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A design consideration for durability of high-performance concrete

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Abstract

Environmental factors, especially the climate, have significant influence on concrete structure. This paper aims to investigate the harmful effects of maritime climate on the durability of concrete structures built in coastal areas. Singly reinforced beam specimens of traditional design and those of densified mixture design algorithm (DMDA) were employed to study the potential problems of concrete structure. Results indicate that cracks on the concrete structure, if go unnoticed, may cause failures. Thus, it is important to know the methodology of achieving high strength and durable concrete in order to avoid formation of cracks in the structural member. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: High-performance concrete; High strength; Durability; Densified mixture design algorithm

1. Introduction

The castatrophic earthquake that took place in Taiwan on 21 September 1999 caused serious causality and attracted much attention to the quality of construction in terms of its strength, ductility and durability. Poor quality has often been a shortcoming of traditional concrete. It poses danger to the safety of the users' life and property. Comparatively speaking, greater emphasis is usually paid to the strength and workability of the concrete mixture while durability has never been given much attention in the mix design. Consequently, two kinds of problems arise. One is the over-stiffness of the mixture which lacks in workability. To remedy such a problem, water is added, leading to further deterioration in quality. The other is the serious drying shrinkage cracking as a result of excessive amount of cement used. In the past, ACI 318-89 used to take account of the water to cement ratio (W/C) as a safety criterion. As a result, deterioration, corrosion, bleeding, efflorescence or cracks were commonly found in many buildings within a few years after construction. These problems are signs of aging caused by the neglect of durability in the concrete design.

The mixture design of high-performance concrete (HPC) relies heavily on the appropriate amount of paste used. In addition, chemical admixture and pozzolanic materials as well as the low water content and low amount of cement paste were used to achieve high durability [1]. ACI 318-95 [11] has been recently revised, specifying that structural concrete should have high durability, as presented by the water to binder ratio (W/B) [2]. A long-term monitoring device should be made available for large structures so as to establish durability data and to accumulate further experience in following up on concrete quality which can serve as feedback for future design. In this study, the corrosion behavior of singly reinforced HPC beams under repeated loading in marine environment was examined. The results, thus obtained, may shed light on the design of highway structure concrete in humid coastal environments.

2. HPC mix proportioning

HPC designed according to the densified mixture design algorithm (DMDA) has to be safe, durable, workable, economic and ecological. However, this eugenic mixture logic is different from that of the traditional ACI mixture design [3]. The following is a comparison between the two mixture designs with

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respect to considerations of workability, safety, durability, economy and ecology.

2.1. Workability

The amount of water used is employed as a criterion by the ACI. The water to cement (W/C) ratio has a direct influence on the cement content. Generally speaking, a low W/C ratio represents a high paste content indicating high strength. As a result, the amount of water has often been wrongly employed as an index for controlling the slump and workability of concrete. In fact, for HPC to achieve high workability, it has to be most densely packed with least voids. In addition, it requires the use of sufficient amount of paste, along with pozzolanic materials and superplasticizers.

2.2. Safety

The W/C ratio is also taken as an indicator of safety for both HPC and traditional concrete. The only difference is that HPC employs the W/B ratio as an additional control criterion for medium and long-term strength; as well as the water to solid (W/S) ratio for its long-term properties. The safety of HPC is chiefly built upon the force transferred through aggregates. This is different from traditional concrete which relies on paste as its main support.

2.3. Durability

Traditional concrete achieves durability by controlling mainly the W/C ratio while HPC uses both the W/B and W/S ratios as criteria. The water content is minimized in order to reduce water channels. Similarly, the cement content is kept to the minimum so as to reduce the yield of calcium hydroxide which, in turns, lower efflorescence, and sulfate attack (SA) reaction. In addition, decreasing the amount of alkali can reduce aggregates attack risk (AAR). Increasing the density of water and resistivity can decrease infiltration of harmful substances and electron movement while increasing the addition of pozzolanic materials can seal the cracks formed. This can ensure homogeneity and stability in concrete, thus leading to continuous development in strength.

2.4. Economy

Traditional concrete does not consider economy in its mixture design. The average efficiency of conventional cement calculated is 0.07 MPa/kg, while that of HPC is 0.14 MPa/kg [3]. As far as cement paste is concerned, void volume (Vv) can be reduced and harmful alkali materials (CH, KH, NH) can be transformed into beneficial binder to attain strength. Consequently, this can reduce the content of expensive cement needed. Another means to achieve economy is to employ the cheap indigenous resources and recycling materials, such as fly ash and slag.

