防蝕工程　第九卷第四期　第205～214頁　民國84年12月
Journal of Chinese Corrosion Engineering, Vol.9, No.4, PP.205～214(1995)

增進混凝土結構免腐蝕耐久性之全球設計

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A Global Design/Management Strategy to Enhance Corrosion-Free Durable Service Life of Concrete Constructions

R.N. Swamy

摘　要

鋼筋腐蝕已被公認爲影響混凝土結構的材料穩定性及結構完整性的主要因素。在嚴苛的侵蝕性環境下，因鋼筋腐蝕所引起的材料劣化與結構損害，會降低結構壽命，影響其強度、穩定度與安全性，而且導致提前毀壞。本論文旨在提供一整合性之方法，即全球設計／管理策略，來設計經久耐用之新結構，並增進現在正劣化中的結構物之壽命。對於新建或因環境侵害正劣化中的混凝土結構，本文均明列各項設計參數及應採用之策略，以確保其免於腐蝕。相關測試數據亦一併提出佐證。

關鍵詞彙：腐蝕控制，混凝土結構，設計策略，高性能混凝土，表面塗裝，環氧樹脂塗覆之鋼筋，鍍鋅鋼筋，整合管理策略

ABSTRACT

Corrosion of steel reinforcement is now universally recognised as the major factor affecting the material stability and structural integrity of concrete structures. In very aggressive environments, the material degradation and structural distress arising from steel corrosion can dramatically reduce the useful service life of structures, affect their strength, stability and safety, and indeed, even lead to premature failure. The aim of this paper is to offer an integrated, holistic approach – a global design/management strategy – which will enable us to design new structures with a specified durable service life, and which will also enable us to enhance the durable service life of existing deteriorating structures. The paper identifies the design parameters that need to be satisfied and the strategy that needs to be adopted to ensure long term corrosion – free service life of concrete structures, whether they are to be newly built or are existing but deteriorating due to environmental attack or otherwise damaged. The paper is accompanied by relevant and appropriate test data.

Key words: Corrosion Control, Concrete Structures, Design Strategy, High Performance Concrete, Surface Coatings, Epoxy Coated Rebars, Galvanized Reinforcement, Integrated Management Strategy.

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INTRODUCTION

Concrete is, in many respects, a wonder material of this century. Of all construction materials, it has the best ecological profile for a given engineering property such as strength or elastic modulus. It is probably the most widely and extensively used building material in the world, due to its low relative cost, easy availability of constituents, versatility and adaptability. It is easily prepared and fabricated into many conceivable shapes and structural systems in the realms of infrastructure, transport and habitation that the material is often identified with a nation's stability and economic progress, and the quality of human life. The most outstanding asset of the material is its inherent alkalinity, providing a passivating mechanism, and a safe, non-corroding environment for the steel reinforcement embedded in it. Long experience and a good understanding of the material have confirmed that concrete is a reliable and durable construction material, when it is exposed to normal or even moderately aggressive environments. It thus seems reasonable to assume that in a rapidly changing world, the concrete industry and technology can offer one of the best ways forward to satisfy the social and human needs resulting from the massive movement of peoples from rural areas to urban cities that the latter part of this century has seen, and that will continue well into the twenty first century.

In spite of these intrinsic technical and economic advantages of the material, and in spite of the tremendous scientific advances that have been made in our understanding of its microstructure and engineering, deterioration of concrete has become a major global problem, and there is widespread concern about its lack of durability. In recent times, in many parts of the world, reinforcement corrosion has become the main cause of early and premature deterioration, and sometimes failure, of reinforced concrete structures. One of the major factors contributing to this deterioration process is the environment and climatic conditions to which a concrete structure is exposed. Hot/dry and hot/wet salt-laden environments probably provide the most aggressive forces that undermine the stability and durability of concrete structures. When the severity of environment is compounded with poor quality concrete and/or defective design and construction practices, the process of deterioration becomes interactive, cumulative and very rapid, and a cancerous growth that cannot be easily stopped.

This present dichotomy poses two major challenges to the material scientist and design engineer

— First, how do we preserve and maintain the durable service life of the current stock of structures? i.e., how do we protect, rehabilitate and strengthen deteriorating or other wise structurally inadequate constructions?

— Second, how do we design and construct structures that have a long and durable service life and which will require a minimum of repair and retrofitting?

