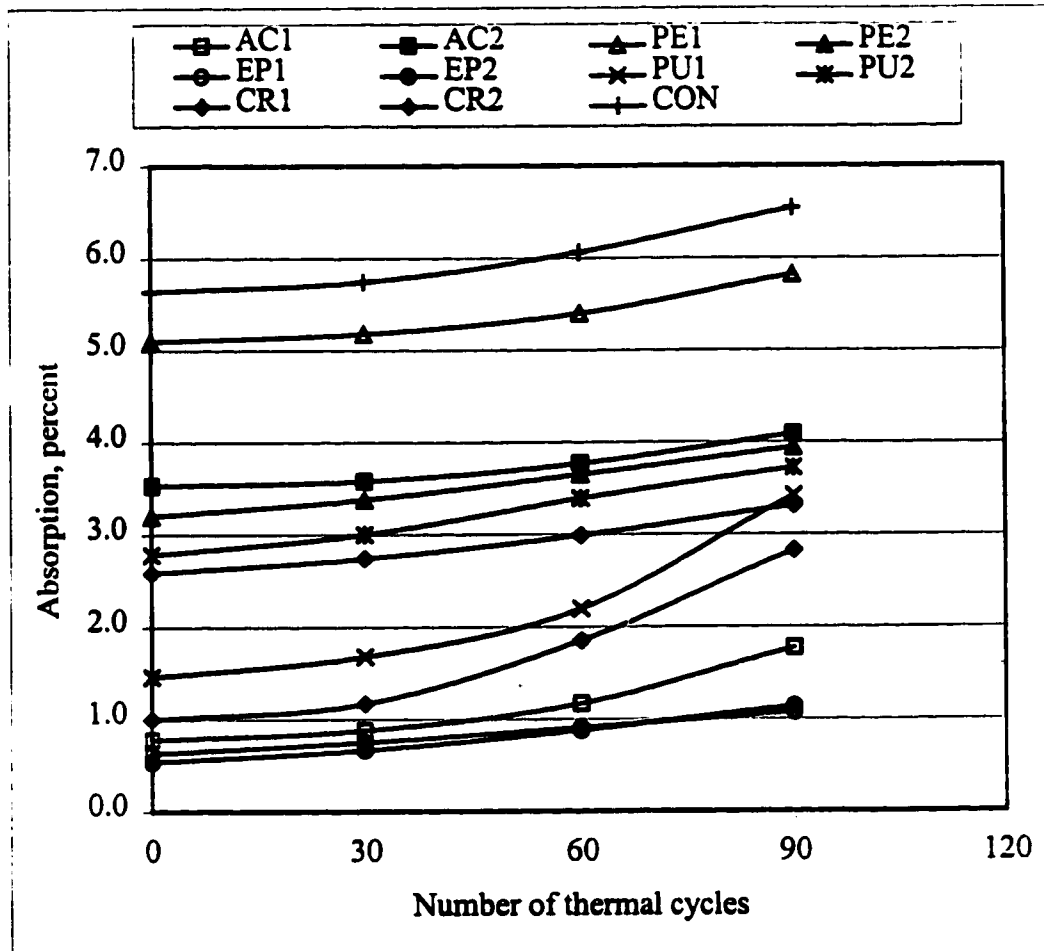
Figure 4.24: Variation of water absorption in the coated and uncoated concrete specimens exposed to heat-cool cycles.
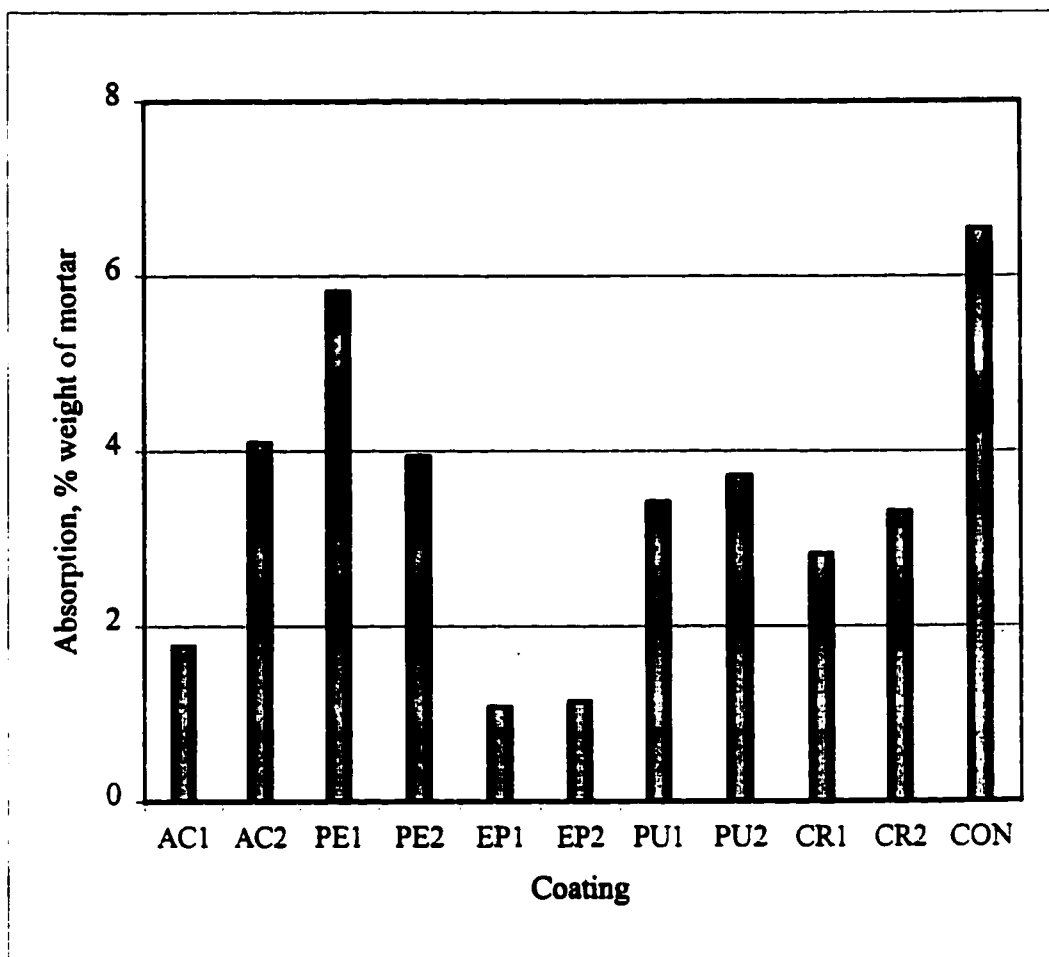
Figure 4.25: Absorption in the coated and uncoated mortar specimens after exposure to 90 heat-cool cycles.

specimens coated with polymer emulsion coatings was in the range of 4.0 to 5.8% while in the specimens coated with acrylic coatings it was in the range of 1.8 to 4.1%. The samples coated with chlorinated rubber coatings absorbed 2.8 to 3.3% water after exposure to 90 heat-cool cycles, whereas those coated with polyurethane coatings absorbed 3.4 to 3.7% water. The epoxy coatings were the best with water absorption of only 1.1% after exposure to 90 heat-cool cycles.

Swamy and Tanikawa [35] exposed concrete slabs coated with an acrylic rubber coating to temperatures in the range of 80 to 100 °C for 150 days and observed the degradation of the coating. They concluded that the acrylic rubber coating could withstand the temperatures in the specified range.

The performance of the selected coatings after exposure to 90 heat-cool cycles is in the following descending order:

i) Epoxy resin coating, EP1

ii) Epoxy resin coating, EP2

iii) Acrylic coating, AC1

iv) Chlorinated rubber coating, CR1

v) Chlorinated rubber coating, CR2

vi) Polyurethane coating, PU1

vii) Polyurethane coating, PU2

viii) Polymer emulsion coating, PE2

ix) Acrylic coating, AC2

x) Polymer emulsion coating, PE1

4.7 MOISTURE VARIATION

The effect of wet-dry cycling on the coated and uncoated mortar specimens was evaluated by exposing them to wet-dry cycles of saline water. Each wet-dry cycle consisted of immersing the specimens in water for 4 hours and drying them in air for 8 hours. The samples were exposed to 60, 120 and 180 wet-dry cycles. The oven dry weight of the samples was recorded before and after the exposure and the loss in weight of the specimen was recorded.

The average weight loss measured in the coated and control samples is summarized in Table 4.9 and it is plotted against the number of wet-dry cycles in Figure 4.26. Both coated and uncoated cement mortar specimens continued to loose weight with the number of wet-dry cycles. The weight loss after 180 wet-dry cycles was 3.5% in the control specimens and in the range of 1.7 to 2.3% in the specimens coated with epoxy coatings. The weight loss in the specimens coated with polyurethane coatings was in the range 1.4 to 2.4%, whereas for the chlorinated rubber coatings it was in the range of 2.0 to 3.2%. The specimens coated with acrylic coatings lost about 1.3 to 1.5% of their weight and those coated with polymer emulsion coatings lost weight in the range of 0.9 to 1.4% after exposure to 180 wet-dry cycles. The loss in weight of the coated and uncoated

Table 4.9: Weight loss in the coated and uncoated mortar specimens exposed to wet-dry cycles.

Coatings	Weight Loss, % after		
	60 cycles	120 cycles	180 cycles
Acrylic coating AC1	1.091	1.288	1.530
Acrylic coating AC2	0.968	1.000	1.254
Polymer emulsion coating PE1	1.015	1.180	1.374
Polymer emulsion coating PE2	0.411	0.619	0.900
Epoxy coating EP1	1.471	1.537	1.693
Epoxy coating EP2	1.359	1.432	2.290
Polyurethane coating PU1	2.055	2.275	2.400
Polyurethane coating PU2	0.461	0.587	1.360
Chlorinated rubber coating CR1	1.388	1.694	1.996
Chlorinated rubber coating CR2	1.669	1.862	3.156
None	1.450	1.930	3.448
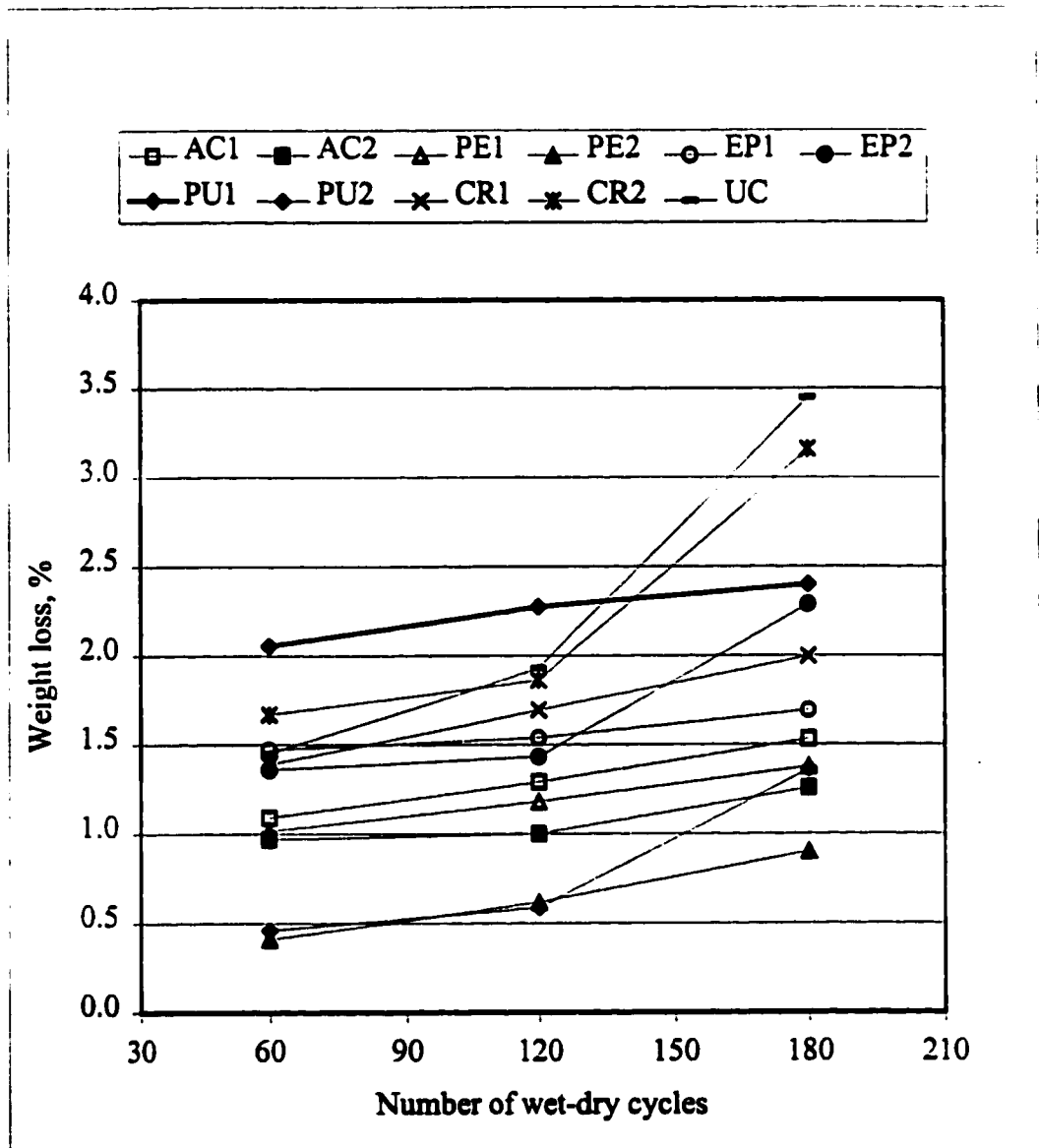
Figure 4.26: Weight loss in the coated and uncoated cement mortar
specimens exposed to wet-dry cycles

cement mortar specimens could be attribute d to the damage caused by the alternate wetting and drying and leaching out of the products of cement hydration.

Most of the coated samples lost less than 2% in weight at the end of 180 wet-dry cycles and there were no visible signs of coating deterioration. Some of the epoxy and chlorinated rubber coatings lost more than 2% of their weight at the end of 180 wet-dry cycles. Hence, it is advisable to select parameters other than the weight loss for the evaluation of concrete coatings in wet-dry cycles.

The performance of the selected coatings under wet-dry environments was in the following descending order:

i) Polymer emulsion coating, PE2

ii) Acrylic coating, AC2

iii) Polyurethane coating, PU2

iv) Polymer emulsion coating, PE1

v) Acrylic coating, AC1

vi) Epoxy resin coating, EP1

vii) Chlorinated rubber coating, CR1

viii) Polyurethane coating, PU1

ix) Epoxy resin coating, EP2

x) Chlorinated rubber coating, CR2

4.8 CHLORIDE DIFFUSION

The chloride diffusion in the coated specimens was evaluated by immersing them in 5% sodium chloride solution for three months with only one face exposed to the solution. At the end of the exposure period, the chloride concentration at various depths was determined and the chloride profile was plotted. The chloride profile was utilized to determine the diffusion coefficients by solving Fick's second law of diffusion.

Table 4.10 gives the chloride concentrations in the coated and uncoated concrete specimens at various depths after the exposure period. Figure 4.27 through 4.32 show the chloride profiles for the coated and uncoated concrete specimens. The chloride concentration in all the specimens decreased with depth. Further, the chloride concentration in the uncoated concrete specimens was more than that in the coated concrete specimens at all depths. The chloride concentration profiles were utilized to calculate the chloride diffusion coefficients by solving Fick's second law of diffusion. These data are summarized in Table 4.11 and plotted in Figure 4.33.

The chloride diffusion coefficient for the uncoated concrete specimens was more than those for the coated specimens. This value in the control samples was 19.2×10^{-8} cm^2/s. In the specimens coated with acrylic emulsion coatings, it was in the range of 2.1 to 3.5×10^{-8} cm^2/s while it was in the range of 8.4 to 16×10^{-8}

Table 4.10: Chloride concentration in the coated and uncoated concrete specimens.

