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Global Strategy to Enhance Service Life of Deteriorating Structures

Stratégie globale pour l'amélioration de la durée de service d'ouvrages détériorés

Umfassende Strategie für die Verbesserung der Lebensdauer von zerstörten Bauwerken

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SUMMARY

This paper presents a strategy to protect and strengthen deteriorating concrete structures and enhance their service life. A dual approach involving an acrylic rubber protective coating to prevent intrusion of aggressive agents such as chlorides and carbonation, and strengthening by bonding plates as external reinforcement can jointly rehabilitate such structures. These operations, however, need an integrated design strategy that interrelates material properties and structural performance and combines engineering science, technology and systems approaches.

RÉSUMÉ

L'article présente une stratégie pour protéger et renforcer des structures en béton abîmées, afin de prolonger leur vie. Il propose une combinaison de deux méthodes, c'est-à-dire, un revêtement en caoutchouc acrylique pour prévenir l'entrée d'agents corrosifs, par exemple, le sel et l'acide carbonique, et un renforcement extérieur comprenant des plaques collées. Ces opérations requièrent une stratégie de projet, intégrant les propriétés des matériaux ainsi que la performance désirée des structures.

ZUSAMMENFASSUNG

Dieser Aufsatz beschreibt eine Strategie zum verbesserten Schutz und zur Verstärkung von geschwächten Betonkonstruktionen, die zu einer verlängerten Lebensdauer führen kann. Eine Kombination zweier Methoden, das heisst, einesteils die Beschichtung der Oberflächen mit einem Acrylgummi zur Verhinderung des Eindringens aggressiver Stoffe (Salze und Kohlensäure) und andernteils die Verstärkung durch äusserlich aufgeklebte Platten, kann es erlauben, solche Bauwerke zu rehabilitieren. Diese Ansätze verlangen allerdings nach einer integrierten Konstruktionsstrategie, die Werkstoffeigenschaften und bautechnische Grundlagen zusammen berücksichtigt.

1. INTRODUCTION

In many respects the concrete construction industry is now at cross-roads. It faces a major two-pronged challenge – the need to preserve and extend the durable service life of existing deteriorating or otherwise structurally inadequate structures, and the capability to build new ones that are more durable and will require much less repair and retrofitting with the passage of time.

The paradox of concrete is that whilst being inherently durable and protective to steel through its alkalinity, the nature of the material and construction technology are such that sooner or later it will permit the ingress of deleterious elements which could destroy the electrochemical stability of steel and the integrity of the concrete. Concrete will set, harden and carry loads to a great degree even if it is not made with the correct constituents and proportions or not placed and cured properly. Its excellent performance in normal environments has led to the assumption that the material virtually needs no maintenance, that it will not deteriorate, and that the impermeability of concrete and protection of the embedded steel are somehow automatically and adequately catered for by the cover thickness and the presumed quality of concrete. Experience has shown that neither can be achieved as a normal and natural consequence of the process of concrete fabrication, and that deicing salts, marine exposure and aggressive salt-laden environments in severe climatic conditions can all lead to premature deterioration and loss of serviceability, strength and safety.

Extending the life span of deteriorating concrete structures would then involve two processes. One relates to stopping the deterioration process which may involve one or more mechanisms such as chloride/sulphate intrusion, moisture penetration, carbonation and/or alkali-aggregate reactivity. The second involves structural rehabilitation to correct deficiencies and to enhance structural stiffness, serviceability life, safety and total load capacity. These two processes are interactive and inter-related, and often there is no simple solution, no single approach, no easy magic formula that will ensure long-term trouble-free service life when concrete is exposed to elements that are known to damage it.

This paper advocates an integrated, global ***Design Strategy*** which would involve a thorough understanding of material behaviour and structural performance and which would unify engineering science, technology and systems approach in tackling engineering problems [1].

2. PROTECTION OF CONCRETE

2.1 Need for Protection

Concrete exposed to an unfriendly environment will suffer a slow, steady but continual and progressive process of deterioration. Long experience of material and structural degradation has taught us that such deterioration is an overall, synergistic and time-dependent 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. The mechanism of the development of strength and a tight, refined pore structure in concrete is also a time-dependent process so that there is always the possibility and opportunity for aggressive agents to permeate concrete, particularly at the very early ages of its life. Further, concrete is a material of low tensile strain capacity, of the order of 150–200 microstrains, such that microcracking will always occur in some form or other, providing another means for deleterious agents to penetrate concrete.