It is clear that the only way to achieve these challenging goals is to develop and adopt a **"Global Holistic/Design Strategy"** that will integrate material properties with those factors that produce durable insitu structural performance and preserve structural integrity. Such a **"Design Strategy"** will involve three distinct but inter-related and interactive approaches, namely,

— **"A Material Strategy"** to develop a high performance concrete, i.e. **"High Strength through Durability"** rather than High Durability through Strength.

— **"A Management Strategy"** to develop an efficient "Protective System" to protect concrete from aggressive environmental attack.

— **"A Design Strategy"** to integrate material properties with structural performance that will ensure **"Material Stability and Structural Integrity"**.

This paper attempts to show how some of these concepts can be achieved in practice.

THE INGREDIENTS FOR HIGH PERFORMANCE CONCRETE

One of the intriguing characteristics of concrete is its double-faced nature. Whilst being intrinsically protective to steel, it is also the same material that controls and permits the ingress of water, air, oxygen, chlorides, sulphates and other deleterious agents that lead to the progressive destabilisation of steel. Hence the core property that will control the overall long-term stability of reinforced concrete has to be its **"impermeability"** and, therefore, its **"pore structure"** [1]. However, one of the great advantages of concrete is that it is possible to choose its constituents, and then it is up to us to exploit and optimize the unique properties of each of these components. This freedom to choose the constituents leads to what I consider to be one of the great qualities of concrete. Concrete materials provide the best "home" for the disposal of millions of tons of industrial siliceous by-products such as fly ash, blastfurnace slag, silica fume and rice husk ash. This interaction between concrete and siliceous by-products brings out two outstanding benefits – engineering and economic. From an engineering point of view, the incorporation of these by-products enhances the properties of the concrete not only in its fresh state but also in its hardened state. In the fresh state, a judicious use of these materials can enhance flowability and pumping qualities, and reduce segregation, bleeding and the tendency for plastic shrinkage. In the hardened state, these mineral admixtures can significantly refine the pore structure and thus reduce permeability whilst at the same time improve the resistance of the material to thermal cracking through reduction of the heat of hydration. From an economic point of view, utilisation of siliceous mineral admixtures can directly contribute to conservation of material resources, energy savings and protection of the environment. Concrete can thus provide the ideal building material combining efficiency, environment friendliness with a cost-effective solution to maintain the quality of life [2,3].