Coating	Chloride concentration at depth of					
	0mm	7.5mm	22.5mm	52.5mm	77.5mm	102.5mm
	Percent weight of concrete					
Acrylic coating AC1	0.060	0.056	0.049	0.037	0.032	0.028
Acrylic coating AC2	0.100	0.084	0.061	0.045	0.037	0.032
Polymer emulsion coating PE1	0.400	0.298	0.186	0.108	0.084	0.079
Polymer emulsion coating PE2	0.600	0.396	0.203	0.131	0.089	0.079
Epoxy coating EP1	0.120	0.092	0.045	0.035	0.027	0.019
Epoxy coating EP2	0.140	0.121	0.094	0.066	0.057	0.050
Polyurethane coating PU1	0.070	0.062	0.047	0.031	0.023	0.019
Polyurethane coating PU2	0.040	0.037	0.033	0.023	0.023	0.023
Chlorinated rubber coating CR1	0.280	0.206	0.065	0.051	0.044	0.037
Chlorinated rubber coating CR2	0.210	0.158	0.082	0.037	0.030	0.028
None	1.200	0.750	0.280	0.137	0.080	0.075
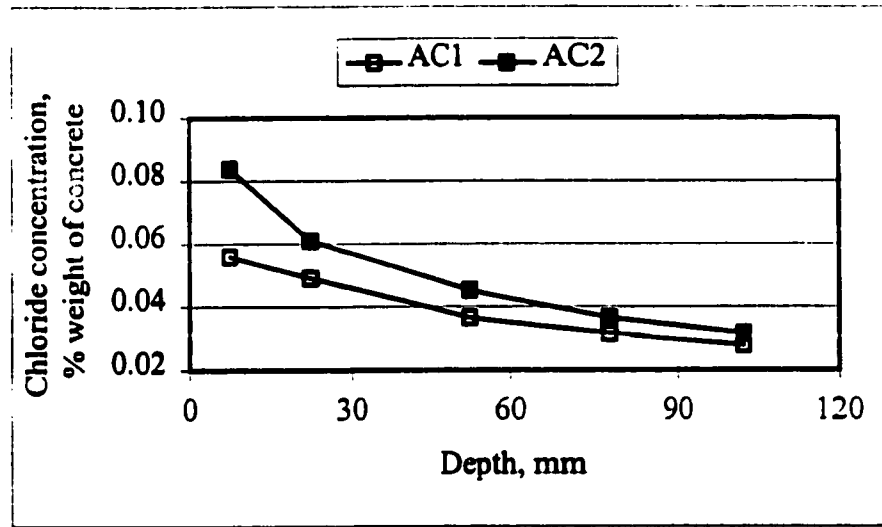
Figure 4.27: Chloride profile for the concrete specimens coated with acrylic coatings
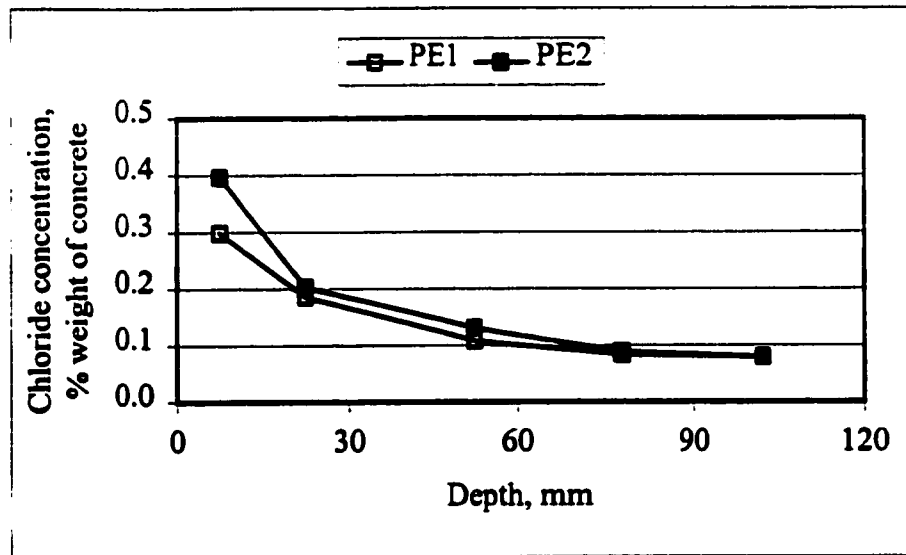
Figure 4.28: Chloride profile for the concrete specimens coated with polymer emulsion coatings.
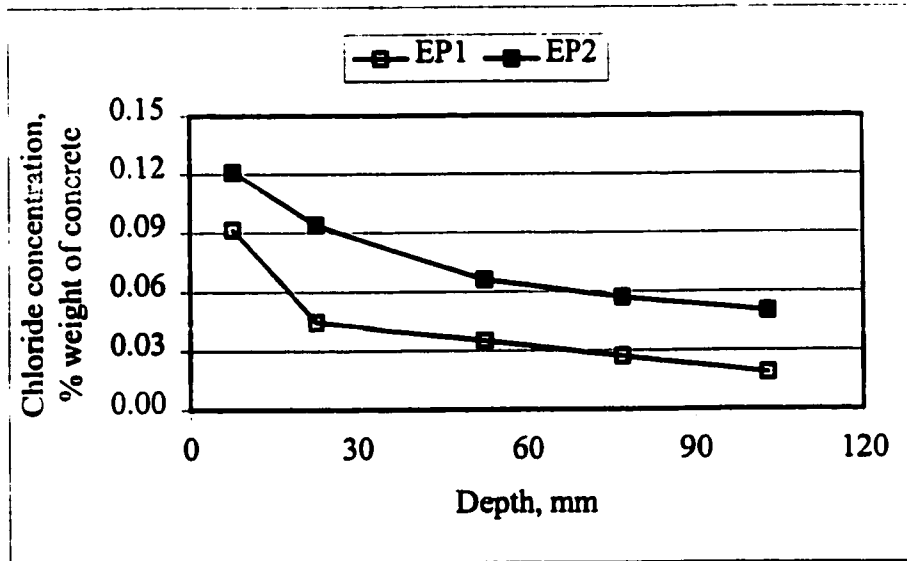
Figure 4.29: Chloride profile for the concrete specimens coated with epoxy coatings
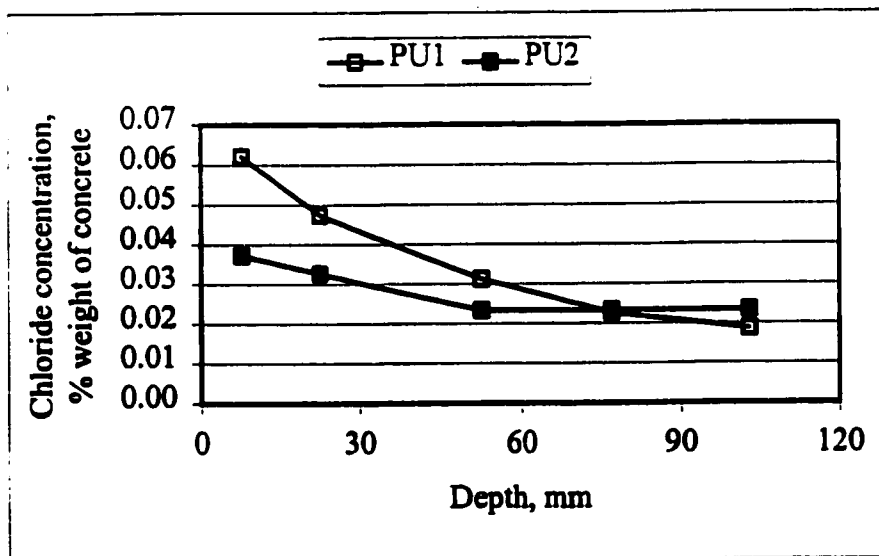
Figure 4.30: Chloride profile for the concrete specimens coated with polyurethane coatings
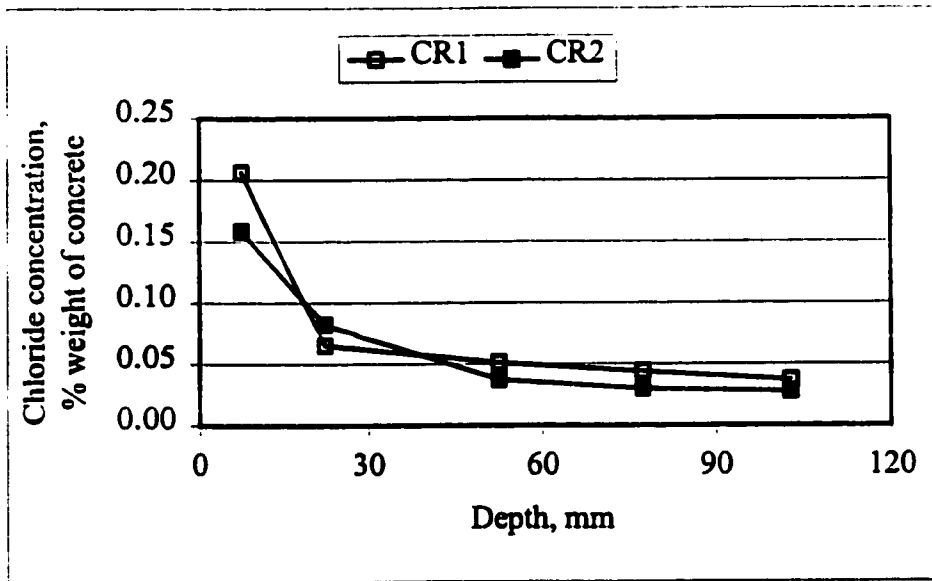
Figure 4.31: Chloride profile for the concrete specimens coated with chlorinated rubber coatings
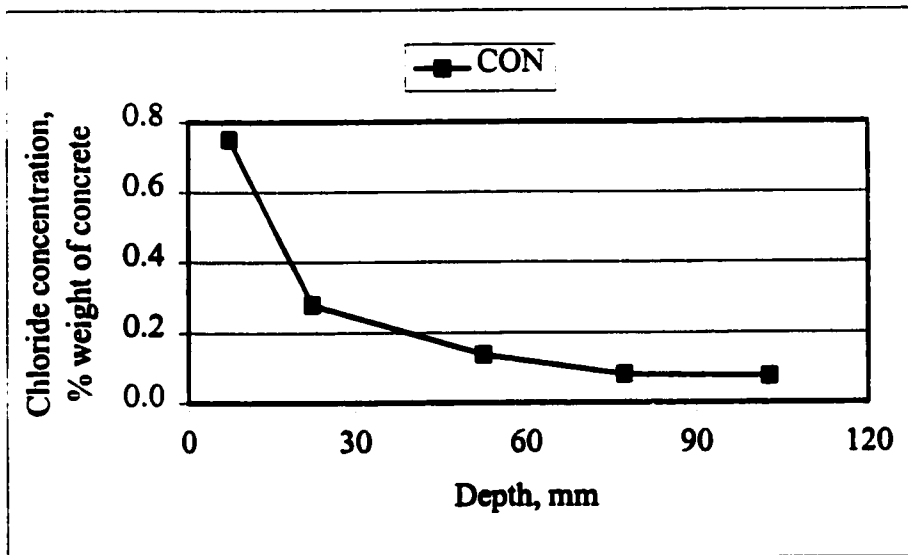
Figure 4.32: Chloride profile for the uncoated concrete specimens

Table 4.11: Chloride diffusion coefficients for the coated and uncoated concrete specimens.

Coating	Coefficient of chloride diffusion, 10^{-8} cm^2/s
Acrylic coating AC1	2.08
Acrylic coating AC2	3.49
Polymer emulsion coating PE1	8.40
Polymer emulsion coating PE2	15.94
Epoxy coating EP1	7.67
Epoxy coating EP2	2.59
Polyurethane coating PU1	1.83
Polyurethane coating PU2	0.70
Chlorinated rubber coating CR1	9.56
Chlorinated rubber coating CR2	8.40
None	19.18
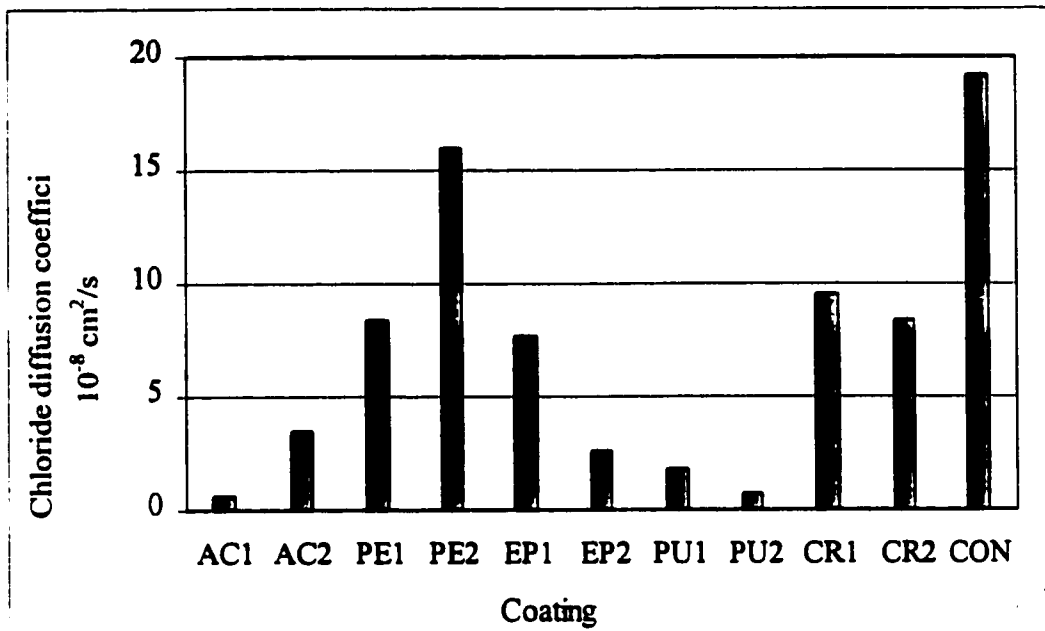
Figure 4.33: Chloride diffusion coefficients for the coated and uncoated concrete specimens.

cm^2/s for the specimens coated with polymer emulsion coatings. Chloride diffusion coefficients were in the range of 2.6 to 7.7 x 10^{-8} cm^2/s for concrete specimens coated with epoxy coatings and they were in the in the range of 8.4 to 9.6 x 10^{-8} cm^2/s for specimens coated with chlorinated rubber coatings. The lowest chloride diffusion coefficients were noted for the specimens coated with polyurethane coatings. These values were in the range of 0.7 to 1.8 x 10^{-8} cm^2/s.

It was found that the polyurethane and acrylic coatings were approximately 10 times more effective in resisting the diffusion of chloride ions as compared to the uncoated concrete specimens. Only one of the epoxy coatings tested gave concentrations that were 15 percent of those in the control samples. The chlorinated rubber coatings were half as effective as the epoxy coatings and the polymer emulsion coatings gave high concentrations that were 60 to 70 percent of those for the control samples at the same depths.

McCurrich [48] observed that the chloride concentration in the uncoated concrete at a depth of 5 to 10 mm from the surface was about 1.5% and for concrete coated with a silane primer and acrylic topcoat it was found to be about 0.2% at the same depth. Pfeiffer and Scali [41] evaluated the chloride diffusion resistance of 21 generic types of treatments and concluded that epoxy and moisture cured urethanes were the most effective in preventing chloride ingress. Dulaijan et al. [60] calculated the coefficients of chloride diffusion for uncoated concrete and concrete coated with resin-based coatings. The coefficients were in the range of 0.77 to 1.67 x 10^{-7} cm^2/s for resin based coatings and higher for the uncoated specimens.