2.2 Acrylic Rubber (AR) Surface Coating

The most effective solution to enable concrete to develop its strength and, more importantly, a closed pore structure, and at the same time cut off the transportation path of chlorides, sulphates and other deleterious ions is to use a concrete surface coating which will act as a curing/durability agent. An "***Acrylic Rubber Coating***" developed by the authors provides such a protective system [2]. To be effective such a coating should not only have adequate diffusion characteristics, but also possess excellent engineering properties in terms of tensile strain capacity, elasticity, thermal stability and bonding strength, as well as weathering resistance. The only test and evidence of the long-term capability of a surface coating to maintain its stability and integrity is its performance characteristics in an aggressive environment [3].

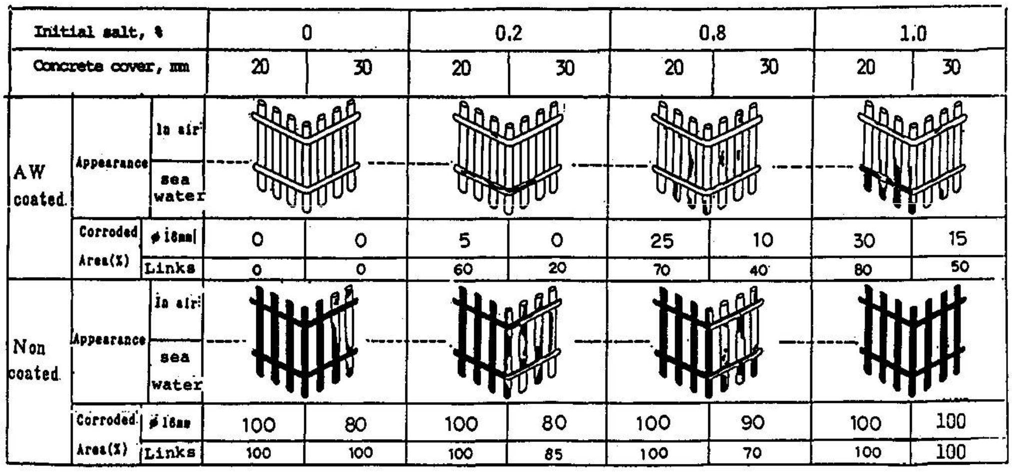
Fig. 1 shows the extent of corrosion suffered by steel bars embedded in 200x200x300 mm uncoated and coated prisms of concrete without and with NaCl contamination and partially immersed in sea water. The results show the ability of AR coating in preventing the penetration of chlorides from the surrounding sea water and also effectively and significantly reducing the damaging effects of the trapped slat within the concrete. This AR coating can also act as a water-proofing material, as confirmed in Fig. 2, which shows the loss in flexural strength of concrete prisms containing alkali-reactive aggregates and subjected to outside exposure. Although the coating did not prevent the expansive alkali silica reactivity fully (for reasons not discussed here), the strength loss was much less than that in specimens coated with an epoxy resin, or in uncoated specimens.

The total ability of the AR coating in controlling chloride penetration into concrete is illustrated in Fig. 3 which shows chloride distribution in uncoated and coated reinforced concrete beams made with 0.5% salt added during mixing and built in an aggressive marine environment with sub-tropical weather conditions of high temperature, humidity and wind, and exposed to salt-laden breeze and sea water splash. The performance data over 8 years is ample proof of the role and effectiveness of the coating and its ability to maintain its continuity and integrity.

Penetration of carbonation is a time-dependent process, and the effectiveness of the AR coating in controlling its penetration is illustrated in Table 1 which shows the depth of carbonation obtained from core tests drilled from four structures, located at distances of 0.1 to 10 km from the sea, and which had been coated as part of a rehabilitation process. The data in the table show that the coating has not only prevented the progress of further carbonation, but also enabled a "***realkalisation process***" of the carbonated concrete. This is a unique property of the AR coating.