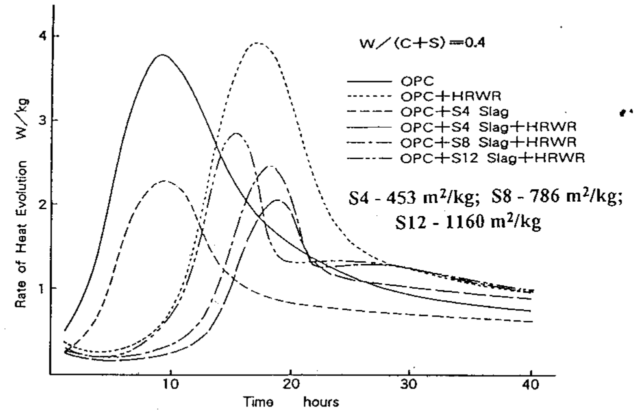


圖 1　熔渣對水化熱之效果

Fig. 1 Effectiveness of slag on heat of hydration

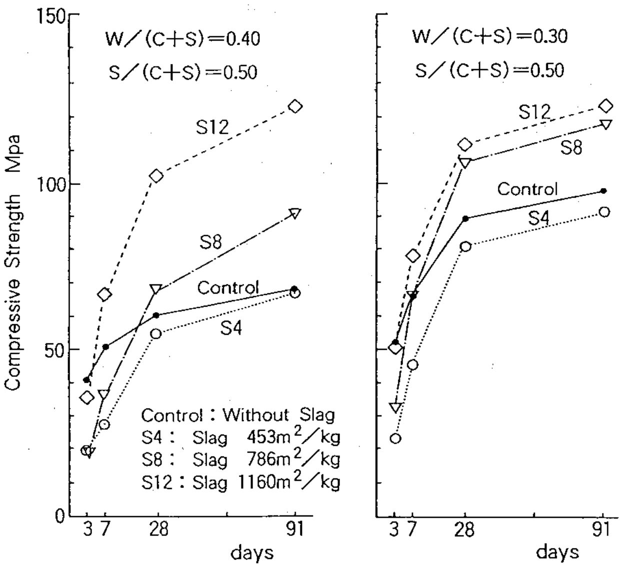


圖 2　熔渣混凝土強度變化

Fig. 2 Strength development of slag concrete

Strength through Durability

However, mere incorporation of siliceous admixtures will not per se, lead to high performance concrete. The ability of these materials to contribute to strength, stiffness and durability is chemically-bound within the concrete system and it is only through **"Design"** that we can mobilise and extract this unique property of pozzolanic materials. This magic of **"Synergic Interaction"** is illustrated in Figs 1 to 3 and Tables 1 and 2 for a concrete combining portland cement (specific surface 323 m^2/kg) and ground granulated blastfurnace slag (GGBFS) of three different fineness, namely, 453 (S4), 786 (S8) and 1160 (S12) m^2/kg. These concrete mixtures had a cement-slag combination of 1:1, and the water content in all the mixtures was kept constant at 160 kg/m^3. The mixtures were designed to give slumps of 150 to 200 mm, with 1% to 2% air content. To enhance workabil-

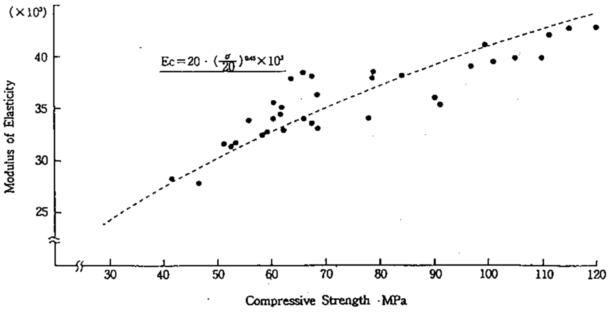


圖 3 彈性模數－強度變化
Fig. 3 Variation of elastic modulus with strength

ity and control of slump loss, a high range water-reducing admixture (HRWR), a polyether carboxylic acid, was used in all the mixtures [4].

Fig 1 shows the rate of heat evolution in portland cement and cement-slag mixes of 1:1 ratio at a water-binder ratio of 0.40. The presence of slag of different fineness can be seen to be beneficial in not only reducing the peak heat evolution but also in extending the time at which the peak heat evolution occurs. Heat of hydration is a major factor influencing the long term durability of concrete. Early age thermal cracking, arising from undesirable thermal gradients, does not heal quickly and takes a long time to disappear. Whilst the presence of slag cannot be an absolute guarantee against thermal cracking, it can go a long way to enhance the resistance of concrete to thermal cracking.

Porosity and Water tightness

In any exposure condition, the pore structure and porosity are the key factors that determine the ability of any concrete to resist the intrusion of aggressive elements that damage it. In extreme and severely aggressive climatic conditions, chlorides can penetrate concrete even during very briefest of exposure periods. These problems are then further compounded if the ground water is also heavily contaminated with chlorides and sulphates, as it is only a matter of time that damaging elements will intrude into concrete

表 1 溶渣孔隙度變化
Table 1 Development of porosity with slag.

Mix	Slag specific surface m^2/kg	Cylinder comp. st.* MPa		Total pore volume, mm^3/g			
		7d	28d	3d	7d	28d	91d
1	None	48.9	59.5	64.9	57.4	46.7	33.5
2	453	27.7	58.7	60.4	55.9	30.7	13.0
3	186	36.4	67.8	68.5	47.6	22.8	12.0
4	1160	64.8	101.8	41.5	31.6	16.8	11.9

* Water/binder : 0.40; Water curing
Cement replacement 50%

表 2 熔渣對水密性之效應
Table 1 Effect of slag on water tightness

Mix	Slag specific surface m2/kg	Cylinder strength *, MPa		Water permeability	
		7d	28d	Depthof penetration mm	Diffusion coefft x 10-2mm2/s
1	None	48.9	59.5	12.3	2.27
2	453	27.7	58.7	8.1	0.99
3	786	36.4	67.8	7.1	0.76
4	1160	64.8	101.8	2.9	0.13

* Water/binder : 0.40; Water curing
Cement replacement 50%

below ground, and by capillary action, penetrate into concrete above the ground water table. The development of a tightly knit pore structure is thus an essential requirement for long term durable service.