The efficiency of the coatings in preventing the ingress of chloride ions can be further emphasized by calculating the concrete cover required for the reinforcement for an estimated service life of 50 years. The mathematical model proposed by Poulsen et al. [65], given in Equation 4.3, was utilized to estimate the minimum concrete cover that would be required for each coating if the chloride concentration at the end of 50 years was to be less than 0.06% by weight of concrete, at the level of the rebar, in concrete with w/c ratio of 0.45.

$$c_{min} = \sqrt{4t_{LT}D_a} \times inv\psi_p \left\{ \frac{C_{cr} - C_i}{S(t_{LT}D_a)^p} \right\}$$ (4.3)

where, c_{min} = minimum cover to reinforcement

t_{LT} = service lifetime

D_a = achieved diffusion coefficient

ψ_p = a function tabled by Mejlbro [66]

C_{cr} = critical chloride concentration

C_{ci} = initial chloride concentration in the concrete

S, p = constants chosen by Swamy [67] for concrete exposed to land-splash zone

The minimum concrete cover for the rebar required to prevent the ingress of chloride ions to the rebar surface within a service life of a 50 years is summarized in Table 4.12 for each coating and the control samples. It can be seen that the concrete cover can be reduced drastically if the coating being applied is effective in preventing the diffusion of chloride ions to the substrate. Uncoated concrete would require a cover of almost 120 mm to prevent the diffusion of the chlorides to the rebar surface whereas a cover of only 10 to 20 mm would suffice if the concrete is coated with a polyurethane coating. A cover of 28 to 60 mm would be required for

Table 4.12: Minimum cover to reinforcement for a service life of 50 years.

Coating	Minimum Cover, mm
Acrylic coating AC1	27.8
Acrylic coating AC2	37.5
Polymer emulsion coating PE1	62.8
Polymer emulsion coating PE2	96.1
Epoxy coating EP1	60.0
Epoxy coating EP2	28.4
Polyurethane coating PU1	19.5
Polyurethane coating PU2	9.4
Chlorinated rubber coating CR1	67.0
Chlorinated rubber coating CR2	62.8
None	119.5

epoxy coatings while for chlorinated rubber coatings the cover could range from 62 to 67 mm. Concrete coated with acrylic coatings would require a cover of 27 to 38 mm and if polymer emulsions are used the cover could range from 63 to 100 mm.

The effectiveness of the coating could also be emphasized by calculating the time to initiation of reinforcement corrosion in a concrete structure with a cover to reinforcement of 50 mm. A mean surface chloride concentration of 0.36%, by weight of cement, proposed by Swamy [67] was utilized and the time required for the chloride concentration at the rebar level to reach 0.06% by weight of concrete was calculated using equation 4.3. The time to initiation of corrosion for the coated and uncoated concrete specimens have been tabulated in Table 4.13. Reinforcement in the uncoated concrete specimens would start corroding in about 1 year from the time of casting, whereas, in the concrete specimens coated with polyurethane coatings this value would range from 11 to 30 years. In the concrete specimens coated with epoxy coatings the rebar could be safe up to 3 to 8 years and in the concrete specimens coated with acrylic coatings the time to initiation of corrosion would be in the range of 6 to 10 years. In the concrete specimens coated with polymer emulsion coatings rebar corrosion will initiate within 1 to 2.5 years.

The effectiveness of the polyurethane and epoxy coatings in retarding the diffusion of chloride ions and limiting reinforcement corrosion could be attributed to the tough film formation that acts as a barrier to the flow of aggressive ions in the concrete mix.

Table 4.13: Time to initiation of reinforcement corrosion with a concrete cover of 50 mm.

Coating	Time to initiation of corrosion, years
Acrylic coating AC1	9.96
Acrylic coating AC2	5.94
Polymer emulsion coating PE1	2.47
Polymer emulsion coating PE2	1.29
Epoxy coating EP1	2.70
Epoxy coating EP2	7.99
Polyurethane coating PU1	11.3
Polyurethane coating PU2	29.59
Chlorinated rubber coating CR1	2.17
Chlorinated rubber coating CR2	2.47
None	1.08

The performance rating of the selected coatings in decreasing the diffusion of chloride ions can be rated in the following descending order:

i)   Polyurethane coating, PU2

ii) Polyurethane coating, PU1

iii) Acrylic coating, AC1

iv) Epoxy resin coating, EP2

v)   Acrylic coating, AC2

vi) Epoxy resin coating, EP1

vii) Chlorinated rubber coating, CR2

viii) Polymer emulsion coating, PE1

ix) Chlorinated rubber coating, CR1

x)   Polymer emulsion coating, PE2

4.9 ACCELERATED REINFORCEMENT CORROSION

The ability of the coatings to protect the steel reinforcement embedded in the concrete from corrosion was evaluated by impressing an anodic potential of 4 volts on the steel bar and measuring the current required to maintain that potential. The current was measured by connecting the two leads of the resistor to a data acquisition system. The current flowing through each specimen was plotted against

time, as shown in Figures 4.34 through 4.44 and time–current curves were utilized to evaluate the time to cracking of concrete due to reinforcement corrosion. A sudden increase in the current requirements implies that the concrete had cracked due to initiation of reinforcement corrosion. The time required for corrosion initiation is summarized in Table 4.14 and plotted in Figure 4.45.

As expected, the uncoated concrete specimens were the first to crack within 34 hours. The concrete specimens coated with polymer emulsion coatings cracked next within 156 to 198 hours. None of the other coated specimens cracked up to 1000 hours. One of the concrete specimens coated with an epoxy coating failed next at 1050 hours. The concrete specimens coated with the acrylic coating cracked after 1268 hours and the concrete specimens coated with a chlorinated rubber coating cracked after 1628 hours. One of the concrete specimens coated with polyurethane coating cracked after 1716 hours. The current readings were recorded up to 2076 hours, i.e. almost 3 months, and none of the remaining coated specimens had cracked.