2.5. Ecology

To minimize the possible pollution to the environment, industrial wastes are filled into the cracks and voids through densified logic infiltration which solidifies industrial wastes without damaging the concrete. In some cases, this even helps to achieve better quality. In addition, reducing the cement content can lower the emission of CO_2, which in turn reduces the green house effect and contributes to ecological protection. Another key point is prolonging the life cycle of a structure so that repairs and deterioration can be reduced.

3. Experimental plan

The durability of beams made according to the HPC mixture proportion algorithm and those fabricated following the ACI 318-89 [11] are compared with respect to the following: (1) optimum packing density of materials; (2) application of pozzolanic materials; (3) boundary activator.

3.1. Materials

The cement used was Portland Cement Type I produced by Taiwan Cement Company, Blast-furnace slag was provided by China Steel Company. Class F fly ash was produced by Taiwan Power Shingta Station. Superplasticizer, silica fume and steel fiber are available from the local market.

3.2. Experimental procedures

The properties of the different constituent materials were first determined. The concrete strength was designed according to the least void method. Singly reinforced concrete beam specimens (12 cm $\times$ 20 cm $\times$ 80 cm) as shown in Fig. 1 were made with W/B ratios of 0.28, 0.32 and 0.4. All specimens were cured in water for 120 days, and then submerged in 3% artificial sea water solution to simulate marine environment. RC corrosion-related performance tests as well as repeated loading tests (10 Hz, 10^6 cycles) were conducted. The most representative specimen was tested for the content of chloride and hydroxyl ion content. The permeability index before and after corrosion was measured to evaluate the anti-corrosion efficiency of HPC.

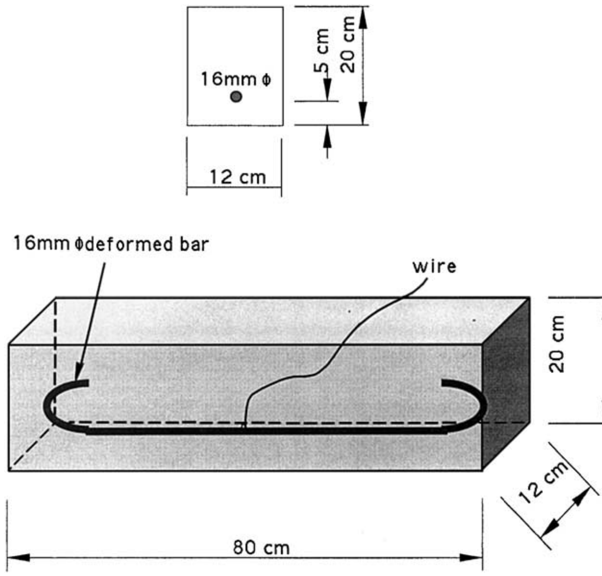

Fig. 1. Singly reinforced concrete beam specimens (12 cm × 20 cm × 80 cm).

4. Results and discussion

4.1. Medium and long-term durability index

As the W/C ratio can only control early-age strength of concrete [3], the major influence on long-term strength development lies in the W/B ratio because it takes into account the pozzolanic effect. Among the existing mixture specifications, durability is guaranteed by controlling the air entrained, the W/B ratio and the content of chloride content without considering the negative effect of physical and chemical interactions [1]. Meanwhile, low W/B ratio may reduce the amount of cement required and minimize problems caused by a high paste content. Thus, ACI 318-95 has adopted the sum of W/B, cement and pozzolanic materials ratio, to make concrete of high quality and low permeability. In addition, W/S is the ratio of weight of water to that of the solid components. Fig. 2 shows the relationships between all W/S parameters and resistivity under any type of cement paste systems [4]. It can be seen that the lower the W/S and longer the age, higher is the electrical resistivity efficiency. In particular, when the W/S is less than 8%, the resistivity at the age of 56 days exceeds over 20 KΩ cm. No corrosion phenomenon would occur when the resistivity is larger than 20 KΩ cm [5]. In other words, a W/S ratio of <8% indicates greater durability of concrete.