The role of slag in developing a very fine pore structure and high water tightness is shown in Tables 1 and 2 respectively. These data show the dramatic improvements that slag can impart to control the total pore volume and water permeability of the concrete. Even at the risk of a lower early strength, or where such low strength is not critical, the incorporation of even the coarsest slag of 453 m^2/kg fineness can substantially reduce chloride diffusivity and water penetration, whilst strength and elastic modulus development are restored with age as shown in Figs 2 and 3. Hot environments accelerate the setting time, and have, therefore, an important effect on strengths up to about 7 days. However, long term strength is not altered.

The data in Tables 1 and 2 and Figs 1 to 3 demonstrate how high early strength and high long term strength can be achieved through **"design for durability"**. High strength does not automatically guarantee high durability, whereas a focus on high durability can be designed to produce high strength. This is where the choice of the type and amount of a pozzolanic siliceous admixture becomes important. Very fine pozzolans tend to be naturally highly reactive and they give the advantages of reduced curing time needed to obtain a desired level of strength and water tightness. Less fine or reactive pozzolans help to improve the resistance to thermal cracking whilst maintaining strength development. The data in the Tables and Figures show a way forward in this strategy to develop a high performance concrete.

STRATEGY FOR PROTECTION OF CONCRETE

Need We Protect Concrete?

Concrete is basically a heterogeneous, discontinuous composite material with an intrinsically porous matrix. The paradox of concrete is that whilst being protective to steel through its alkalinity, the nature of the material and construction technology are such that it will permit the ingress of deleterious elements which will slowly but surely destroy the electrochemical stability of steel. Concrete thus needs to be protected, particularly from an aggressive environment, for two reasons. The hydration process, and hence the development of strength and a highly impermeable pore structure, is itself a time-dependent operation, and further, it requires a favourable wet environment for the chemical interactions to continue. A high performance concrete therefore needs to be protected from adverse environmental conditions, particularly at early ages, when the material is highly vulnerable to drying as well as diffusion processes arising from external environment.

Similarly, the degradation process of concrete, apart from being also time-dependent, is not the result of one factor, one process or one set of aggressive agents. With a complex composite system such as concrete, an aggressive environment becomes a major factor in initiating a progressively cumulative damage activity – indeed, the development of deterioration becomes an overall synergistic process, a complex combination of many individual mechanisms, the exact role, effect and contribution of each of which to the totality of damage is not clearly understood.

Concrete Surface Coatings

It is thus clear that if we want to produce high quality concrete in new constructions, as well as stop the deterioration process of existing structures exposed to aggressive environments, the most effective solution is to use surface or barrier coatings which will ensure continued hydration whilst at the same time cutting off the transportation path into concrete of water, air, chlorides and sulphates. Unfortunately, surface coatings have a chequered reputation in this respect, mainly because we have disregarded the engineering requirements of these chemicals. It is, however, possible to develop good surface coatings that can combine basic engineering properties with the required chemical, diffusion and weathering characteristics [5].

The acrylic rubber coating referred to here consists of a primer, base and top coat with an overall thickness of about 1000 μm. The ability of this coating to prevent chloride penetration was tested on 200×200×300 mm prisms reinforced with 12-16mm diameter bars and 2-9 diameter stirrups made with concrete of water-cement ratio of 0.58. Some of the prisms were also made with added NaCl during mixing at a level of 0.2% to 1.0% by weight of mortar. Prisms without the coating and with the acrylic rubber coating were then partially immersed in sea water. The results of the chloride penetration after 5 years of exposure are shown in Fig 4. These data show that this particular acrylic rubber coating has not only prevented the ingress of chlorides from outside, but has also facilitated the mobility of the already trapped chloride ions inside the body of the concrete into a more uniform distribution, preventing their concentration in the vicinity of the rebars. The extent of corrosion suffered by the rebars after 8 years' exposure is shown in Fig 5. The implication of the data shown in Figs 4 and 5 is that even in concrete deteriorating due to chloride contamination and further exposed to a salt environment, the coating is not only able to significantly and effectively reduce the damaging effects of the salt and surrounding environment, but also maintain its efficacy and integrity.