The initial current required for maintaining an anodic potential of +4V on the steel bar was also utilized to evaluate the relative performance of the selected coatings in enhancing the corrosion-resistance of concrete. These data are particularly useful when no significant increase in the current requirement, denoting cracking of concrete, is noted. The initial current requirement for the coated and uncoated concrete specimens to maintain an anodic potential of +4 V is tabulated in Table 4.15 and plotted in Figure 4.46. The initial current requirement in the uncoated concrete specimens was 3.0 mA whereas for the samples coated with
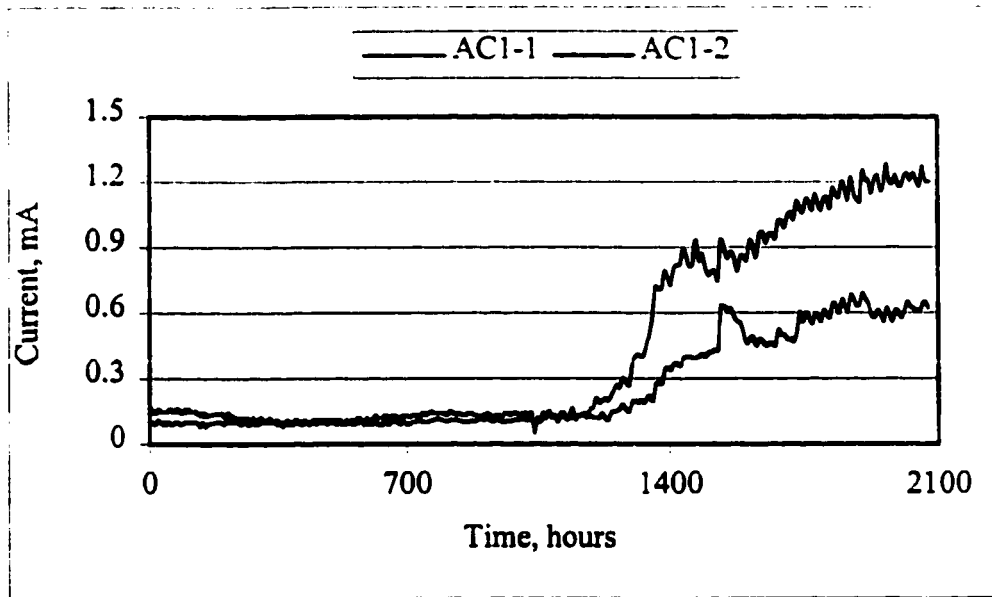
Figure 4.34: Variation of current with time in the concrete specimens coated with acrylic coating AC1.
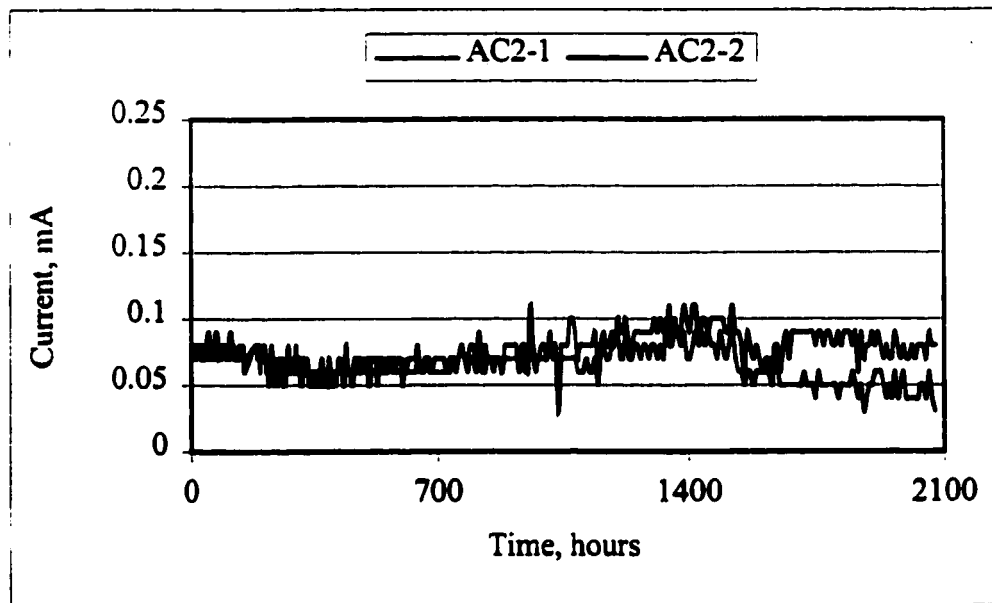
Figure 4.35: Variation of current with time in the concrete specimens coated with acrylic coating AC2
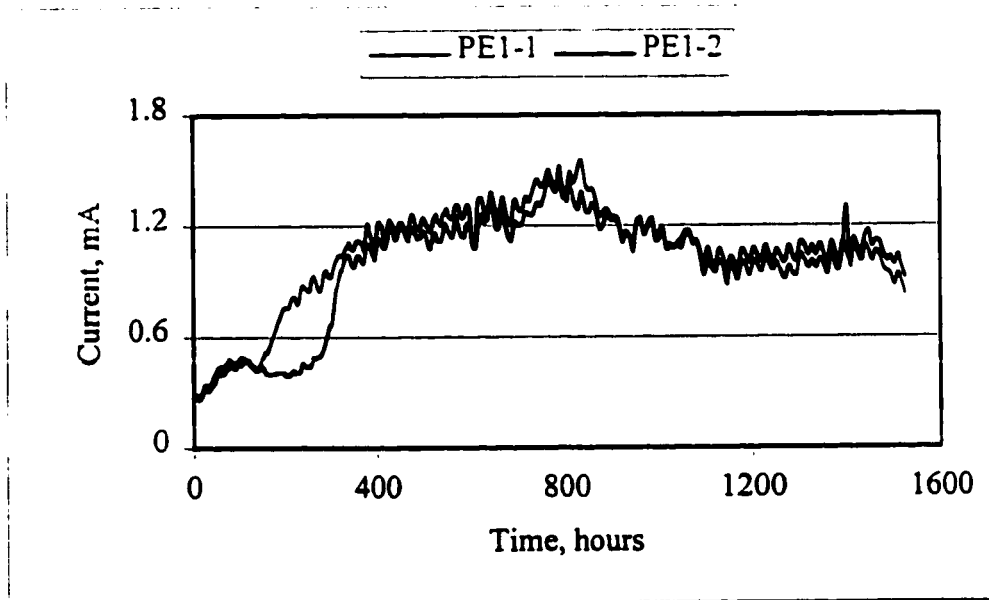
Figure 4.36: Variation of current with time in the concrete specimens coated with polymer emulsion coating PE1.
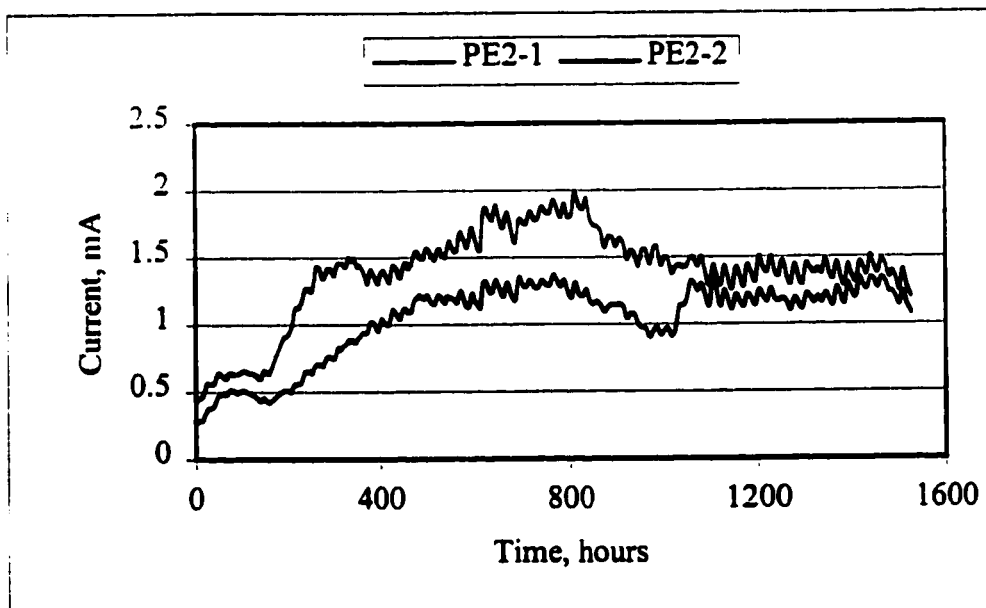
Figure 4.37: Variation of current with time in the concrete specimens coated with polymer emulsion coating PE2.
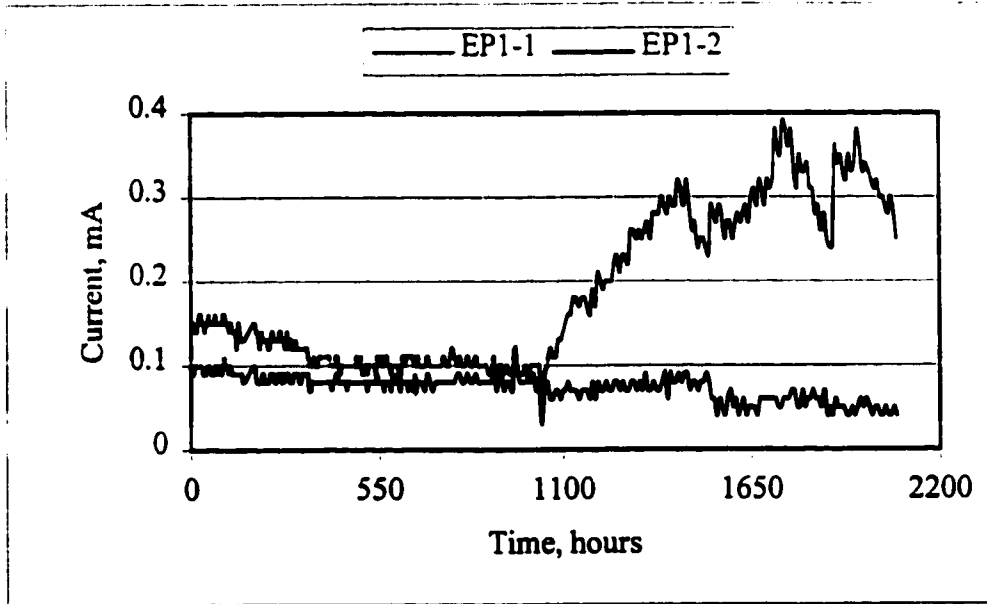
Figure 4.38: Variation of current with time in the concrete specimens coated with epoxy coating EP1.
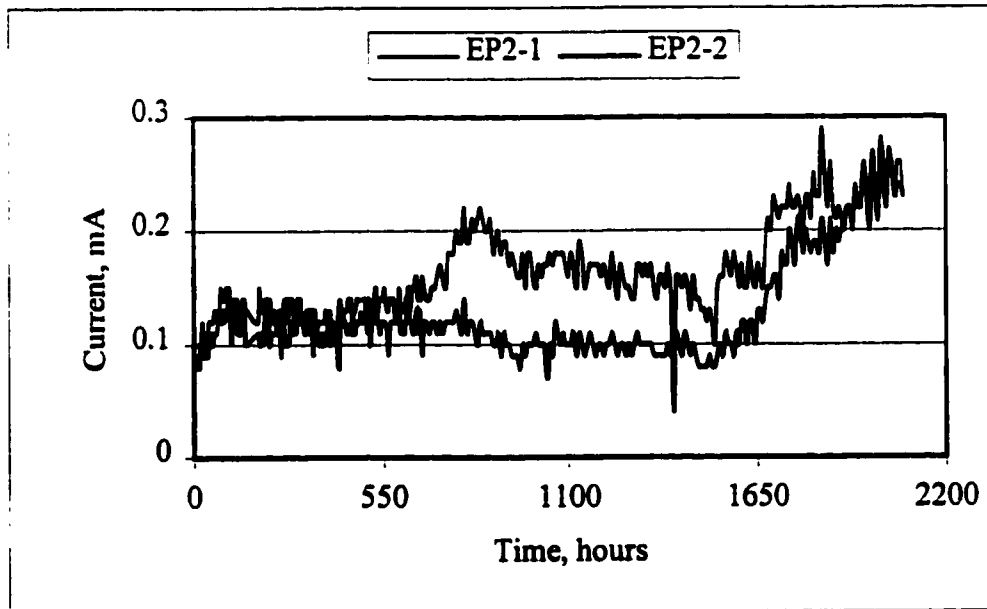
Figure 4.39: Variation of current with time in the concrete specimens coated with epoxy coating EP2.
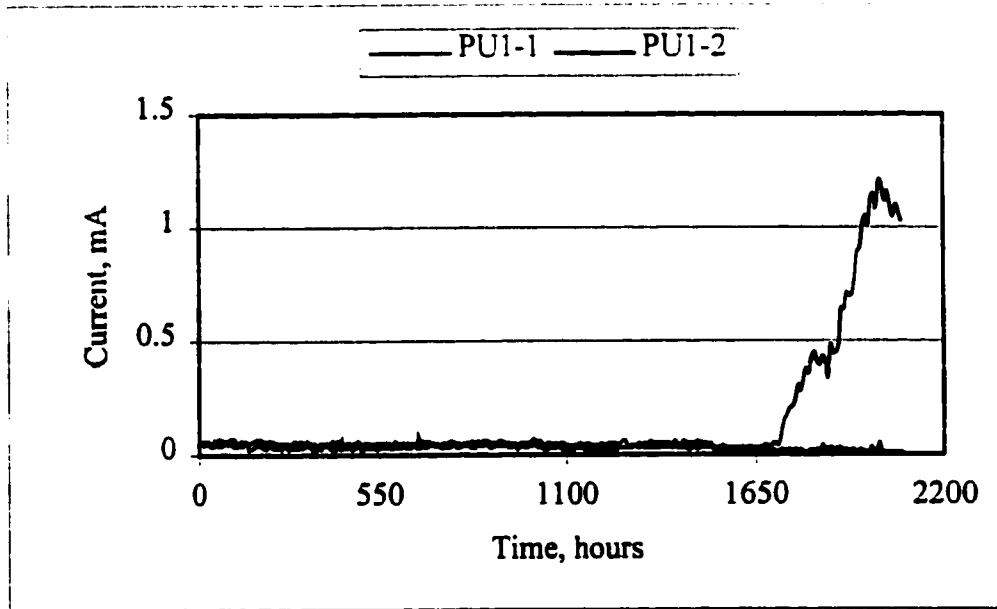
Figure 4.40: Variation of current with time in the concrete specimens coated with polyurethane coating, PU1.
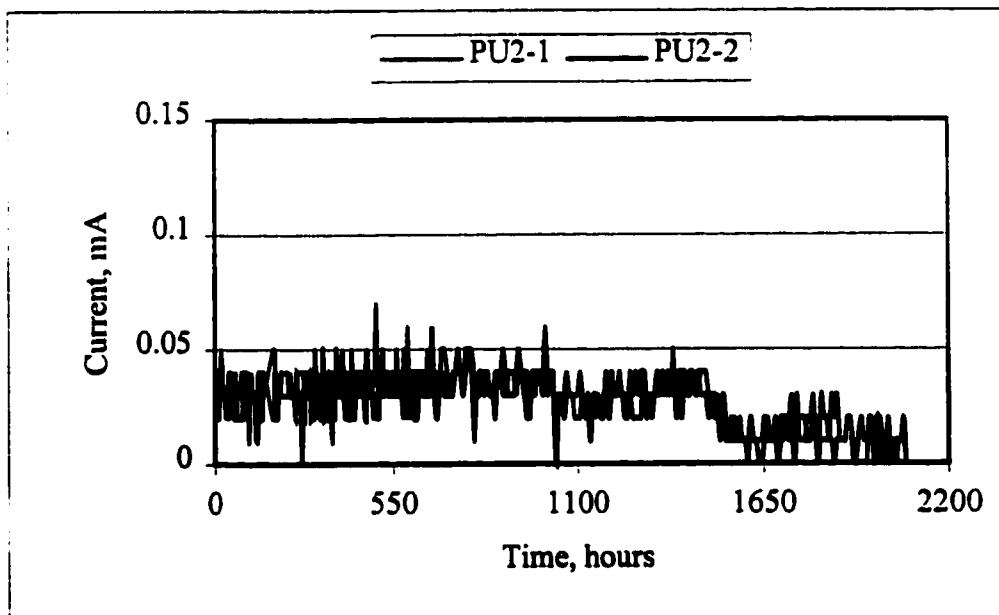
Figure 4.41: Variation of current with time in the concrete specimens coated with polyurethane coating PU2.
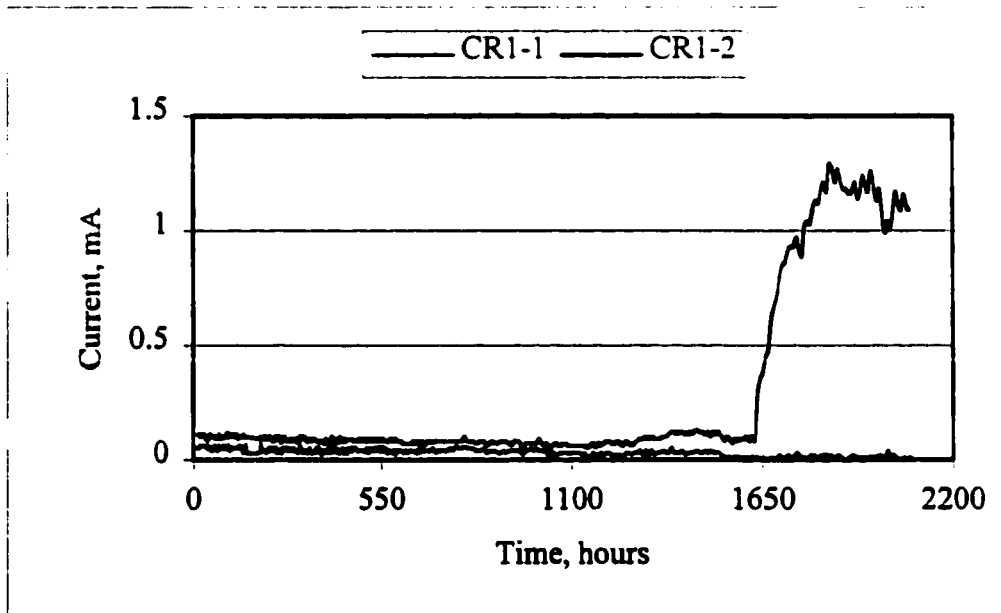
Figure 4.42: Variation of current with time in the concrete specimens coated with chlorinated rubber coating CR1.
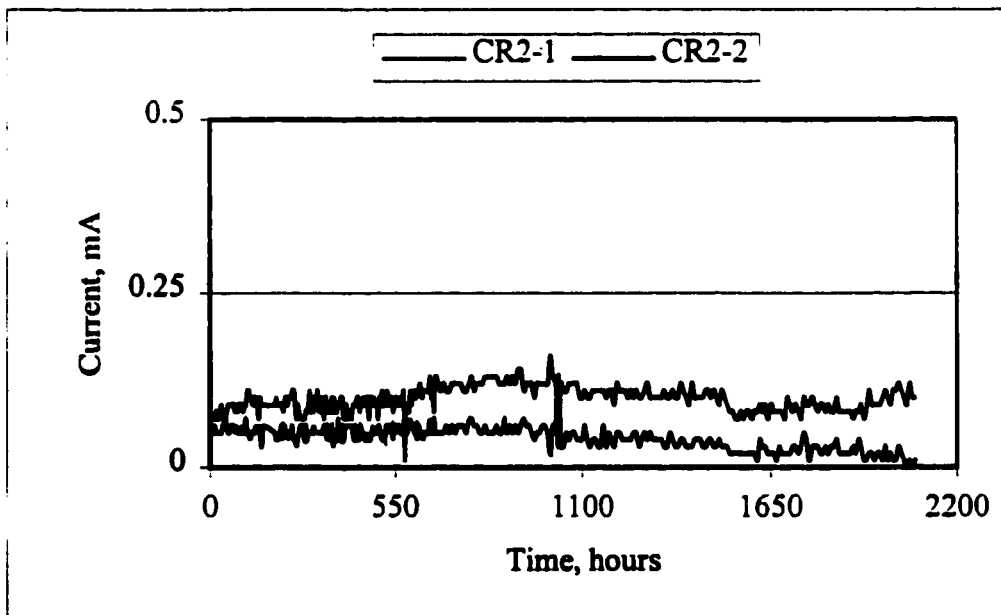
Figure 4.43: Variation of current with time in the concrete specimens coated with chlorinated rubber coating CR2.
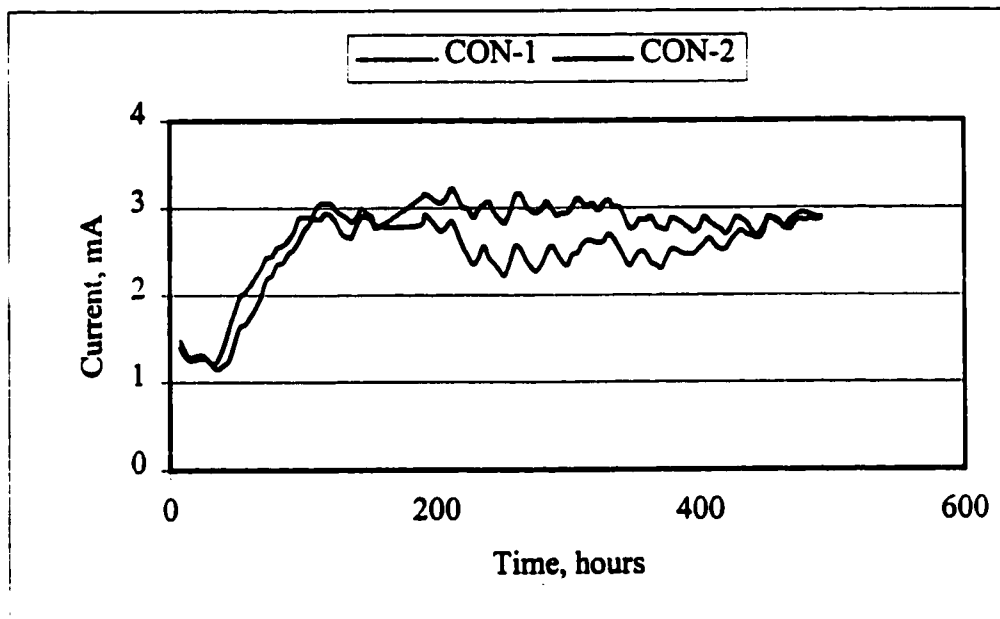
Figure 4.44: Variation of current with time in the uncoated concrete specimens.

Table 4.14: Time to initiation of cracking of the coated and uncoated concrete specimens due to reinforcement corrosion.

Coating	Time to initiation of cracking, hours		
	Sample 1	Sample2	Average
Acrylic coating AC1	1180	1356	1268
Polymer emulsion coating PE1	264	132	198
Polymer emulsion coating PE2	156	156	156
Epoxy coating EP1	1050	no cracks	1050
Polyurethane coating PU1	1716	no cracks	1716
Chlorinated rubber coating CR1	1628	no cracks	1628
None	32	36	34
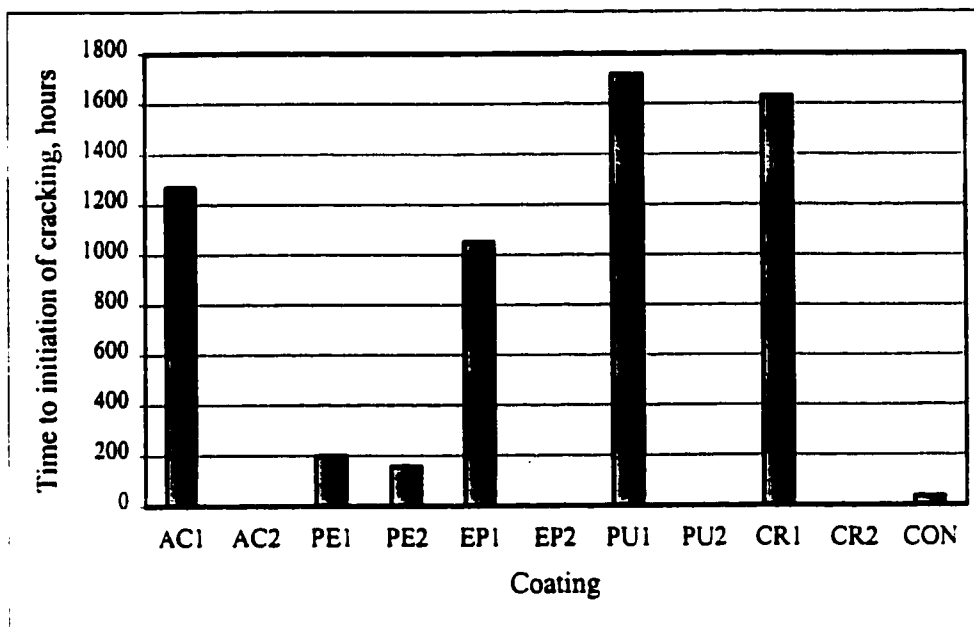
Figure 4.45: Time to initiation of cracking due to reinforcement corrosion in the coated and uncoated concrete specimens.

Table 4.15: Initial current required to maintain a potential of +4 V on the reinforcement in the coated and uncoated concrete specimens.