Besides, conventional high-strength concrete usually has W/C ratio of less than 0.42 inducing self shrinkage to occur [3]. Excessive cement paste content also results in volume stability problem which has often been neglected in the past mixture designs. Therefore, in this

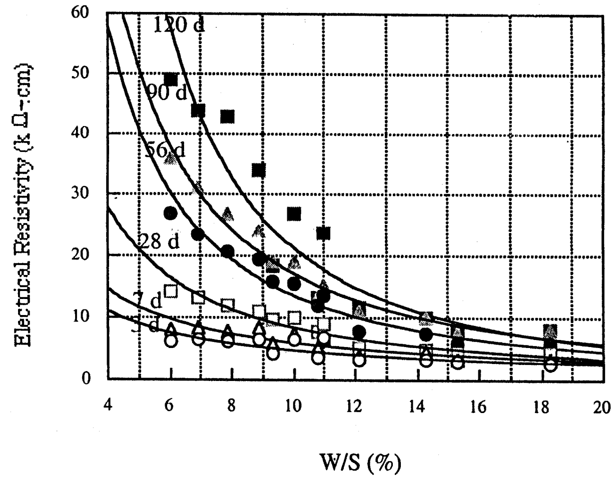

Fig. 2. Relationship between concrete age, electrical resistivity and W/S ratio.

study, the amount of mixing water and cement is limited. In other words, it is specified that W/C≠W/B; the amount of pozzolanic materials (p) is more than 0; and W/S is less than 0.08.

4.2. Analysis on corrosive behavior of beams under repeated loading and marine environment

As shown in Fig. 3, there is no significant change in the half-cell potential under repeated loading before fatigue cracks occur. However, when fatigue cracks appear, there is a sudden decline in the half-cell potential which fall rapidly into the corrosive potential range of −270 mV SCE. Before the cracks appear, the stress from repeated loading is sustained by concrete and less by the steel beams; therefore there is no significant change in potential reinforcement before and after repeated loading. However, when cracking occurs in concrete, the cracking passes the location of reinforcement, thus

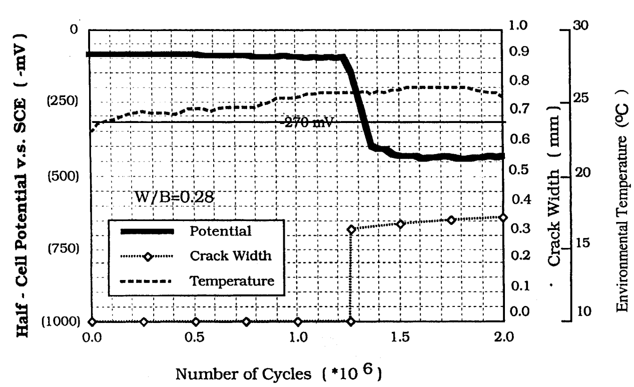

Fig. 3. Relationship between repeated loading, half-cell potential and crack width of singly reinforcd HPC beam.

Table 1
Measurement of corrosion rate in HPC beam under repeated loading[a]

Number of specimen	Repeated loading	Cl^-		Half-cell	AC impedance		Mapping of corrosion condition		Max. displacement under repeated loading mm
		Concentration ppm	Resistivity KΩ cm	Potential −mV, SCE	Rp W cm^2	Corr. rate mm/yr	According ASTM C876	Actual	
RCC	Before	36	9.7	−219	15	2.11	N.C.	–	–
	After	80	4.9	−413	5.5	5.76	C.	W.C.P.	3.5
RCS	Before	26	14.9	−223	50	0.63	M.C.	–	–
	After	71	7.5	−402	26	1.58	C.	W.C.P.	3.26
RCSF	Before	35	3.3	−117	43	0.74	N.C.	–	–
	After	53	2.6	−321	23	1.38	C.	W.C.P.	3.39
HC	Before	26	4	−130	130	0.24	N.C.	–	–
	After	61	3	−387	13.5	2.28	C.	W.C.P.	2.87
HS	Before	9	16.8	−234	180	0.17	M.C.	–	–
	After	67	13.9	−354	30	1.04	C.	W.C.P.	2.57
HA	Before	17	14.8	−125	150	0.21	N.C.	–	
	After	63	11.4	−267	21.4	1.45	M.C.	W.C.P.	2.67
HSF	Before	–	4.8	−237	1300	0.02	N. C.	–	–
	After	–	3.6	−375	1200	0.022	C.	Slight stains	–