3. STRUCTURAL REHABILITATION

Structural inadequacy may arise for a number of reasons such as material degradation, deficiencies in design or construction, or merely the need to upgrade load capacity necessitated, for example, by heavier axle loads in bridges. Of all the techniques available for structural strengthening, the plate bonding technique – which consists of providing external reinforcement in the form of adhesive–bonded steel plates – provides a structurally efficient, technically sound and economically efficient method of enhancing both the serviceability load and ultimate load carrying capacity of the member. The practical advantages of the technique are the comparative ease and economy with which the operations can be carried out, and the strengthening operations can be carried out when the structure is still in use and loaded. The engineering merits of the method are that there are no major redistribution of existing stresses, and the changes in overall structural sizes are very small.



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(%)	ø 16mm	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(%)	ø 16mm	100	80	100	80	100	90	100	100
		Links	100	100	100	85	100	70	100	100

Fig. 1 **Effect of AR coating on steel corrosion after 8 years' exposure**

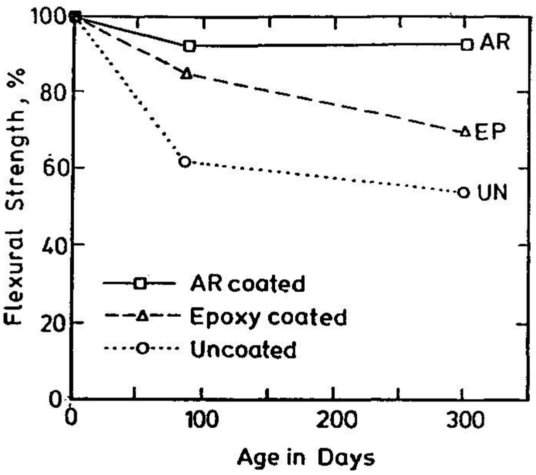


Fig. 2 **Loss of flexural strength due to ASR expansion**

Structure	History			Carbonation depth, mm		
	Con-struction	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

Table 1 **Effect of AR coating on carbonation**

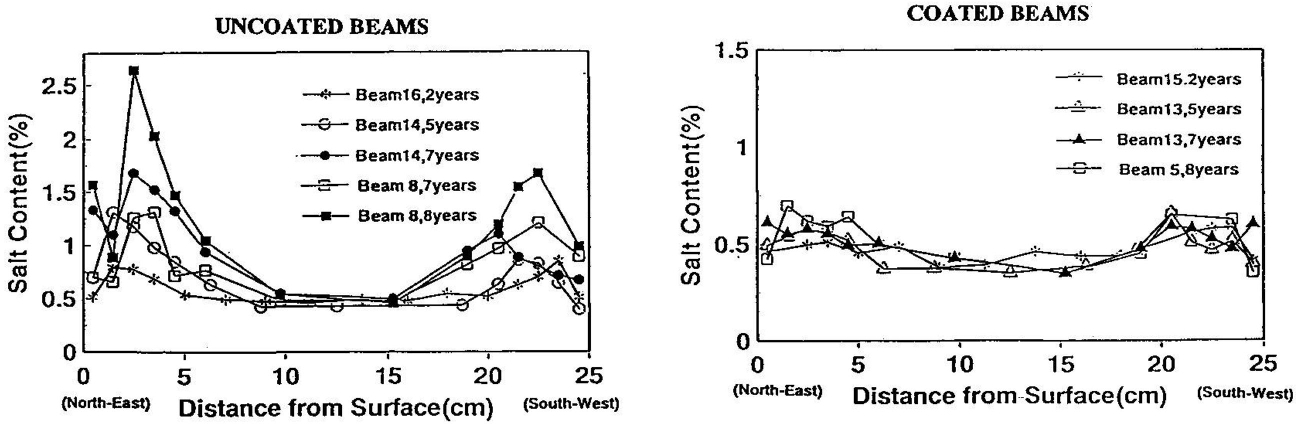


Fig. 3 **Chloride distribution in beams with 0.5% salt**

With the correct choice of adhesives and plate geometry, and taking care of the anchorage stresses at the ends of the plates, design guidelines are now available to ensure that the concrete–adhesive–plate composite system can develop full composite action at all stages of loading and fail in a ductile manner, after attaining full flexural strength [4,5].

3.1 Structural Benefits

The provision of a steel plate at the tension face of a beam significantly reduces both deflections and crack widths, more than what would be achieved by additional internal reinforcement equivalent to that of the external plate, (Figs 4 and 5). The stiffening and crack controlling action of the plates can lead to substantial increases in serviceability loads for various serviceability conditions as shown in Table 2. Plating structurally damaged beams can also lead to substantial reductions in deformations and increases in serviceability loads, as shown in Table 3.

