8th ICAAR 1989 KYOTO
8th Internationl Conference
on Alkali-Aggregate Reaction

PROPERTIES OF CONCRETE SPECIMENS DAMAGED BY ALKALI-AGGREGATE REACTION, LAUMONTITE RELATED REACTION AND CHLORIDE ATTACK UNDER MARINE ENVIRONMENTS

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1. INTRODUCTION

The durability of concrete under marine environments has been studied and several series of long term exposure tests have been carried out at the Port and Harbour Research Institute since 1963. As one of the test series, RC (reinforced concrete) beams, PC (prestressed concrete) beams and their control specimens have been exposed at three ports (Sakata, Kagoshima and Kurihama) for 10 years since 1975.

After the 10 years' exposure, the specimens at Kagoshima are damaged only by chloride attack. Whereas, the specimens at Sakata are damaged by AAR as well as chloride attack and those at Kurihama are damaged by laumontite related reaction as well as chloride attack.

Mechanical and chemical characteristics of the specimens were investigated and the corrosion of the reinforcements and PC tendons were also investigated. For this purpose, bending tests of the beams, chemical analyses and physical tests of the cylinder specimens were performed.

In this report, the test results are presented and the characteristics of the specimens damaged by three different causes are discussed.

2. TEST PROCEDURE

As presented in Table 1, 28 beams were fabricated and tested. At Sakata and Kagoshima, both RC and PC beams have been exposed and at Kurihama, PC beams have been exposed.

For the PC beams, there are "R" and "O" types. "R" type is the pretensioned beam, and "O" type is the bonded post-tensioned beam as shown in Figs.1 and 2. For the RC beams, there are two types as shown in Fig.1. All reinforcements in the beams are JIS-SD30 (Japanese Industrial Standard). Whereas, prestressing wires used in "R" types are JIS-SWPR2 and prestressing tendons used in "O" types are JIS-SBPR 95/110 Ø17.

The mix proportions of the concrete used for the specimens are presented in Table 2. Ordinary portland cement is used for the RC specimens and high early strength portland cement is for the PC specimens. The aggregates used in this study are summarized in Table 3.

After casting, the specimens were moisture cured for a day and demoulded. Then, RC specimens were cured in air until the exposure and the PC specimens were steam cured (highest temperature was 60°C) for about 10 hours followed by curing in air until the exposure. As presented in Table 1, the effective prestress of the "R" type beams is about 12.7 MPa and that of the "O" type

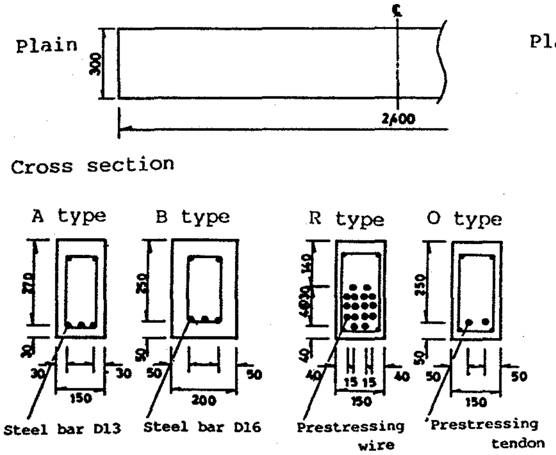

Fig.1 Outlines of the beam specimens
(Exposed at Sakata or Kagoshima)

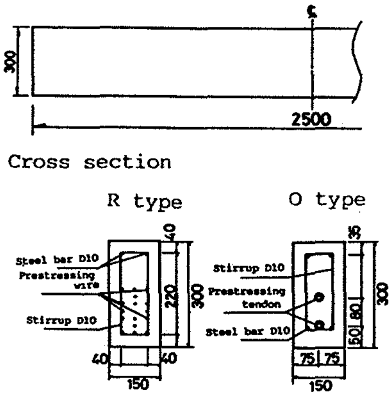

Fig.2 Outlines of the beam specimens
(Exposed at Kurihama)

beams is about 13.7 MPa. The ends of each beam were covered with a pad of cement mortar to prevent corrosion of the ends of strands or end anchorages.

For the cracking and loading condition, they are categoried into three conditions, "A", "B" and "C". The "A" condition is the most severe one, and in this condition the beams were precracked by bending and the external moment has been continuously applied during the exposure. In the "B" condition, the beams were precracked by bending, however, no load was applied during the exposure. The "C" condition is the mildest one, and in this condition no crack and no load was introduced to the beams.