[a] W.C.P. – representation of without corrosion product. N.C. – representation of no corrosion. M.C. – representation of may be corrosion. C. – representation of corrosion. RCC – representation of reinforced concrete control team. RCS – representation of reinforced concrete add slag. RCSF – representation of reinforced concrete add slag and fiber. HC – representation of high performance concrete control team. HS – representation of high-performance concrete add slag. HA – representation of high-performance concrete add alumina powder. HSF – representation of high-performance concrete add slag and fiber.

causing the position of the beam neutral axis to be raised and the moment of inertia to drop. After cracking, harmful substances (especially chloride ions) diffuse to the steel surface and breaking the passive film, resulting in a sharp drop in the corrosion potential into the corrosive range [6]. As for HPC [9,10], produced with the addition of pozzolanic materials, the reinforcement can obtain better protection and the cracks can be sealed. Thus, when HPC cracking occurs, the declining range of the reinforcement potential will be less than that in the normal, showing that the HPC group has better corrosion resistance.

4.3. Analysis of concrete cracking and reinforcement corrosion rate

When cracks are found in concrete, exterior harmful substances will invade into the reinforcement resulting in deterioration. Normally, corrosion rate can be obtained by measuring the common instant corrosion rate, but in this research the AC resistivity analyzer is used to measure the corrosion rate [6]. Table 1 and Fig. 4 show the impact of concrete cracking on reinforcement corrosion in the artificial sea water solution [7]. It can be seen that the width of almost all the cracks is less than 0.3 mm. Taking the RC beams as an example, the wider the crack width is, the faster the corrosion rate is. In terms of reinforcement surface covering condition, for hot-dip galvanized reinforcement, corrosion rate is somewhat lower. Therefore, the coating of steel in RC can give reinforcement more protection. It can also prove that after cracking, no existing admixture can be added to the concrete for improving its quality, even

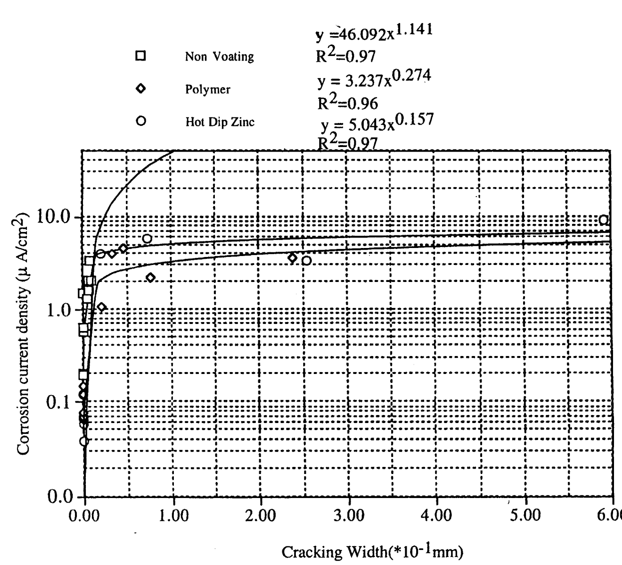

Fig. 4. Relationship between crack width of concrete and corrosion current of steel.

though the cracks have not reached the boundary cracking width of 0.1 mm according to the specification. This is because the corrosive ions can still penetrate the cement surface through the channel.

4.4. Corrosion behavior of reinforcement in HPC

Concrete is a multiphase material. Concrete electrical resistivity can be the main criterion for judging concrete quality with reinforcement potential as an auxiliary means. Fig. 5 shows the relationship between reinforcement and electrical resistivity after submerging HPC in sea water. It indicates that the reinforcement potential is decreasing with increasing days of submergence. It is because chloride ions in sea water diffuse to the steel surface and breaks the passive film and, thus, leads to a sharp decline in the reinforcement potential [7]. Moreover, electrical resistivity of concrete increases steadily due to the completion of hydration at the age of more than 56 days. While cracks occur, concrete electrical resistivity declines sharply, but its declining range is smaller than that of concrete with steel fibre added.

4.5. Relationship between beam behaviour and steel corrosion under repetitive loading

In the early design stage of concrete structures, cracking is permitted to exist. However, in order to avoid fatigue corrosion of steel in marine environment, the growth speed and size of cracks must be controlled. Under repeated loading, the bonding force of steel and concrete will decrease while beam deflection will increase with increasing fatigue. Fig. 6 shows the relationship between the cycles of fatigue loading and deflection of beam [8]. With respect to reinforced concrete, beam deflection is lower than that of plain concrete owing to steel taking tension force. In addition, different kind of admixtures has influence on beam deflection. The fall in beam stiffness (EI) value reveals that EI will decrease in accordance with the increasing number of fatigue cycles under repeated loading. However, if steel fibre is added to the concrete, the decline in EI value is smaller. Under the same fatigue number, the concrete with steel fiber added has a higher EI value than that without steel fiber added. In other words, concrete with steel fiber added can maintain preferred residual strength under repeated loading [8].