Coating	Initial Current, mA
Acrylic coating AC1	0.985
Acrylic coating AC2	0.105
Polymer emulsion coating PE1	1.535
Polymer emulsion coating PE2	1.685
Epoxy coating EP1	0.255
Epoxy coating EP2	0.285
Polyurethane coating PU1	0.635
Polyurethane coating PU2	0.065
Chlorinated rubber coating CR1	0.680
Chlorinated rubber coating CR2	0.145
None	3.215
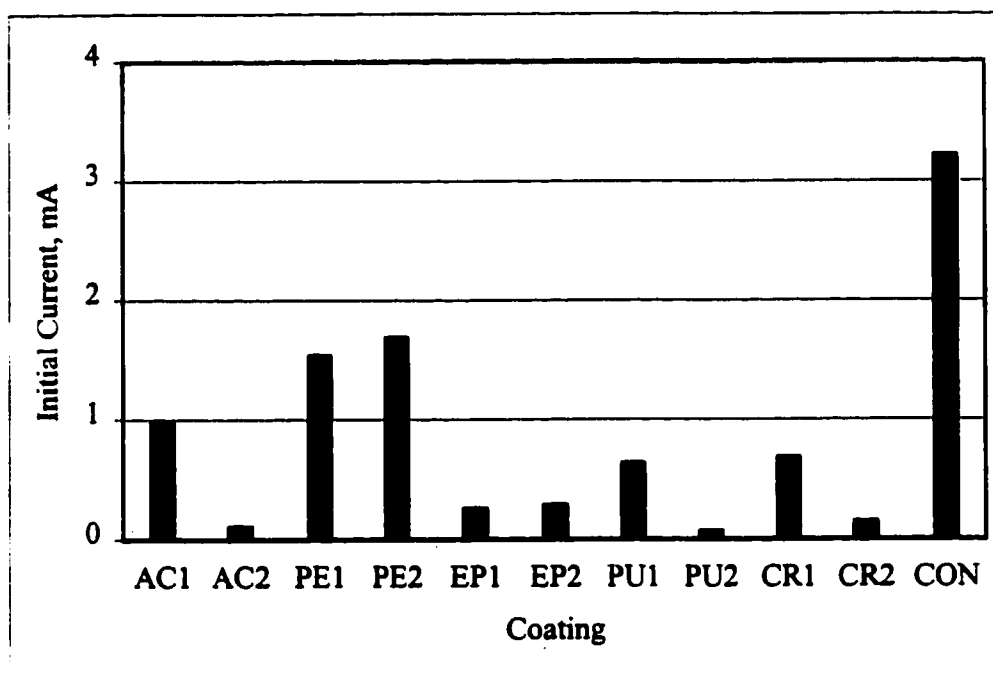
Figure 4.46: Initial current required to maintain a potential of +4 V on the steel in the coated and uncoated concrete specimens.

polyurethane coatings it was in the range of 0.1 to 0.6 mA. The specimens coated with epoxy coatings required a current of 0.26 to 0.29 mA to maintain an anodic potential of +4V while those coated with acrylic coatings required a current of 0.1 mA. In the specimens coated with chlorinated rubber coatings the initial current requirement was in the range of 0.15 to 0.7 mA and in the concrete specimens coated with polymer emulsion coatings it was 1.5 to 1.7 mA.

Figures 4.47 through 4.57 show the coated and uncoated cement concrete specimens after 2076 hours of exposure to an impressed anodic voltage of +4 V. About half of the coatings tested did not fail, i.e. the concrete specimens coated with these coatings did not crack, even after 2000 hours of exposure to an impressed potential of +4V on the embedded steel bar. Both the polymer emulsion coatings failed within 200 hours. Hence, these coatings should not be used on reinforced concrete in the presence of moisture and chlorides. Among the two acrylic coatings, only one failed within 1200 hours whereas the other acrylic coating showed no signs of deterioration. One coating each from the remaining generic types failed within the duration of testing. A large variation was observed in the performance of coatings from the same generic type procured from different manufacturers.

The current-time curves for the coated and uncoated concrete specimens shows that minimum deterioration was noted in the concrete specimens coated with polyurethane and chlorinated rubber coatings. Hence, in conditions where reinforced concrete is to be used in humid or wet conditions in the presence of
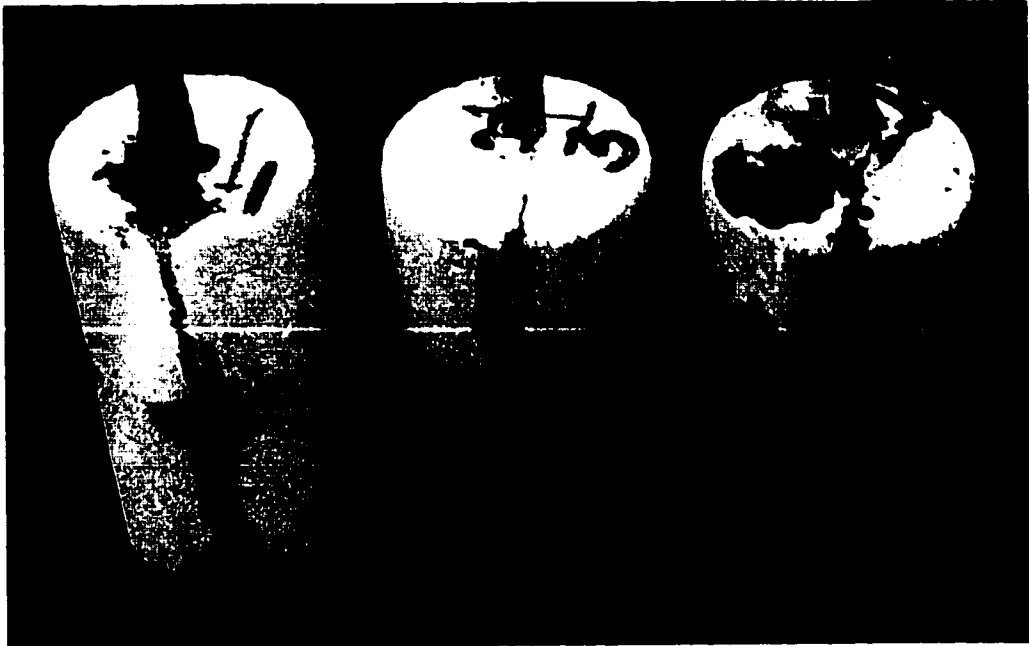
Figure 4.47: Concrete specimens coated with acrylic coating AC1.
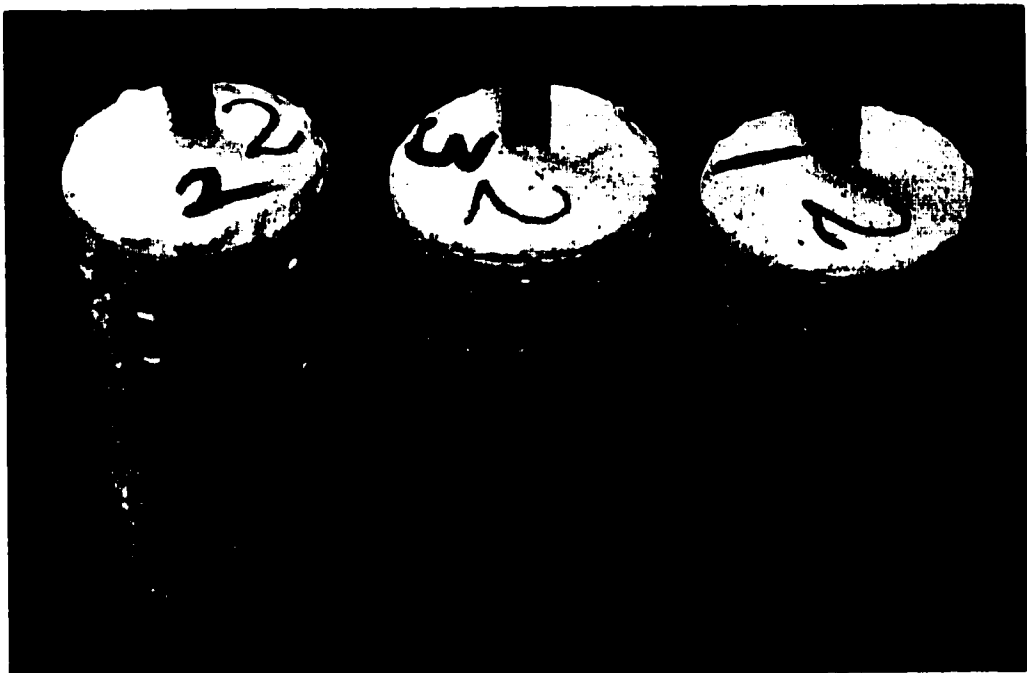
Figure 4.48: Concrete specimens coated with acrylic coating AC2

Figure 4.49: Concrete specimens coated with polymer emulsion coating PE1.

Figure 4.50: Concrete specimens coated with polymer emulsion coating PE2.

Figure 4.51: Concrete specimens coated with epoxy coating EP1.
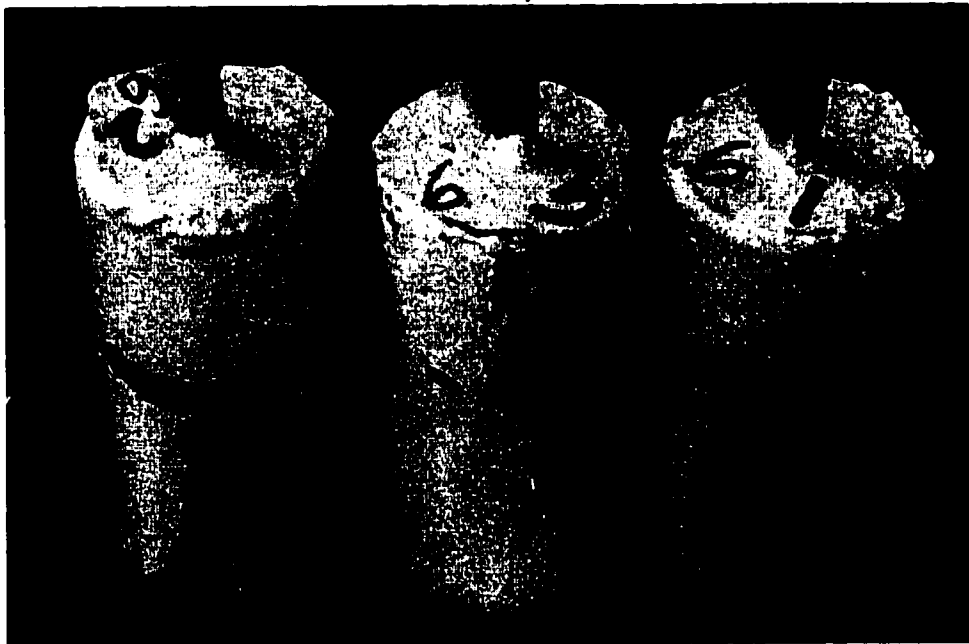
Figure 4.52: Concrete specimens coated with epoxy coating EP2.

Figure 4.53: Concrete specimens coated with polyurethane coating PU1.
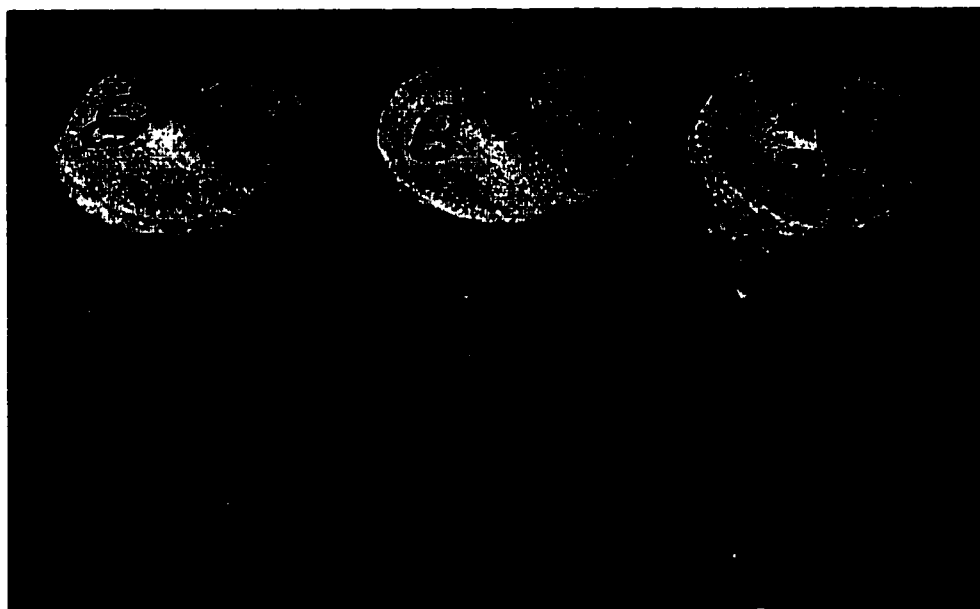
Figure 4.54: Concrete specimens coated with polyurethane coating PU2.
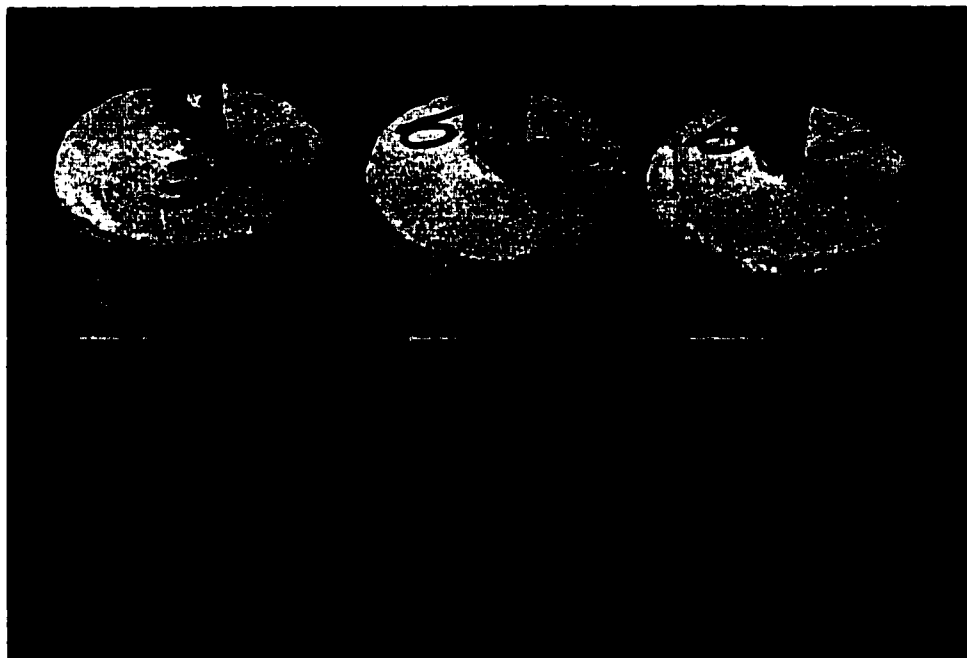
Figure 4.55: Concrete specimens coated with chlorinated rubber coating CR1.
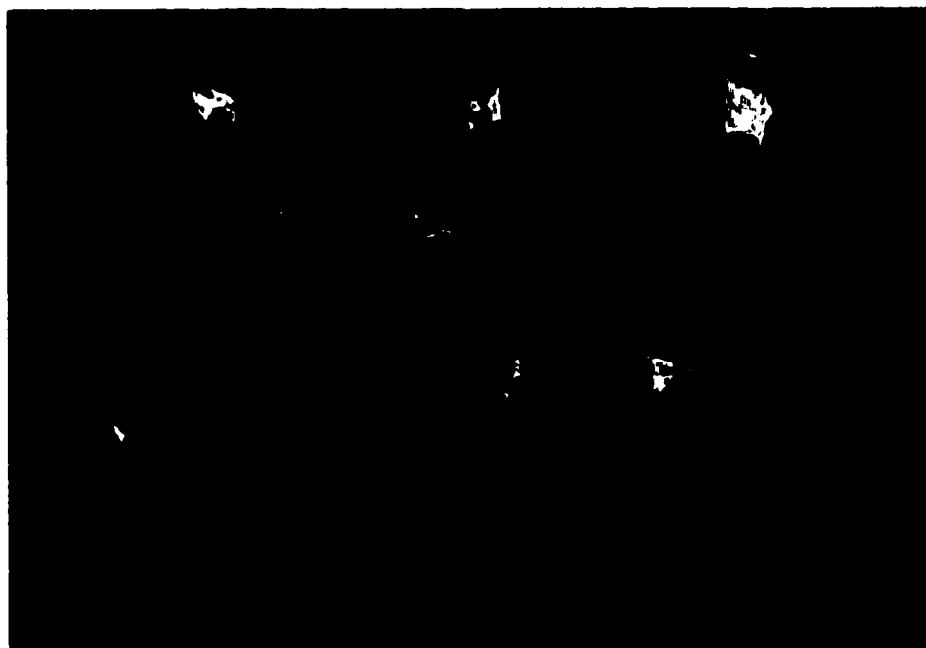
Figure 4.56: Concrete specimens coated with chlorinated rubber coating CR2.

Figure 4.57: Uncoated concrete specimens.

chlorides, it would be advisable to apply polyurethane or chlorinated rubber coatings.