The specimens were placed in tidal or submerged zone after 2 months old. In tidal zone, the specimens were alternately subject to wet and dry conditions by the tidal action, and in submerged zone they were always in sea water. At Kagoshima and Kurihama, freeze and thaw action did not occur. However, at

Table 1 Summary of the beam specimens

Port	RC or PC	Type	Cover Depth (cm)	Cracking and Loading Condition	Exposure zone	Number of specimen (No.)	Effective Prestress (MPa)
Sakata	RC	A	2.3	C	Tidal	1 (1)	
				A	"	1 (2)	
		B	4.2	C	"	1 (3)	
				A	"	1 (4)	
	PC	R	3.0	C	"	1 (5)	12.7
				B	"	1 (6)	"
		O	2.5	C	"	1 (7)	13.7
				A	"	2 (8,9)	"
				B	"	1 (10)	"
Kagoshima	RC	A	2.3	C	"	1 (11)	
				B	"	1 (12)	
		B	4.2	C	"	1 (13)	
				B	"	1 (14)	
	PC	R	3.0	C	"	1 (15)	12.7
				B	"	1 (16)	"
		O	2.5	C	"	1 (17)	13.7
				A	"	2 (18,19)	"
				B	"	1 (20)	"
Kurihama	PC	R		C	Submerged	1 (21)	12.7
				C	Tidal	1 (22)	"
				A	"	4 (23~26)	"
				B	"	1 (27)	"
		O		C	Submerged	1 (28)	13.7

Table 2 Mix proportion of the concrete

Port	RC or PC	Gmax (mm)	Slump (cm)	Air (%)	W/C (%)	s/a (%)	Unit Weight(kg/m^3) W	C	S	G	Admixture
Sakata	RC	20	12±2	4±1	68.0	47	204	300	793	964	1.20
	PC	20	5±1	3±1	40.7	37	167	410	640	1175	1.64
Kagoshima	RC	20	12±2	4±1	65.4	42.5	170	260	796	1118	1.04
	PC	20	5±1	3±1	39.2	40	157	400	731	1151	1.64
Kurihama	PC	20	5±1	4±1	37.0	40.5	170	460	710	1080	1.84

Note1 : The slump and air are designed values.
Note2 : The admixture used is air entraining agent.

Table 3 Summary of the aggregates

Port	aggregate	specific gravity	fineness modulus	
Sakata	fine	2.25	2.84	river sand
	coarse	2.75	6.63	crushed stone
Kagoshima	fine	2.65	2.84	river sand
	coarse	2.75	6.79	crushed stone
Kurihama	fine	2.65	2.84	river sand
	coarse	2.75	6.80	river gravel + crushed stone

Sakata, the specimens were subject to freeze and thaw action in winter. In these sites, the pH values of sea water are about 7.5.

After the 10 years' exposure, the specimens were taken out to the PHRI for laboratory tests. All the tests were carried out in conformity to JIS, JCI (Japan Concrete Institute) and ASTM.

3.TEST RESULTS

3.1 Specimens exposed at Sakata

Photos 1 and 2 show the conditions of the damaged PC beam and cylinder specimens respectively. In the PC specimens, deterioration of concrete is clearly observed, but in the RC specimens no deterioration is recognized. In the damaged beam specimens, the end parts are damaged severely, however, the other parts are not damaged. In the damaged cylinder specimens, some obvious cracks and expansion were observed on the surface.

Photo 1 Damaged beam specimen (Exposed at Sakata)

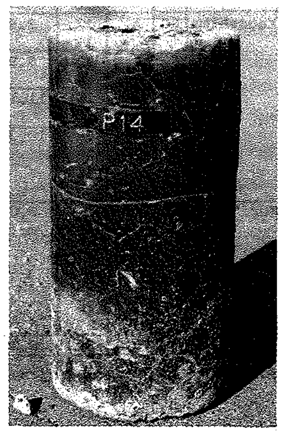

Photo 2 Damaged cylinder specimen (Exposed at Sakata)

Fig.3 shows the results of chemical analysis of the aggregate used for the specimens. It can be seen that the coarse aggregate is not reactive for AAR, but the fine aggregate is reactive. Kondo et al studied properties of fine aggregate which comes from the same origin as those used herein and concluded that they were reactive for AAR [1].

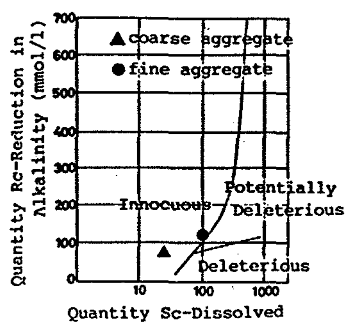

Fig.3 Chemical analysis of the aggregate - ASTM C 289 -

The test results of the beams and the cylinders are summarized in Tables 4 and 5 respectively. Chloride corrosion of reinforcing steel bars is found in all the beams. However, no reduction of maximum bending moments is observed. From Table 5, it appears that the strength and modulus of elasticity of PC specimens are reduced to the level of 30% of their original ones, but those of the RC specimens are not reduced. In both the RC and PC specimens, a large amount of chlorides presents. Average chloride content in the PC specimens, however, is larger than that in the RC specimens. From X-ray analysis, the ettringite is detected in both RC and PC specimens.