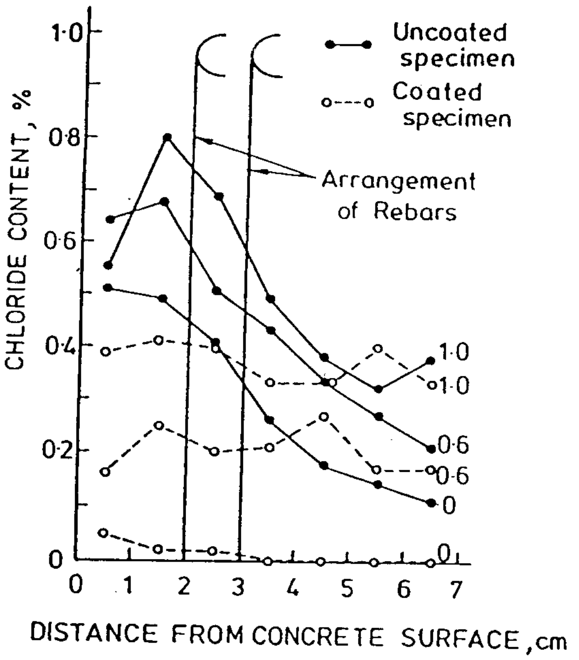


圖 4 塗裝與未塗裝混凝土氯之滲透量

Fig. 4 Chloride penetration into uncoated and coated concrete

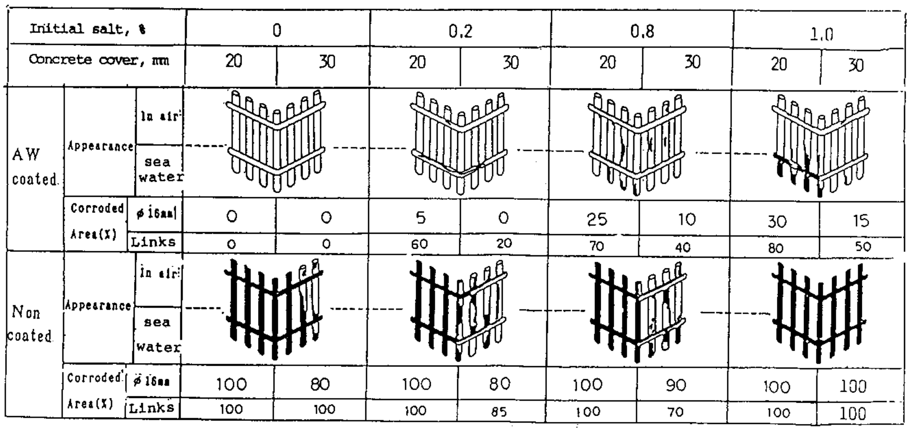
These data on small scale specimens are fully supported and confirmed by results monitored over several years from a beam, slab and column construction, built in 1984, in a marine environment and exposed to sub-tropical weather conditions of high temperature and humidity, and subjected to salt-laden breeze, sea water splash and splash during high winds. Typical information presented in Fig 6 in uncoated and coated reinforced concrete beams made with 0.5% salt added during mixing is ample proof of the total ability of the coating in controlling chloride penetration into concrete.

Coatings must also prevent the penetration of carbonation, and some results obtained from cores drilled from actual structures which had been coated with the acrylic rubber as part of a rehabilitation process, are shown in Table 3. These structures are located at distances of 0.1 to 10 km from the sea, and one structure had concrete made with a mixture of sea sand and river sand as fine aggregate. The results in Table 3 show that the coating has not only prevented the progress of further carbonation, but has also facilitated further hydration enabling a reduction in carbonation depth. This "realkalisation" of carbonated concrete is a unique property of the acrylic rubber coating described here.

DESIGN STRATEGY FOR STRUCTURAL INTEGRITY

Protection of Steel

It is always debatable whether one can rely on the quality of concrete alone to protect from corrosion the steel embedded in it, or, if the steel would need additional protection of some kind or other. Because of the nature of concrete construction and because, in severe environments, a wide range of aggressive agents can penetrate concrete and initiate a damage process in a very short time of exposure, a sensible solution for long term durability, where the risk of chloride-induced corrosion exists, is to adopt a global design strategy in which the concrete is designed and protected to develop its high strength and quality through