Swamy and Tanikawa [35] studied the corrosion resistance of concrete coatings by exposing coated specimens to aggressive environment for 100 days and then evaluated the extent of corroded area by visual examination. Their results show that the epoxy coating performed best with only 0 to 1% corrosion of the reinforcement. Specimens coated with acrylic rubber coatings showed 3 to 7% corrosion of the reinforcement and those coated with polyurethane coatings showed about 10% corrosion of the embedded steel. A corrosion damage of 60 to 80% was noted in the uncoated concrete specimens.

Figure 4.58 shows a typical service-life model for reinforced concrete coated with the selected coatings. The point on the X-axis from which the lines take-off represents the time required for the chloride concentration at the rebar level to reach 0.06% by weight of concrete, in a concrete specimen coated with the selected coating and with 50 mm cover to the steel reinforcement. These values were determined by chloride diffusion analysis as given in Table 4.13 and detailed in section 4.8. The slope of each line is the reciprocal of time to initiation of cracking observed in the coated and uncoated concrete specimens during the accelerated corrosion with an impressed potential of +4V. These values were obtained from Table 4.14 and they were available only for those specimens that had cracked. Thus, the time required for the reinforcement corrosion to reach an unacceptable level could be estimated using this model. It can be seen from the model that the steel bars in the uncoated concrete specimens would corrode very early followed by
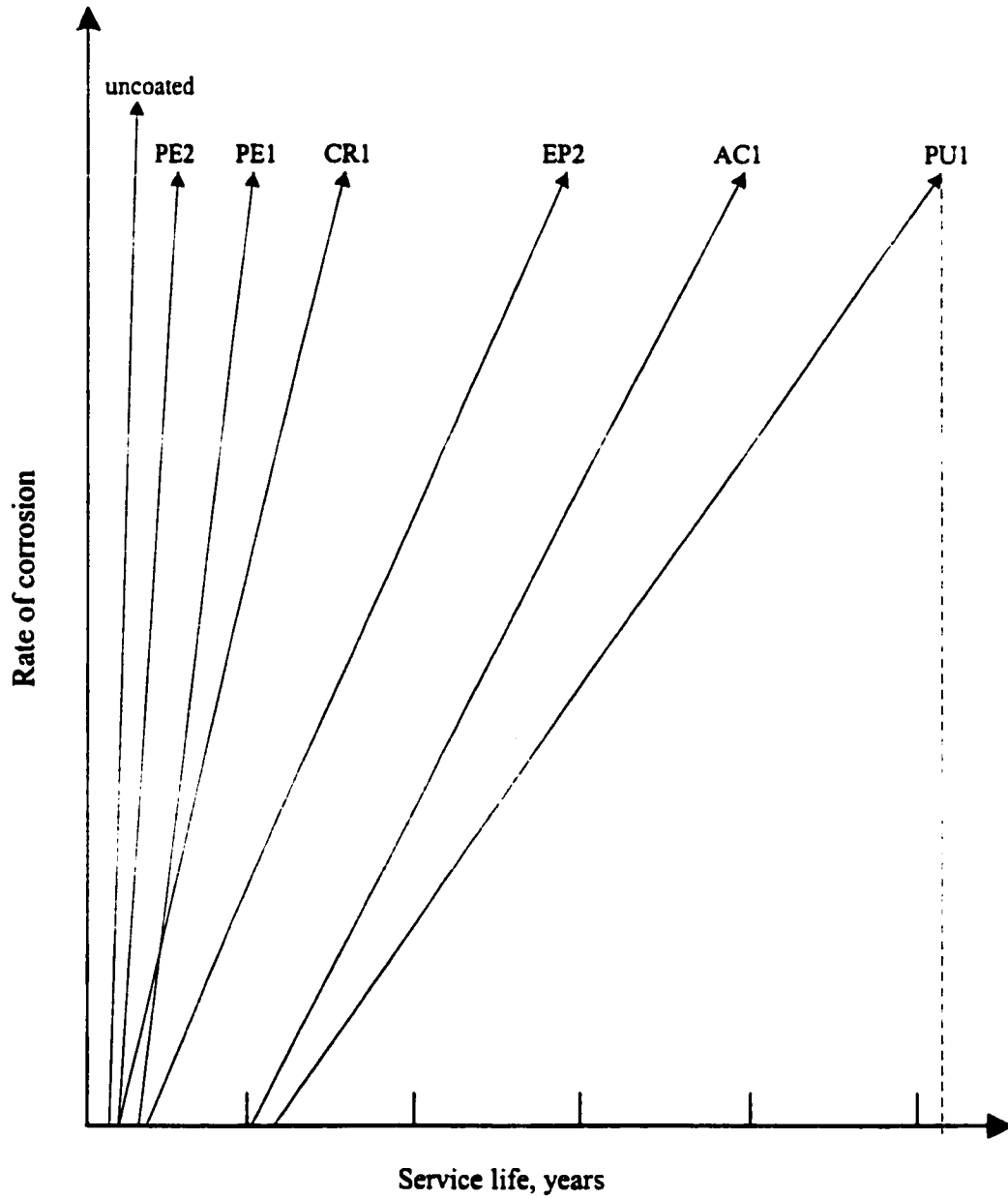
Figure 4.58: A service life model for reinforced concrete coated with the selected coatings.

the bars in the concrete specimens coated with polymer emulsion coatings. The steel bars in the concrete specimens coated with chlorinated rubber and acrylic coatings will corrode next and the concrete specimens coated with epoxy and polyurethane coatings will be the last to corrode under identical exposure conditions.

The performance of the selected coatings in resisting reinforcement corrosion, particularly after corrosion initiation is in the following descending order:

i)   Polyurethane coating, PU2

ii)   Acrylic coating, AC2

iii)   Chlorinated rubber coating, CR2

iv)   Epoxy resin coating, EP1

v)   Epoxy resin coating, EP2

vi)   Polyurethane coating, PU1

vii)   Chlorinated rubber coating, CR1

viii) Acrylic coating, AC1

ix)   Polymer emulsion coating, PE1

x)   Polymer emulsion coating, PE2

4.10 CARBONATION

The coatings were evaluated for their resistance to carbonation by exposing the coated samples to an accelerated carbonation environment for three months, and then splitting them open and spraying the freshly cut surface with phenolphthalein indicator to demarcate the carbonated region. The colorless region represents the uncarbonated area while the pink colored region is the carbonated area.

The depth of carbonation was measured at 12 points at the periphery of the carbonated area and the average of these readings was taken as the depth of carbonation for that specimen. Table 4.16 summarizes the depth of carbonation in the coated and uncoated mortar specimens after 1, 2 and 3 months of accelerated carbonation exposure and the same data has been plotted in Figure 4.59.

Figures 4.60 through 4.70 show the carbonation depth observed in the coated and uncoated mortar specimens. The depth of carbonation increased with the period of exposure in both the coated and uncoated cement mortar specimens. After 3 months of exposure, the depth in the uncoated mortar specimens was 17.2 mm. In the mortar specimens coated with polymer emulsion coatings, the depth of carbonation was in the range of 10.9 to 12.5 mm, whereas in the mortar specimens coated with acrylic coatings, it was in the range of 6.8 to 8.4 mm. The depth of carbonation in the mortar specimens coated with chlorinated rubber coatings was in the range of 7.5 to 7.7 mm and in those coated with epoxy coatings it was in the range of 6.6 to 6.8 mm. The depth of carbonation in the mortar specimens coated with polyurethane coatings was the least, being in the range of 5.3 to 5.6 mm.

Table 4.16: Carbonation depth in the coated and uncoated concrete specimens after exposure to accelerated carbonation environment.

Coating	Depth of carbonation, mm		
	30 days	60 days	90 days
Acrylic coating AC1	4.1	5.6	6.8
Acrylic coating AC2	4.6	6.4	8.4
Polymer emulsion coating PE1	6.9	10.8	12.5
Polymer emulsion coating PE2	7.5	9.9	10.9
Epoxy coating EP1	3.4	4.9	6.6
Epoxy coating EP2	3.3	5.1	6.8
Polyurethane coating PU1	3.0	4.1	5.3
Polyurethane coating PU2	2.5	4.2	5.6
Chlorinated rubber coating CR1	4.5	5.3	7.5
Chlorinated rubber coating CR2	4.2	5.8	7.7
None	8.3	13.0	17.2
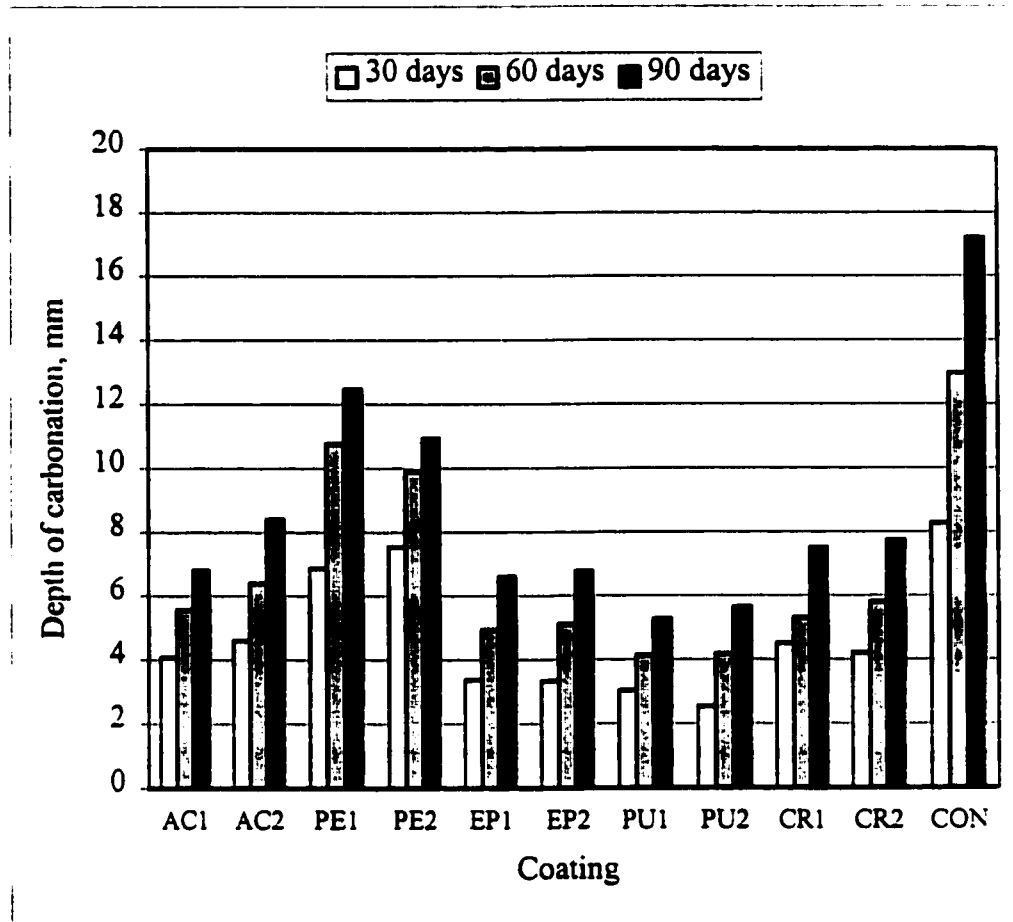
Figure 4.59: Carbonation depth in the coated and uncoated mortar specimens after end of 1, 2 and 3 months of accelerated carbonation exposure.
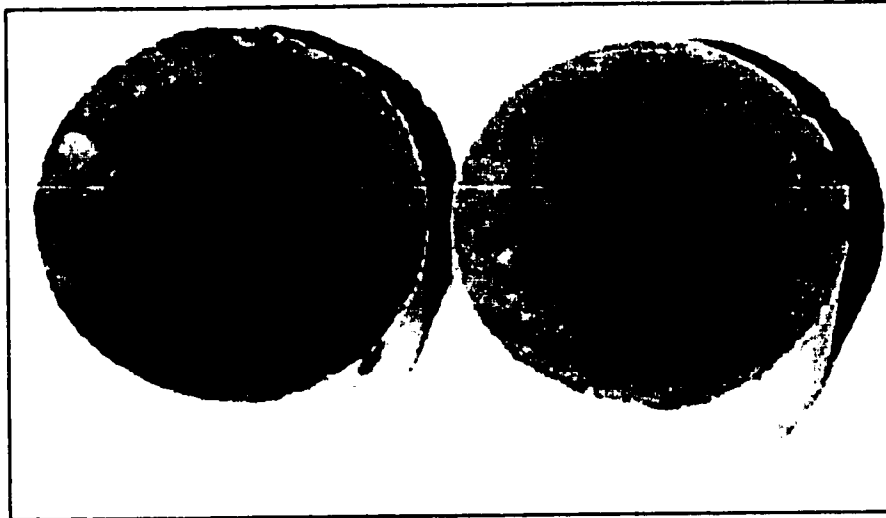
Figure 4.60: Mortar specimen coated with acrylic coating AC1.
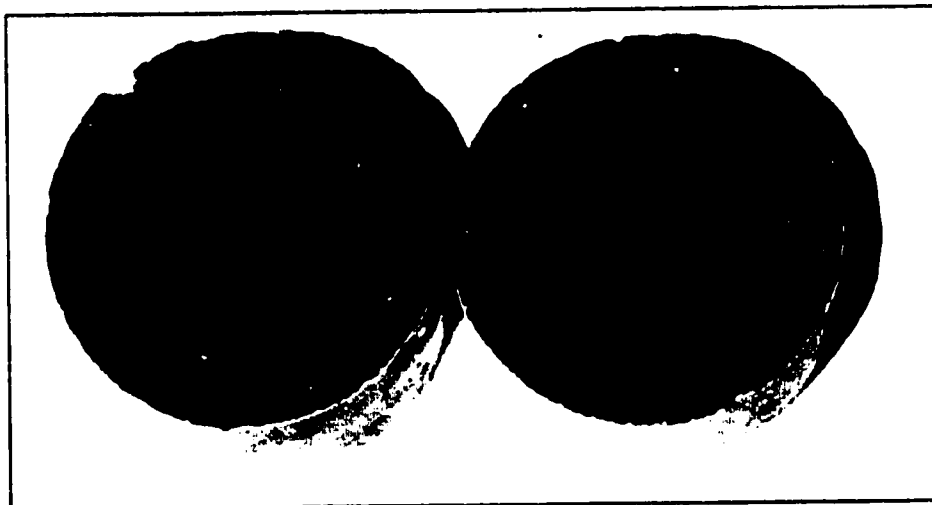
Figure 4.61: Mortar specimen coated with acrylic coating AC2.
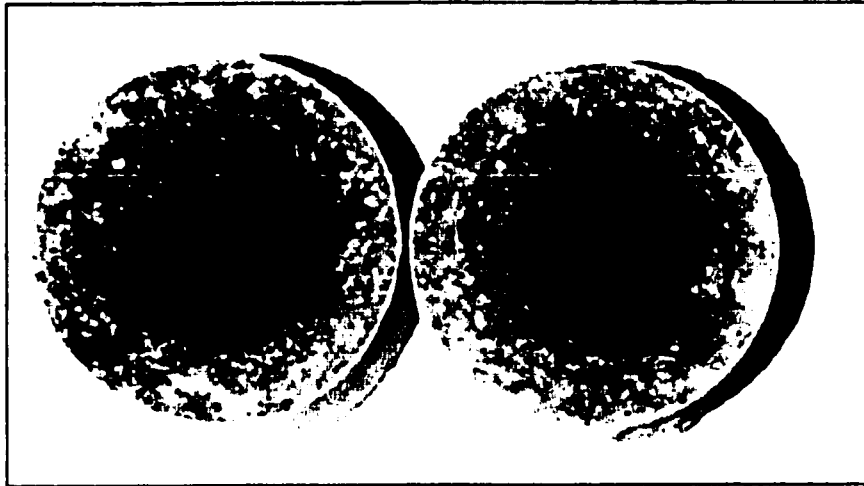
Figure 4.62: Mortar specimen coated with polymer emulsion coating PE1.