3.2 Specimens exposed at Kagoshima

In the specimens exposed at Kagoshima, longitudinal cracks are observed on several RC beams at the level of the reinforcement and some rust stains on the

Table 4 Summary of test results for the beam specimens

Port	RC or PC	Type	No. of Beam	Ultimate Bending Moment Initial	Ultimate Bending Moment 10years	Ultimate Bending Moment 10years/Initial	Corroded Area 1 (%)	Corroded Area 2 (%)	Degree of End Anchorage Corrosion	Note
Sakata	RC	A	1	3.99			6.4			
			2		3.96	0.99	22.4			
		B	3	5.34	6.06	1.14	6.8			
			4		5.88	1.10	2.3			
	PC	R	5	8.79	9.52	1.08	23.6	12.5		(Possibly)
			6		9.00	1.02	37.5	26.4		Cracked by AAR
		O	7	8.58	9.28	1.08	0.9		3.5	"
			8				1.0		4.0	(Possibly)
			9				1.8		3.5	Cracked by AAR
			10		9.03	1.05	0.8		4.0	"
Kagoshima	RC	A	11	3.92	3.92	1.00	20.0			
			12		3.64	0.93	44.5			Longitudinal Crack
		B	13	5.99	5.92	0.99	21.7			"
			14		5.67	0.95	26.7			"
	PC	R	15	11.17	11.06	0.99	29.8	1.8		
			16		11.24	1.01	16.3	1.6		
		O	17	10.33	10.61	1.03	15.3		3.5	
			18		10.82	1.05	23.6		3.0	
			19		10.43	1.01	24.9		3.0	
			20		8.75	0.85	20.6		3.0	
Kurihama	PC	R	21	8.05	7.28	0.90		16.6		Cracked by LRR ,
			22		8.44	1.05		0.2		
			23		7.70	0.96		17.6		Cracked by LRR
			24		7.91	0.98		18.9		"
			25		7.28	0.90		12.5		
			26		7.35	0.91		9.3		
			27		7.77	0.97		20.4		Cracked by LRR
		O	28	9.23	10.08	1.09			4.0	"

Note 1 : Ultimate Bending Moment is in $\times 10^5$ kgf cm

Note 2 : Corroded Area
Area1 : Reinforcing steel bars in tensile zone
Area2 : Prestressing wires

Note 3 : Degree of End Anchorage Corrosion
Degree3 : Corroded Area is about 50%
Degree4 : Corroded Area is about 80%

Note 4 : Note
AAR : Alkali Aggregate Reaction
LLR : Laumontite Related Reaction

Table 5 Summary of test results for the cylinder specimens

Port	RC or PC	Exposure zone	Compressive Strength Initial	Compressive Strength 10years	Compressive Strength 10years/Initial	Modulus of Elasticity Initial	Modulus of Elasticity 10years	Modulus of Elasticity 10years/Initial	Chloride content (10years)	X-ray Analysis Fri.	X-ray Analysis Ett.	X-ray Analysis CH.	X-ray Analysis Bru.
Sakata	RC	tidal	max 319	400		2.28	3.09		12.96				
			min 292	247		2.45	3.02		8.61	oo	o	oo	-
			Ave 309	304	0.98	2.35	3.06	1.30	10.87				
	PC	tidal	534	229					13.57				
			519	190					12.71	oo	o	o	-
			528	208	0.39				13.04				
Kagoshima	RC	tidal	288	489		2.52	3.87		17.08				
			251	298		1.84	3.25		8.08	o	-	-	-
			267	342	1.28	2.20	3.47	1.58	11.25				
		submerged		327			3.76						
				281			3.44						
				304	1.14		3.63	1.65					
	PC	tidal	568	732		3.29	4.40		10.67				
			541	408		2.85	3.33		4.83	o	-	o	-
			556	566	1.02	3.12	3.90	1.25	7.28				
		submerged		676			4.50						
				481			4.21						
				580	1.04		4.36	1.40					
Kurihama	PC	tidal							13.22				
									8.41	o	oo	-	o
									11.15				

Note 1 : Compressive strength, Modulus of elasticity, Chlorida content are in kgf/cm^2, $\times 10^5$ kgf/cm^2 and kg/m^3 (Cl v.s concrete), respectively.
Note 2 : X-ray analysis
Fri. : Friedel's salt, Ett. : Ettringite, CH. : Portlandite, Bru. : Brucite.
oo : detected clearly, o : detected, - : not detectred

surface of the specimens are also observed. Usually, reinforcing bars situated beneath longitudinal cracks of beams are heavily corroded.