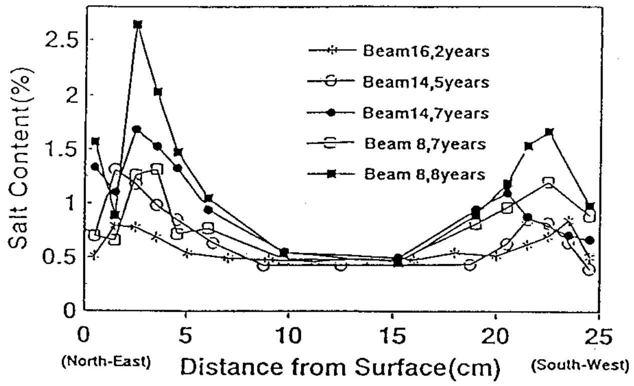


Initial salt, %			0		0.2		0.8		1.0	
Concrete cover, mm			20	30	20	30	20	30	20	30
AW coated	Appearance	in air sea water								
	Corroded Area(%)	φ16mm	0	0	5	0	25	10	30	15
		Links	0	0	60	20	70	40	80	50
Non coated	Appearance	in air sea water								
	Corroded Area(%)	φ16mm	100	80	100	80	100	90	100	100
		Links	100	100	100	85	100	70	100	100

圖 5　經過八年暴露後表面塗裝對腐蝕控制之影響

Fig. 5 Effect of surface coating on corrosion control after 8 year's exposure

UNCOATED BEAMS



COATED BEAMS

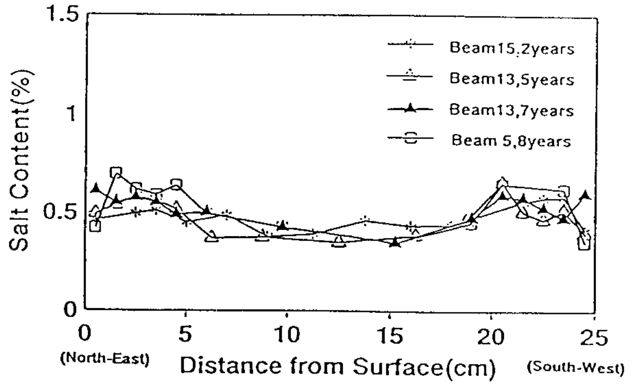


圖 6　樑柱中氯之分布（0.5%鹽）

Fig. 6 Chloride distribution in beams with 0.5% salt

a refined and dense pore structure, whilst the steel is additionally protected to counteract the lack of quality control and poor workmanship [6].

The three major factors that control the electrochemical stability of steel and influence significantly the service behaviour, design life and safety of concrete structures are cracking, the depth and quality of cover to steel, and the overall quality of the structural concrete. Their influence is interactive and interrelated and, therefore, a global design strategy is needed to ensure total protection against chloride-induced corrosion. The tensile strain capacity of concrete is only of the order of 100 to 150 microstrains, and whatever be the quality of materials and fabrication, the nature of concrete construction is such that microcracks and micropores will always exist on the surface and within the body of the cover concrete, which will not only trap the aggressive elements but also provide a path for the transport of these aggressive ions into the interior of concrete. Further, at water-binder ratios of 0.5 and above, continuous capillary channels can never be blocked. Similarly at cover depths of 10 to 20 mm, even the best corrosion protection will begin to deteriorate with time. These factors dictate that an integrated design approach alone can ensure material stability and structural integrity of concrete constructions.

Coatings for Steel

Surface coatings on steel are decidedly the most effective method of ensuring corrosion-free life of steel reinforcement in concrete. Metallurgical coatings have some unique advantages, whilst epoxy coatings, like concrete surface coatings, must satisfy a number

表3 塗裝對碳化之控制

Table 3 Control of carbonation by coating

Structure	History			Carbonation depth, mm		
	Construction	Repair	Investigation	Before Repair	After Repair	
				Uncoated	Uncoated	AR Coated
Building A	1968	1979	1987	12.5	16.4	7.1
Building B	1973	1981	1987	9.8	13.0	8.0
Building C	1961	1983	1987	27.6	30.0	0.0
Building D	1958	1981	1987	22.3	25.0	1.0