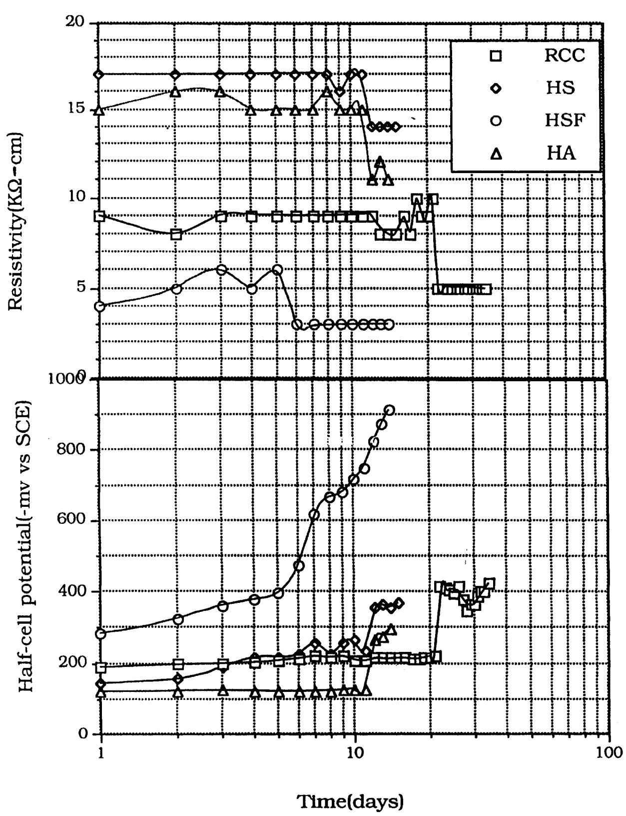

Fig. 5. Variation of resistivity and half-cell in concrete specimens submerge in artificial sea water.

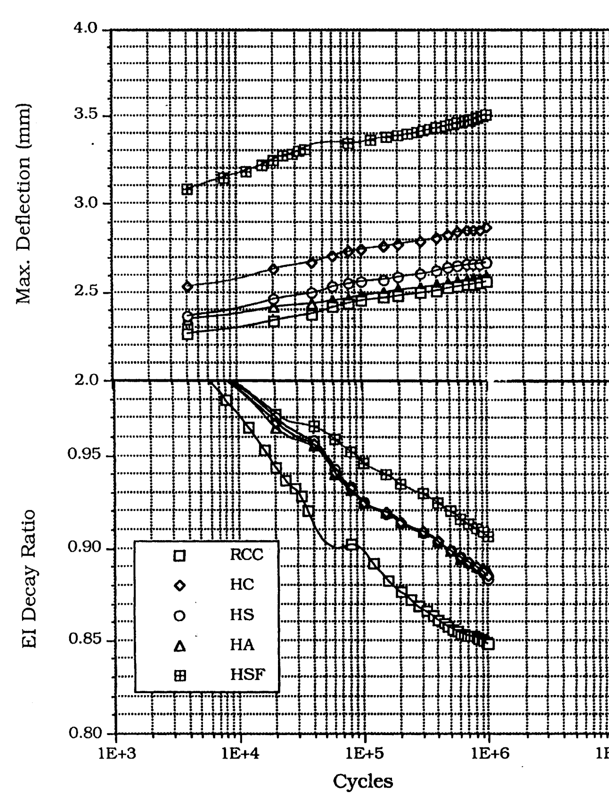

Fig. 6. Max. deflection and EI decay ratio of reinforced concrete beams under fatigue loading.

5. Conclusions and suggestions

1. HPC contains pozzolanic materials such as fly ash, slag for lower water permeability, smaller voids and higher impedance resistivity coefficient, and thus improving durability.
2. The addition of steel fiber could prevent steels from corrosion. However, after concrete cracks, for any mix design of concrete, the steel corrosion would accelerate. However, HPC group has better corrosion resistance.
3. The ACI provisions with respect to cracking width of reinforced concrete structures cannot handle the corroding problem under marine environment, which requires further study.

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