Figure 4.63: Mortar specimen coated with polymer emulsion coating PE2.
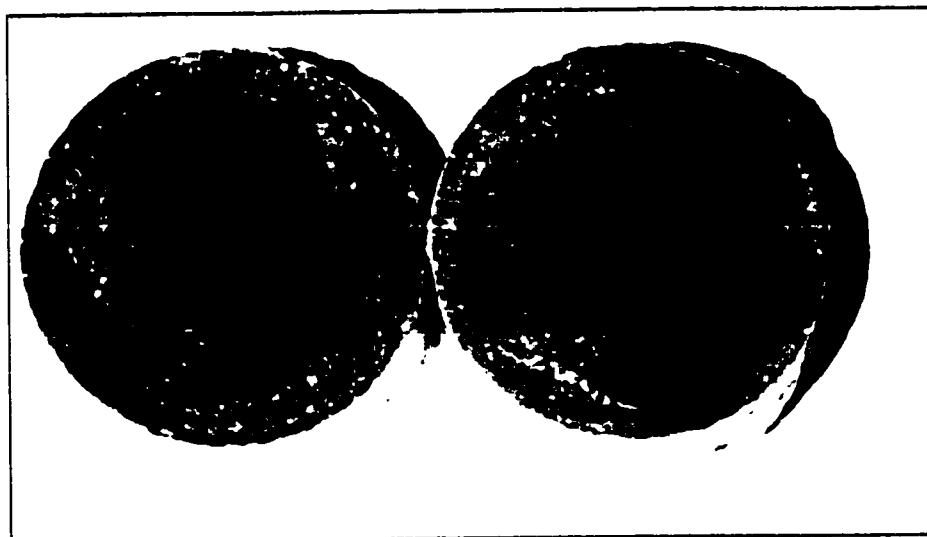
Figure 4.64: Mortar specimen coated with epoxy coating EP1.
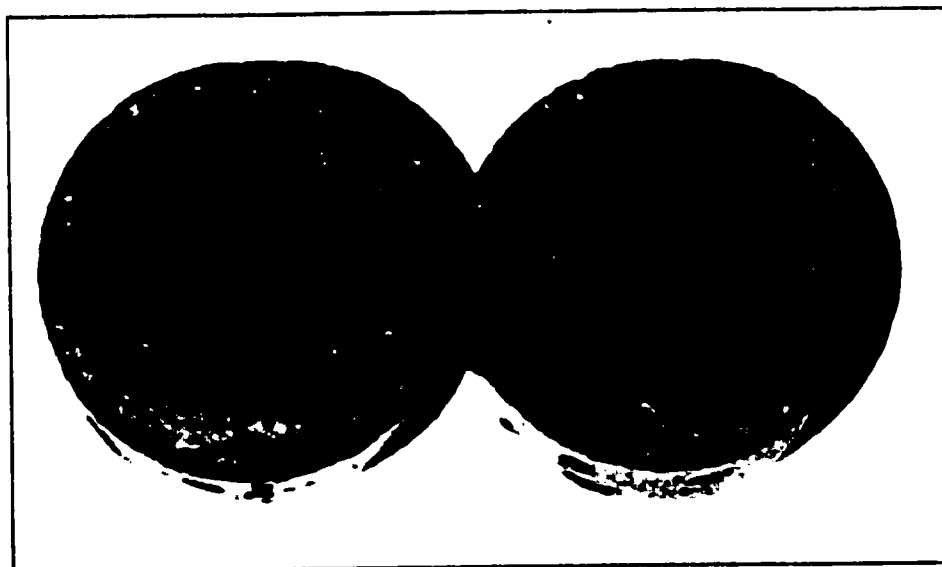
Figure 4.65: Mortar specimen coated with epoxy coating EP2.
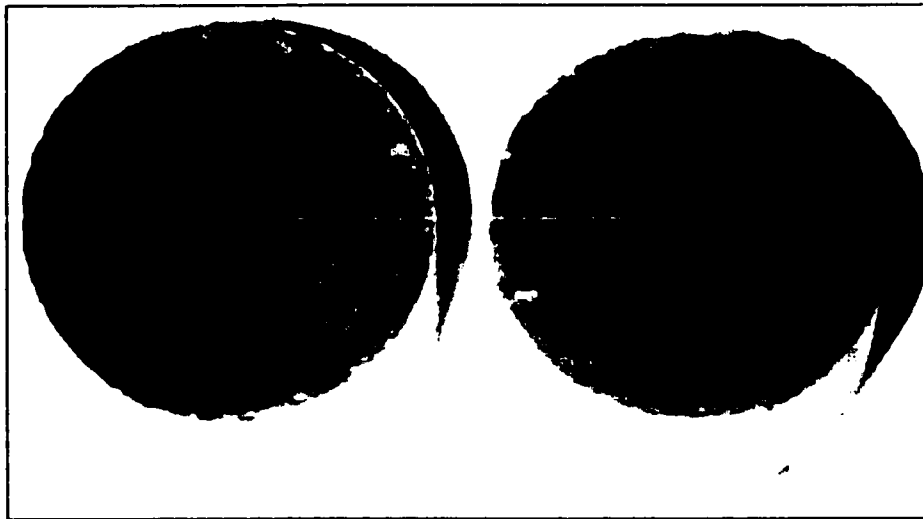
Figure 4.66: Mortar specimen coated with polyurethane coating PU1.
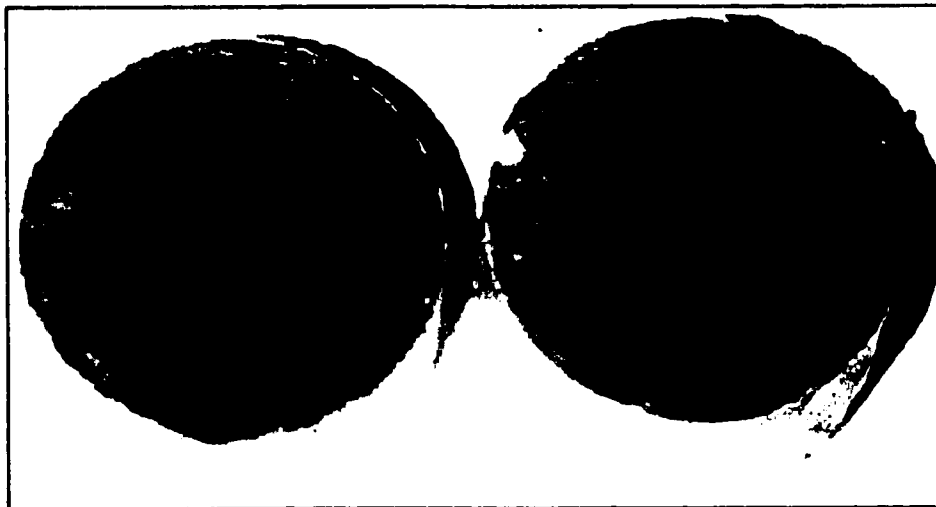
Figure 4.67: Mortar specimen coated with polyurethane coating PU2.
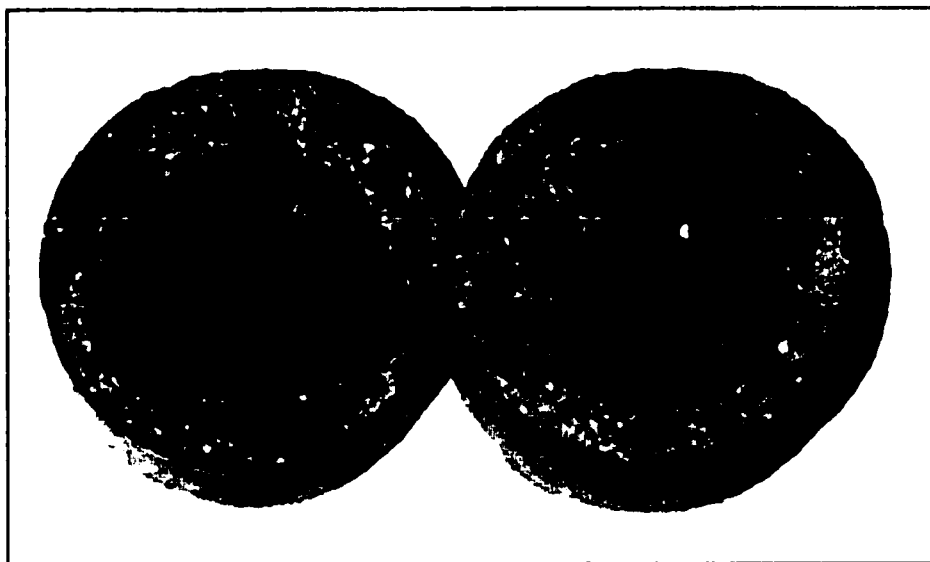
Figure 4.68: Mortar specimen coated with chlorinated rubber coating CR1.
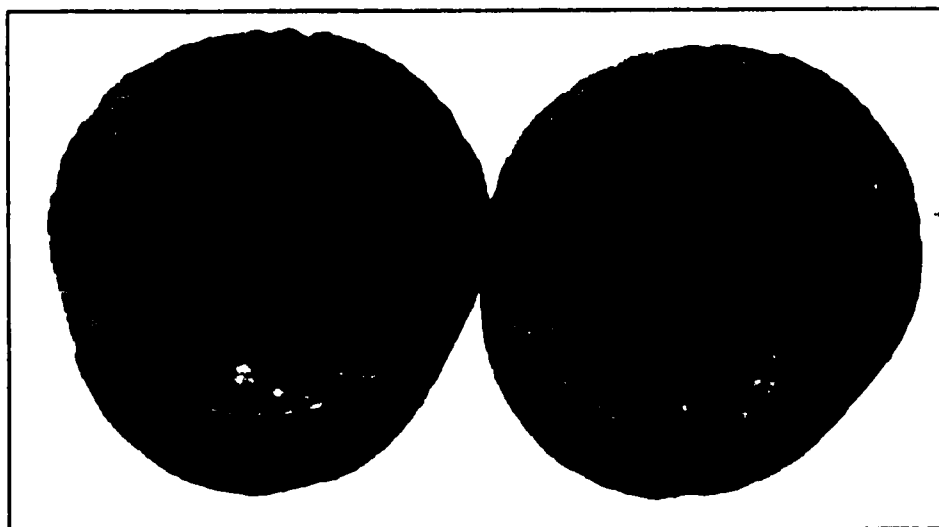
Figure 4.69: Mortar specimen coated with chlorinated rubber coating CR2.
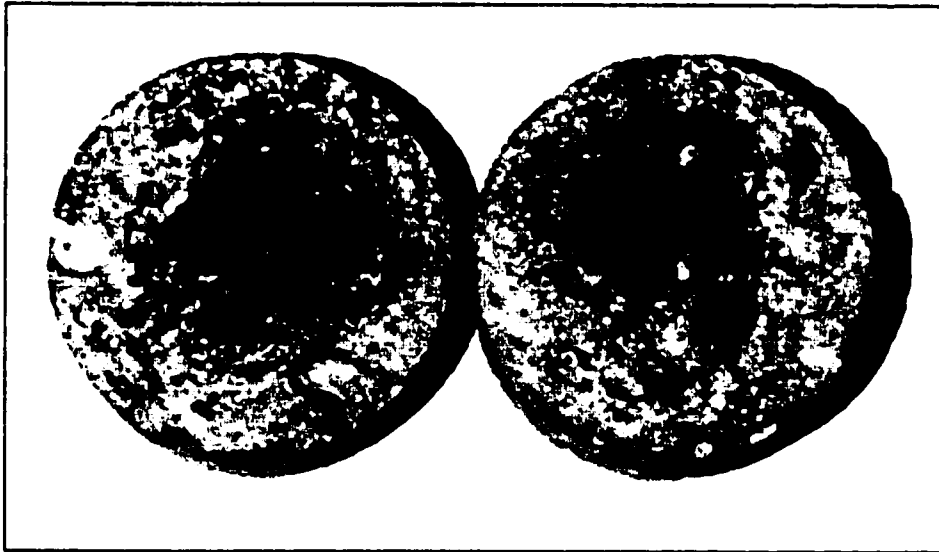
Figure 4.70: Uncoated mortar specimen.

The variation of the carbonation depth with the period of exposure is plotted in Figure 4.71. Initially, the depth of carbonation increases almost linearly. However, it becomes almost constant at higher depths, indicating that carbonation is a diffusion process.

Since carbonation is a diffusion-controlled process, it can be expressed by the following equation.

$$D_c = K\sqrt{t} \qquad\qquad (4.2)$$

where, D_c = carbonation depth, mm

K = coefficient of CO_2 diffusion, and

t = exposure period, days.

Table 4.17 and Figure 4.72 show the coefficients of carbon dioxide diffusion in the coated and uncoated mortar specimens. The coefficient of CO_2 diffusion in the uncoated mortar specimens was 1.8. The diffusion coefficient in mortar specimens coated with acrylic coatings was in the range of 0.7 to 0.9, whereas in mortar specimens coated with polymer emulsion coatings it was in the range of 1.2 to 1.4. The CO_2 diffusion coefficient in the mortar specimens coated with chlorinated rubber coatings was 0.8 and in mortar specimens coated with epoxy coatings it was 0.7. The coefficient of CO_2 diffusion for the mortar specimens coated with polyurethane coatings was in the range of 0.55 to 0.6 which was the least amongst all the selected generic types.
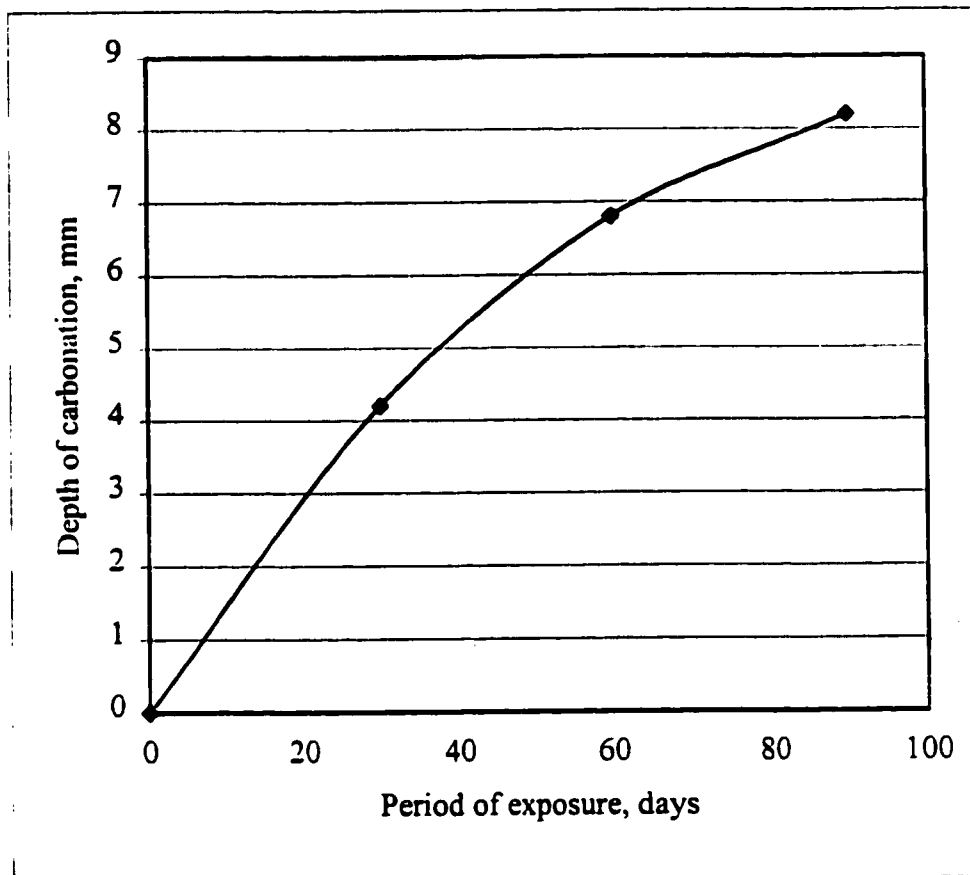
Figure 4.71: Carbonation depths in the mortar specimens coated with acrylic coating AC2, after 30,60 and 90 days.

Table 4.17: Coefficients of carbon dioxide diffusion in the coated and uncoated mortar specimens after exposure to accelerated carbonation environment.