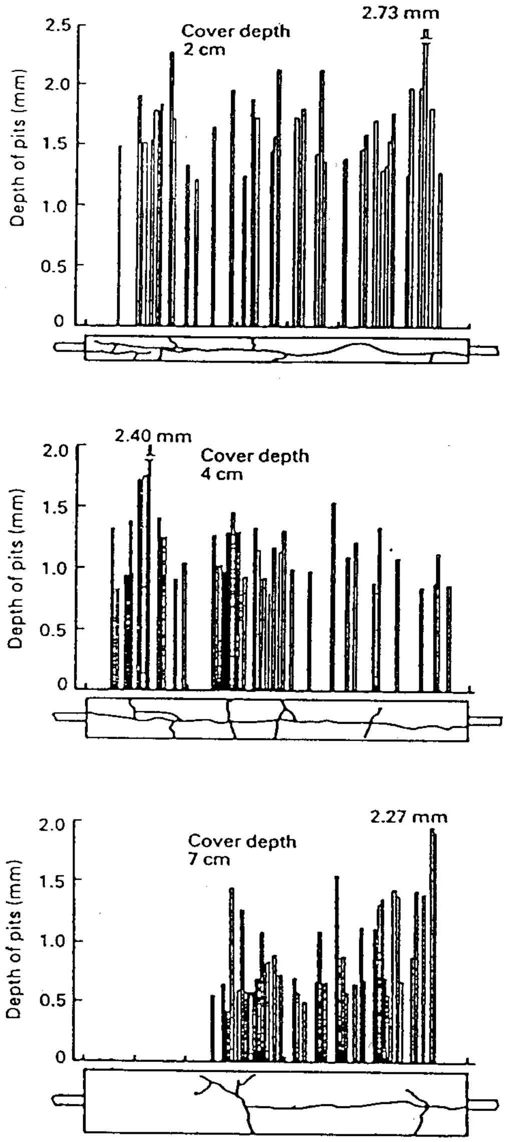


圖7 未塗裝鋼棒

Fig. 7 Uncoated bars

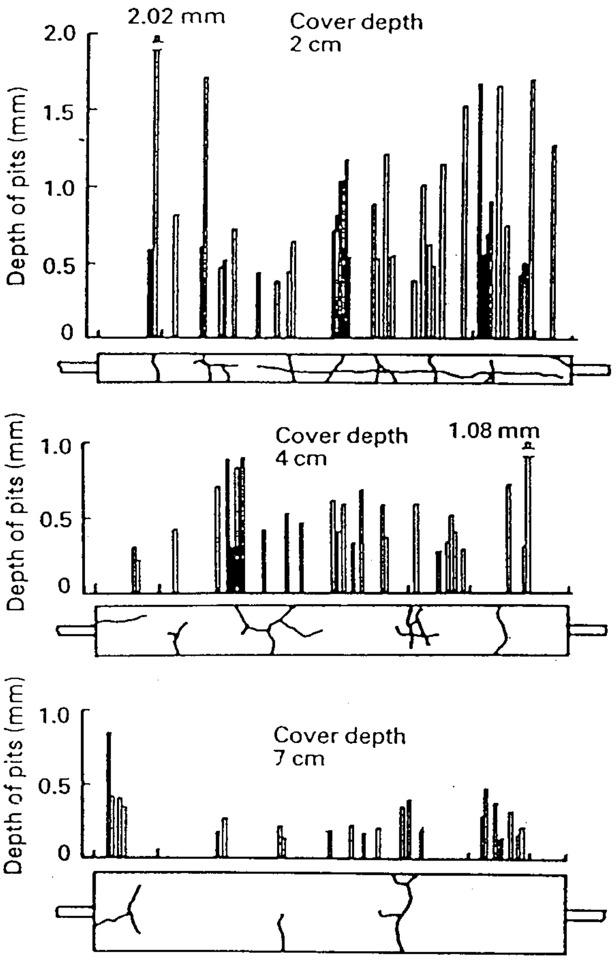


圖8 鍍鋅鋼棒

Fig. 8 Galvanised bars

of stringent specifications if they are to be fully corrosion resistant and effective in practice [9]. A strong, tough and durable coating, with consistent and uniform thickness of 250 ± 50 μm, and able to withstand, without damage, all forces during handling, transportation and fixing can give excellent and long service life. To illustrate the effectiveness of steel surface coatings, some test data are given below.