In all the beams, the corrosion of reinforcing steel bars is found, but no reduction of maximum bending moments is observed as presented in Table 4. As presented in Table 5, no reduction of strength and modulus of elasticity is recognized. A large amount of chlorides presents in both RC and PC specimens. However, an average chloride content in the RC specimens is larger than that in the PC specimens. Anyway, it is clear that the corrosion was caused by chloride attack. From X-ray analysis, ettringite is not detected in both RC and PC specimens.

3.3 Specimens exposed at Kurihama

Photos 3 and 4 show the damaged beam and cylinder specimens respectively. Severe deterioration of concrete is recognized. In the damaged beam specimens, the end parts are damaged severely, however, the other parts are not damaged. In the damaged cylinder specimens, some obvious cracks and expansion are observed on the surface. In the worst case, as shown in Photo 4, the specimens cannot keep the original shape.

Photo 3 Damaged beam specimen

Photo 4 Damaged cylinder specimen

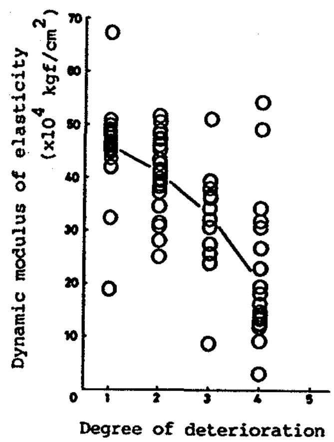

Fig.4 Dynamic modulus of elasticity

From the result of X-ray analyses of the aggregate used for the specimens, it is found that the majority proportion of coarse aggregate is laumontite. In the study by Ono et al [2], it is concluded that the concrete containing laumontite as aggregate is possibly to be damaged heavily in sulphuric or marine environments.

Dynamic modulus of elasticity is plotted against the degree of deterioration in Fig.4. The degree of deterioration is judged by visual inspection. The specimens graded "degree 5" are impossible to be tested. From this figure, it can be seen that the modulus of elasticity decrease with an increase in the degree of deterioration. As shown in Table 4, chloride corrosion of reinfocing steel bars is found in all the beams. However, no reduction of maximum bending moments is observed. In these specimens, the chloride content is high enough to become the cause of corrosion. From X-ray analysis, ettringite is detected clearly in the concrete.

4.DISCUSSION

The effects of "size" and "shape" of the specimens on "the degree of thedamage of concrete" are obvious, that is, the deterioration of cylinder specimens is much heavier than that of the beam specimens. It is considered that the expansion of concrete caused by aggregate reactions can be restrained to some degree by reinforcing steel bars as well as prestressing wires or tendons.

The data in Table 4 show that all actual ultimate moments are not smaller than the original values. It can be concluded that the ultimate moments are not reduced below design levels over the 10-year exposure due to some kinds of aggregate reaction and the corrosion of reinforcement.

The data in Table 5 show that chloride contents in the concrete are large enough to become the major cause of the corrosion of the reinforcement. However, average chloride contents in the concrete damaged by some kinds of aggregate reaction are larger than those in the concrete damaged only by chloride attack. Therefore, the corrosion of prestressing wires and end anchorages of the specimens damaged by aggregate reactions are much larger than those of the specimens damaged only by chloride attack. In the "O" type beams (post-tensioning type), end anchorages of the beams are heavily corroded. However, post-tensioning conduits and tendons are relatively less corroded. This is attributed to the protection of the grout.

The data in Table 5 show that aggregate reaction leads to an increase in the amount of ettringite formation in concrete under marine environments. From a purely empirical point of view, examples of concrete damaged only by sulfate attack in marine environments are very rare. It can be said that the concrete damaged by aggregate reaction is susceptible to sulfate attack in marine environment.

In the specimens exposed at Sakata, deterioration is observed in the PC specimens, but not in the RC specimens. The major differences of the concrete for the PC and the RC beams are the unit amount of cement (PC:410 kg/m^3, RC:300kg/m^3) and the curing method (PC:steam curing, RC:standard curing). High amount of cement and/or steam curing perhaps have a negative influence on the durability of concrete.

5. CONCLUSIONS

The following conclusions are derived from the foregoing results.

1) The compressive strength and the modulus of elasticity are very low for the cylinder specimens damaged by aggregate reactions.

2) In spite of the result mentioned above, the ultimate load carrying capacity of the damaged beams shows little reduction.

3) Chloride contents in the specimens damaged by the aggregate reactions are much larger than those in the specimens damaged only by salt attack.

4) The corrosion of the steel bars in the beams damaged by aggregate reactions is heavier than that of the steel bars in the beams damaged only by chloride attack.

5) The concrete damaged by the aggregate reaction is susceptible to sulfate attack in marine environments.

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