Several practical applications have shown that the technique of plate bonding can provide a cost–effective method of enhancing the life span of structurally inadequate members. The technology can be extended to the use of non–metallic plates, and long–term exposure tests show that the technique is highly tolerant to even fairly large areas of deterioration of the plate–adhesive system without damage to structural performance.

4. CONCLUSIONS

The philosophy put forward in this paper is that engineering operations need an integrated global "***Design Strategy***" that interrelates material properties to structural performance and is based on the concept of "***Structural Integrity***" which combines engineering science, technology and systems approach. Material characteristics have an unpredictable influence on structural behaviour, but microstructural properties cannot directly be extrapolated to engineering performance. An integrated design approach – a "***holistic***" approach – can help us to design structures that show long-term and durable service life.

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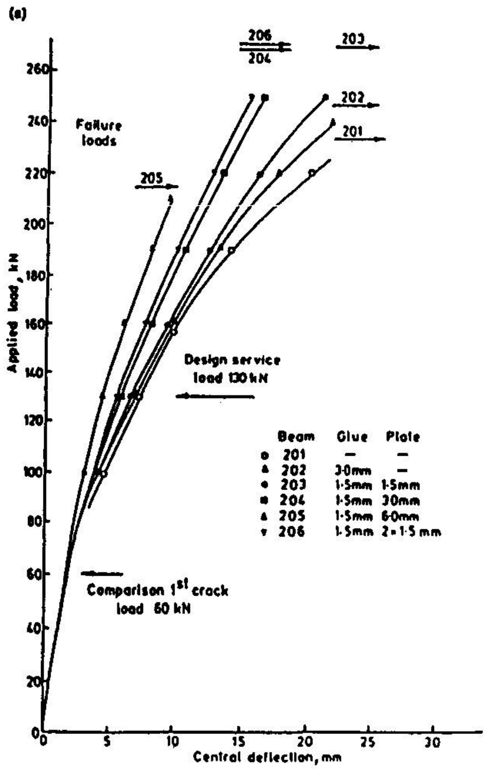

Fig. 4 **Effect of bonded plates on mid-span deflection**

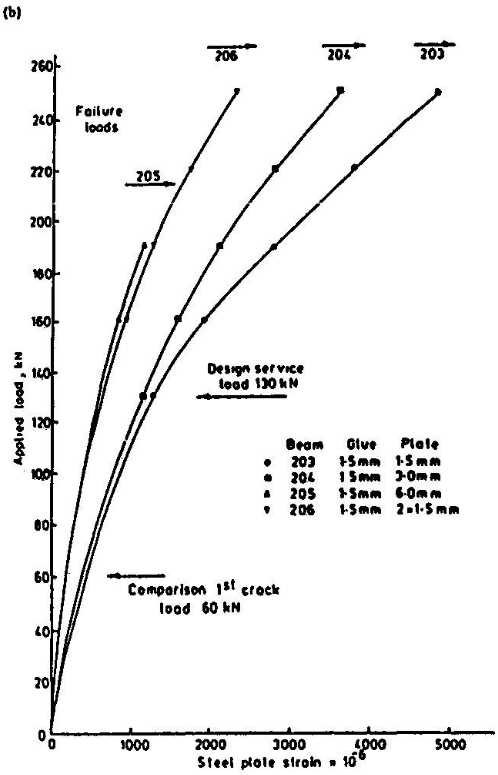

Fig. 5 **Effect of bonded plates on steel plate strain**

	Plate Thickness		
	1.5 mm	3.0 mm	6.0 mm
Adhesive thickness	1.5-6.0 mm	1.5-6.0 mm	1.5-6.0 mm
Deflection	4-11%	10-26%	30-36%
Rotation	6-17%	23-37%	38-56%
Max. crack width	37-53%	38-60%	70-99%
Steel bar strain	16-43%	50-72%	70-110%

Table 2 **Increase in serviceability loads of plated beams**

	Plate thickness	
	1.5 mm	3.0 mm
Adhesive thickness	3.0 mm	3.0 mm
Deflection	0%	20%
Rotation	8-20%	33%
Max. crack width	23%	60%
Steel bar strain	40-43%	72%

Table 3 **Increase in serviceability loads of cracked and plated beams**