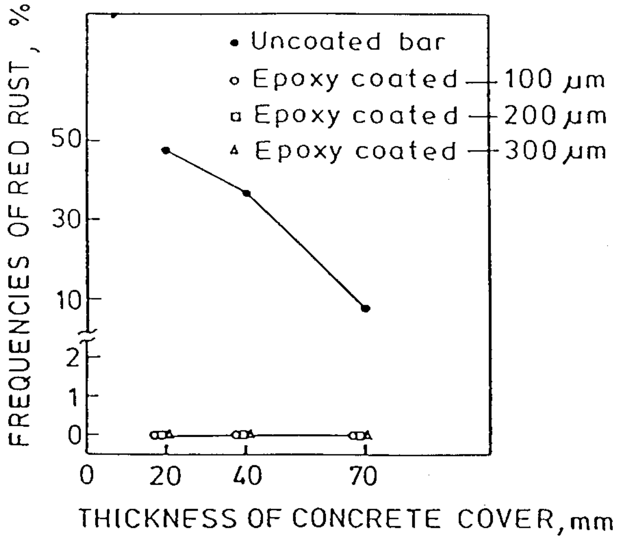


圖 9 加速測試

Fig. 9 Accelerated tests

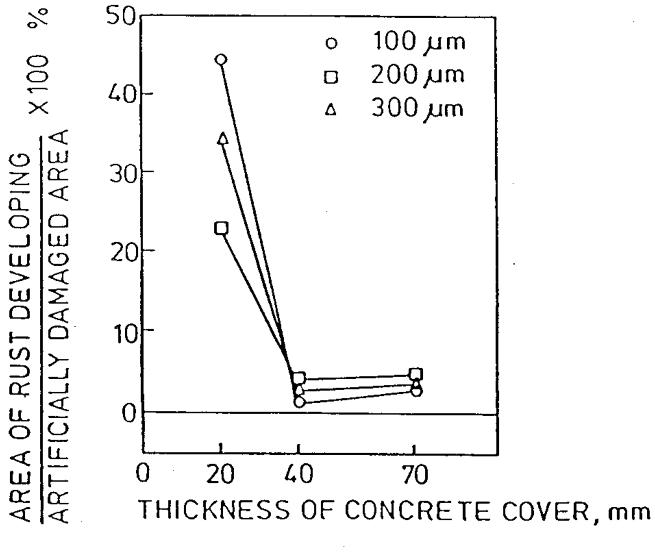


圖 10 潮域測試

Fig. 10 Tidal zone tests

Test Results

The specimens used in these tests were square concrete prisms with a centrally located 19 mm bar having an embedment length of 760 mm. Three reinforcement cover thicknesses were used. To simulate reinforced concrete members, the test specimens were pre-cracked and kept under a stress of about 200 MPa during the tests. Two exposure regimes, namely, an accelerated wet and dry cycle and a highly corrosive tidal zone, were used. The galvanized rebars were chromated, and the results are shown in Figs 7 and 8. These data provide unequivocal evidence that galvanized rebars in concrete can give a very much extended durable service life for concrete structures, bearing in mind that these tests were carried out in ordinary quality concrete.

The results of tests on concrete with epoxy coated bars are shown in Figs 9 and 10, for undamaged and damaged coatings respectively. Again these results are extremely positive and highlight how good quality surface coatings on steel can enhance the durable service life of reinforced concrete structures.

CONCLUSIONS

The aim of this paper is to show that an integrated, global design philosophy that embraces all aspects from conception to completion, and subsequent life of a concrete element or structure is the surest route to ensure its cost-effective, durable service life. Such a strategy should form an integral part of the **"DESIGN"** process just as selection of materials, concrete fabrication, structural calculations, construction, and maintenance. It is shown that it is possible to develop a concrete matrix of excellent durability and high strength by taking advantage of the synergic interactions of the cementitious system, and the portland cement-slag system is shown to offer a good example of this nature. However, development of strength and a highly refined pore structure are time-dependent phenomena, and in most environments, it may well be necessary to protect the concrete from its surroundings, to enable it to attain its full potential for strength and durability. In extreme environments, further protection to steel in the form of metallic or epoxy coatings may also be necessary to ensure the electrochemical stability of steel at all times. A combination of a high-performance cement matrix, an external protective system for the concrete and a surface coating for steel can ensure durable service life even in the most aggressive and unfriendly environmental and climatic conditions.

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