Coating	Coefficient of carbon dioxide diffusion. $mm/\sqrt{days}$
Acrylic coating AC1	0.717
Acrylic coating AC2	0.868
Polymer emulsion coating PE1	1.339
Polymer emulsion coating PE2	1.187
Epoxy coating EP1	0.679
Epoxy coating EP2	0.698
Polyurethane coating PU1	0.548
Polyurethane coating PU2	0.579
Chlorinated rubber coating CR1	0.757
Chlorinated rubber coating CR2	0.795
None	1.776
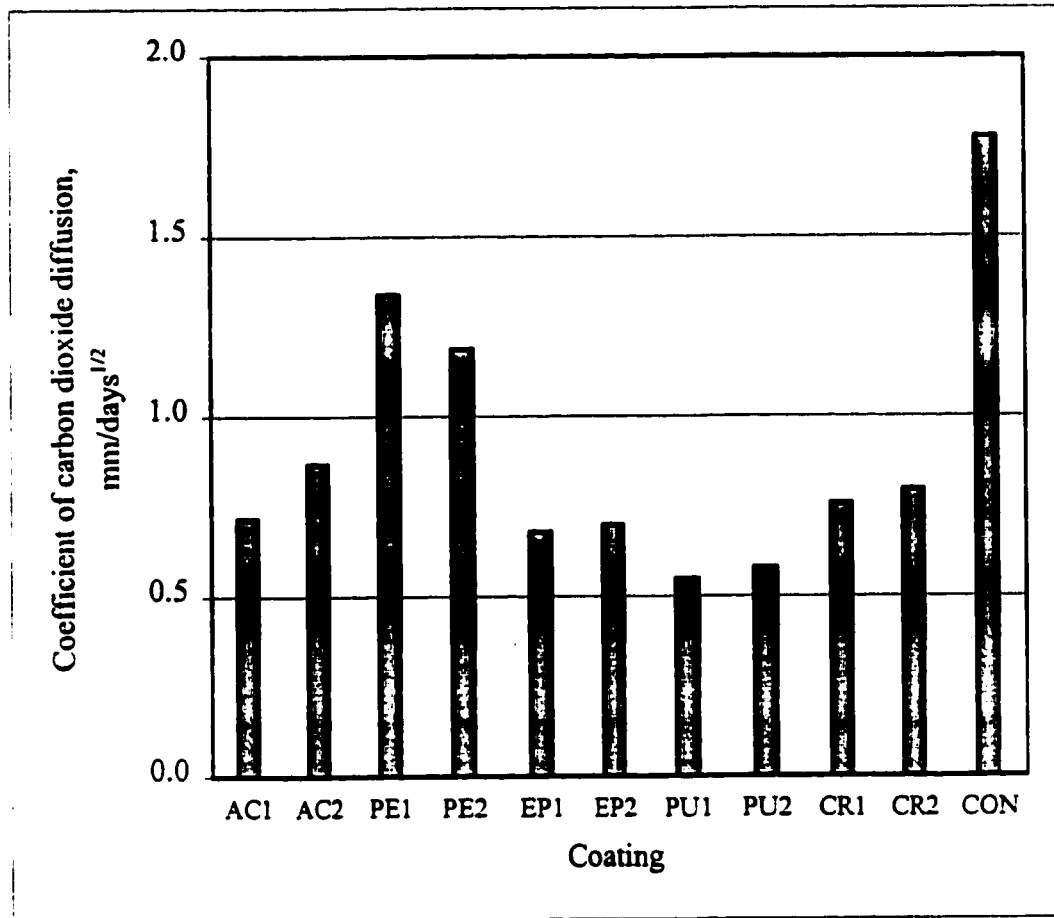
Figure 4.72: Coefficients of carbon dioxide diffusion in the coated and uncoated mortar specimens.

Garcia [54] evaluated the carbonation depths in concrete specimens coated with resin-based coatings in an accelerated carbonation environment. His results show that epoxy and ethylene polymer resin coatings performed the best in resisting the carbonation of concrete. Swamy and Tanikawa [57] exposed concrete slabs coated with an acrylic rubber coating to atmospheric carbonation for 4 years and found that the uncoated specimens had carbonated to a depth of 25 mm whereas the coated samples had carbonated to a depth of 8 mm. Research by Dulaijan et al. [60] on epoxy resin coatings in accelerated carbonation environment showed that the samples coated with the epoxy resin coating had carbonated to a depth of 3 mm only while the uncoated specimens had carbonated to a depth of 11 mm.

The performance of the selected coatings in resisting carbonation is in the following descending order:

i) Polyurethane coating, PU1

ii) Polyurethane coating, PU2

iii) Epoxy resin coating, EP1

iv) Epoxy resin coating, EP2

v) Acrylic coating, AC1

vi) Chlorinated rubber coating, CR1

vii) Chlorinated rubber coating, CR2

viii) Acrylic coating, AC2

ix) Polymer emulsion coating, PE2

x) Polymer emulsion coating, PE1

4.11 COST ANALYSIS OF THE SELECTED COATINGS

Table 4.18 gives the material cost of the selected concrete coatings. The rates were ascertained by a survey of the coatings market in the Eastern Province of Saudi Arabia. The rate per liter of the coating material was converted to the rate per square meter of the area to be coated by utilizing the coverage rates recommended by the manufacturers. It can be seen that the acrylic coatings cost 1.3 to 2.1 SR/m^2 whereas the cost of the polymer emulsion coatings lies in the range of 0.8 to 6.6 SR/m^2. The exorbitant cost of the polymer emulsion coating PE2 could be attributed to its seemingly low coverage rate, which depends on the dry film thickness of the coating. The cost of the epoxy coatings is in the range of 1.9 to 3.6 SR/m^2 and the cost of polyurethane coatings is in the range of 2.5 to 3.2 SR/m^2, whereas the cost of chlorinated rubber coatings is in the range of 2.2 to 2.75 SR/m^2.

Table 4.19 summarizes the material cost and the performance of the selected coatings. The performance ratings were assigned after evaluating their performance under conditions investigated in this study. This information provides a relationship between the cost and the performance of concrete coatings. It can be seen that the epoxy and polyurethane coatings are the best overall and the material cost for these coatings is quite close to the other generic types. The acrylic coatings are the

Table 4.18: Cost of the selected coatings.

Coating	Cost, SR/liter	Coverage rate, m^2./liter	Rate, SR/m^2
Acrylic coating AC1	18.00	8.6	2.09
Acrylic coating AC2	15.11	12.0	1.26
Polymer emulsion coating PE1	9.60	12.0	0.80
Polymer emulsion coating PE2	5.95	0.9	6.61
Epoxy coating EP1	23.40	6.6	3.55
Epoxy coating EP2	23.20	12.0	1.93
Polyurethane coating PU1	29.80	9.4	3.17
Polyurethane coating PU2	29.80	12.0	2.48
Chlorinated rubber coating CR1	14.00	5.1	2.75
Chlorinated rubber coating CR2	15.00	6.8	2.20

Table 4.19: Cost and performance of the selected coatings.

Coating	Cost of the coating material, SR / m^2	Performance Rating
Acrylic coating AC1	2.09	6
Acrylic coating AC2	1.26	7
Polymer emulsion coating PE1	0.80	10
Polymer emulsion coating.PE2	6.61	9
Epoxy coating EP1	3.55	1
Epoxy coating EP2	1.93	4
Polyurethane coating PU1	3.17	2
Polyurethane coating PU2	2.48	3
Chlorinated rubber coating CR1	2.75	8
Chlorinated rubber coating CR2	2.20	5

cheapest but their performance in aggressive conditions is unsatisfactory. The cost

of chlorinated rubber coatings is reasonable and their performance is moderate,

particularly coating CR2. The polymer emulsion coatings were the worst in

performance in aggressive conditions and also the cost of the polymer emulsion

PE2, was the highest due to the large thickness of the film.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The conclusions reached from this study and the performance of the selected concrete coatings is discussed in the following paragraphs.

5.1.1 Adhesion with concrete

The adhesive strength of the selected coatings varied from 0.5 to 3.5 MPa. The epoxy coatings exhibited the highest adhesion with concrete followed by chlorinated rubber and polyurethane coatings. The acrylic and polymer emulsion coatings were poor in adhesion and should be utilized only in situations where adhesion is not the basic requirement.

5.1.2 Crack bridging ability

The selected coatings failed at crack widths varying from 0.24 to 0.77 mm. The epoxy coatings were found to be the best, bridging cracks up to 0.77 mm wide. The chlorinated rubber and polyurethane coatings could bridge cracks in the range of 0.33 to 0.62 mm. The acrylic and polymer emulsion coatings were not so effective in bridging the cracks.

5.1.3 Chloride permeability

The polyurethane coatings were highly effective in reducing the electrical resistivity of concrete. The epoxy and chlorinated rubber coatings also allowed only a negligible charge to pass through. The chloride permeability of acrylic and polymer emulsion coatings also was very low according to ASTM C 1202.

5.1.4 Water absorption

The epoxy and polyurethane coatings were the best in reducing the absorption of water into concrete exhibiting low absorption rates and sorptivities. The acrylic and chlorinated rubber coatings also gained less than 2% water by weight after 56 hours but the specimen coated with polymer emulsion coatings gained more than 3% weight, due to water absorption.

5.1.5 Chemical resistance

The epoxy and polyurethane coatings were found relatively intact, with just the corners of the specimens damaged, after 60 days in 2.5% sulfuric acid solution, whereas all the other coatings had deteriorated completely by that time. The

polymer emulsion coatings dissolved in the acid and the chlorinated rubber coatings peeled off the substrate within a short period.

5.1.6 Thermal Variation

The epoxy coatings were the most effective in reducing water absorption in the coated specimens exposed to thermal cycles. The chlorinated rubber coatings performed better than the polyurethane coatings in resisting deterioration due to thermal variations. One of the acrylic coatings was successful in limiting the increase in absorption due to thermal variations, whereas the other acrylic coating failed to do so. Both the polymer emulsion coatings were ineffective in controlling the deterioration due to thermal variation.

5.1.7 Moisture Variation

All the selected coatings were effective in reducing the weight loss of the coated mortar specimens due to the moisture variation. Least weight loss was noted in the specimens coated with polymer emulsion and acrylic coatings. All the other coatings also prevented any significant loss in weight. Maximum weight loss was observed in the specimens coated with one of the chlorinated rubber coatings.

5.1.8 Chloride diffusion

The least coefficient of chloride diffusion was measured in the concrete specimens coated with the polyurethane coatings followed by the specimens coated with epoxy and acrylic coatings. Polymer emulsion and chlorinated rubber coatings were the least effective in preventing the diffusion of chloride ions in concrete.

5.1.9 Accelerated corrosion

All the selected coatings were effective in controlling the passage of current to the steel reinforcement under an impressed potential of +4V, except the polymer emulsion coatings. The polyurethane coatings were the most effective and only one polyurethane coated concrete specimen cracked after 1600 hours of exposure. One specimen each, coated with the epoxy, chlorinated rubber and acrylic coatings, did not crack up to the end of the exposure period of more than 2000 hours.

5.1.10 Carbonation

Least carbonation depth was measured in the mortar specimens coated with the polyurethane coatings, followed by those coated with epoxy and acrylic coatings. The highest depth of carbonation was noted in the mortar specimens coated with polymer emulsion coatings.

5.2 PERFORMANCE CRITERIA FOR SELECTION OF CONCRETE COATINGS

Based on the results of this study, the performance criteria for selection of concrete coatings, summarized in Table 5.1, is suggested. However, it is recommended to test the selected coatings, particularly under the expected exposure conditions, prior to their selection. This would assure that the coating could last for the period it is designed for.

Table 5.1: Performance criteria recommended for selection of coatings.

Test	Performance criteria
Adhesion with concrete	> 1.5 MPa
Crack bridging ability	> 0.5 mm
Chloride permeability	< 600 Coulombs
Moisture vapor absorption	Sorptivity < 0.3 $mm/\sqrt{hr}$
Chloride diffusion coefficient	< 8 x 10^{-8} cm^2/sec
Carbon dioxide diffusion coefficient	< 0.8 $mm/\sqrt{days}$

5.3 GUIDELINES FOR SELECTION OF CONCRETE COATINGS

Concrete coatings should be selected in accordance with the performance criteria specified in Table 5.1. Table 5.2 gives the recommended coating systems for various exposure conditions.

5.3.1 Acrylic coatings

Acrylic coatings have high chloride permeability and this is a liability in reinforced structures exposed to chloride environments. These coatings are ideal for use in residential structures in dry environments. They can also be used as overcoats for oil based or other coatings. Acrylic coatings can be used as both protective and architectural coatings in the form of primers, intermediate coats, and topcoats.

5.3.2 Polymer emulsion coatings

The adhesion of polymer emulsion coatings is not very good and peeling may occur when applied on glossy surfaces. Polymer emulsion coatings can be formulated to give very flexible films but excessive film thickness may cause cracking and peeling. These paints are not particularly resistant to chemicals and strong solvents. They have high chloride and carbon dioxide diffusion coefficients. Hence, they should be used indoors in moisture-free environments.

5.3.3 Epoxy coatings

Epoxy coatings offer excellent adhesion to concrete and yield tough, durable films with high crack bridging abilities. Epoxy coatings have been found to be

Table 5.2: Generic types of coatings recommended for various service environments.

Service conditions	Generic types of coating recommended in descending order of preference
Cracked substrate	Epoxy, Chlorinated rubber, Polyurethane
Susceptible to Chemical attack	Epoxy, Polyurethane, Acrylic
Excess of Chlorides	Polyurethane, Chlorinated rubber, Epoxy
Thermal variation	Epoxy, Chlorinated rubber, Polyurethane
Moisture variation (without chlorides)	Acrylic, Polyurethane, Polymer emulsion
Exposed to Humidity	Epoxy, Chlorinated rubber, Acrylic
Susceptible to Carbonation	Polyurethane, Epoxy, Acrylic

highly resistant to chemicals. They have very low diffusion coefficients for chloride as well as CO_2 ions. However, their performance in sunlight is questionable as chalking is known to occur when exposed to sunlight [27] and they didn't perform as well when exposed to wet-dry cycles. This tendency limits their use outdoors to primers and as intermediate coats. They can be used indoors in industrial installations, warehouses and other similar structures in almost any exposure condition.

5.3.4 Polyurethane coatings

Polyurethane coatings have been found to be very good in chemical resistance, chloride permeability resistance and carbonation resistance, although their performance under high temperatures is circumspect. These coatings are known for their gloss and color retention and they form a smooth, slick film. The surface can be easily cleaned or decontaminated. These coatings are ideal for use in aggressive environments like those existing in the chemical or petrochemical industries.

5.3.5 Chlorinated rubber coatings

Chlorinated rubber formulations are the material of choice for coating swimming pools because of their resistance to chlorides and crack bridging ability. Good gloss retention is possible with these coatings, so they can be used as topcoats. Chlorinated rubber coatings should not be used on substrates susceptible to chemical attack because of their poor chemical resistance. They also have higher

carbon dioxide diffusion coefficients, therefore their use in environments exposed to CO_2 is not recommended.

5.4 RANKING OF THE GENERIC TYPES OF COATINGS

Based on the results and their analysis, in general, the selected generic types could be ranked for their performance in aggressive environment as follows:

    i)   Epoxy coatings,

    ii)   Polyurethane coatings,

    iii)   Acrylic coatings,

    iv)   Chlorinated rubber coatings, and

    v)   Polymer emulsion coatings.

It is also recommended that whenever a coating is selected for use in aggressive environments, it should be tested under conditions similar to those it will be exposed to during its service life. Also, a variation in the coatings of the same generic type, procured from different sources, was observed, hence, it is recommended that each coating should be tested on an individual basis and the generic type should not be the sole criteria for selection of coating.

5.5 RECOMMENDATIONS FOR FURTHER STUDY

    ➢   The performance of the selected generic types of coatings in the field should be conducted to validate the results of this laboratory work.

> The crack bridging ability and adhesion of the coatings after exposure to heat-cool and wet-dry cycles should be evaluated.

> Some of the coatings tested in this study did not fail even after 2000 hours of accelerated corrosion environment. Hence, a long-term evaluation of the coatings in resisting reinforcement corrosion is necessary.

> Also, the service life prediction models based on actual corrosion measurements, viz. corrosion potentials and corrosion current density, should be established.

> The performance of the concrete coatings in sulfate environment also needs to be evaluated.

CHAPTER 6

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