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Modeling of Surface Deterioration of Concrete Exposed under Cold Sea Environment*

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Abstract

Experiments were carried out on specimens of five kinds of mix proportion concrete exposed to a cold sea environment (Monbetsu) for 7 years. The effect of various factors was compared and considered by a statistical method from the measured data. The main factor on the scaling deterioration of a concrete surface which is related to the cover of the steel is clarified and a model to predict changes in surface deterioration is presented.

1. Introduction

Experiments were carried out on 21 specimens of five kinds of mix proportion concrete exposed to a cold sea environment (Monbetsu) for 7 years. The effect of various factors were compared and considered by the statistical method from the measured data. The main factor on the scaling deterioration of a concrete surface which is related to the cover of the steel is clarified and a model to predict changes in surface deterioration.

2. Experimental Procedures

2.1 Material and mix proportion

The properties and content of the cement mixed are shown in Table 1. The mix of concrete proportions were set up for an air content of 4.5% and a slump of 5 centimeters. The specified mix and the properties of the concrete are shown in Table 2. The aggregates were river coarse aggregate and sea fine aggregate. The content of salt (NaCl wt%) in the sand was 0.026%.

2.2 Curing and exposing condition

The curing conditions of the specimens are shown in Table 3. The location of exposure was beside Okhotsk sea at Komuke-ko Monbetsu Hokkaido. The distance from the sea was between 30 meters to 50 meters and the location was sometimes washed by waves. The number of cycles of freezing and thawing at a depth of 3.5 millimeter to 5.0 milimeters from the concrete surface was an

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Table 1. Type, property and chemical compound of cement

Case	Type of cement	Specific gravity	Admixture	Strength of cement (kgf/cm^2)	Chemical compoun's content (%)							
					ig. loss	insol.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
N	Normal portland cement	3.17	0	443	0.6	0.0	22.1	5.4	3.1	64.8	1.5	1.9
F A	Fly-ash cement Type A	3.09	8	—	0.3	4.6	21.8	5.2	2.9	61.5	1.4	1.4
F B	Fly-ash cement Type B	2.91	15	344	0.6	12.0	20.0	5.2	2.9	55.5	1.3	1.7
F C	Fly-ash cement Type C	2.49	22	—	0.6	14.0	16.6	5.7	2.4	47.4	1.3	1.8
B B	Blast-furnace slag cement Type B	3.05	40*1	368	0.6	0.1	25.0	9.1	1.8	55.8	3.4	2.6

Note; chemical compound according to report in CAJ 1974.

*1; approximately from maker.

Table 2. Mix proportion of concrete

Case	Type of cement	Specified mix					Property of fresh concrete			Compressive Strength				
		W/C (%)	W (kg)	C (kg)	S (kg)	G (kg)	slump (cm)	Air content (%)	Temperature (°C)	Standard curing (kgf/cm^2)	In site curing (kgf/cm^2)			
											F 0	F 5	S 5	F 14
N 55	N	55	136	248	770	1166	6.6	5.6	27	280	198	238	240	270
N 45	N	45	135	300	718	1177	3.9	4.5	28	372	—	340	—	316
F A 55	F A	55	123	224	790	1194	4.3	6.5	22	298	—	259	—	—
F B 55	F B	55	122	222	790	1194	8.5	4.3	22	254	207	250	247	268
F B 45	F B	45	123	274	790	1205	8.0	5.0	24	325	—	263	—	288
F C 55	F C	55	121	220	790	1194	6.5	4.3	21	231	—	222	—	—
B B 55	B B	55	128	233	780	1182	2.9	4.0	25	258	192	225	196	211
B B 45	B B	45	130	289	722	1186	6.0	3.0	23	338	—	285	—	311

Table 3. Case of exposd specimen

No.	C · W/C · CC · CD	No.	C · W/C · CC · CD	No.	C · W/C · CC · CD
1	N 55 F* 0	8	F B 55 F 0	15	B B 55 F 0
2	N 55 F 5**	9	F B 55 F 5	16	B B 55 F 5
3	N 55 F 14	10	F B 55 F 14	17	B B 55 F 14
4	N 55 S* 5	11	F B 55 S 5	18	B B 55 S 5
5	N 45 F 5	12	F B 45 F 5	19	B B 45 F 5
6	N 45 F 14	13	F B 45 F 14	20	B B 45 F 14
7	F A 55 F 5	14	F C 55 F 5	21	Speicmen measuring temperature

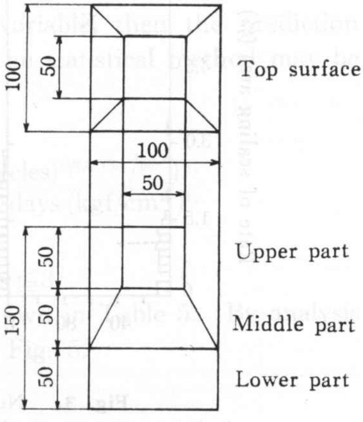
*F : Fresh water curing, S : Sea water curing

** Specimen measuring temperature is the same mix proportion as N55F5 Specimen measuring temperature

Note C : cement, W/C : water cement ratio, CC : curing condition, CD : number of curing days average of 54 in 6 years.

2.3 Measuring method

The method of measuring the surface deterioration of scaling and pop-out was conducted by using a depth gage attached to the upper part, middle part and lower part in four directions and on the top surface totaling 13 points, as shown in Fig. 1. The area of surface deterioration and the location of the point measured were photographed after placing a 10 millimeter mesh frame. The degree of scaling (average degree of damage) was calculated by multiplying the area and depth at the part of scaling, adding up the values for all points, and then dividing by the total area of measurement.



(unit : centimeter) (cm)

Fig. 1. Exposed specimen.

3. Result and Consideration

3.1 Result

(1) The scaling damage was mostly from 0 millimeters to 0.05 millimeters by degree of scaling. The average depth of damage was 1.26 mm. The degree of scaling of specimens using Portland blast furnace cement was larger than the others (Fig. 2, Fig. 3 and Fig. 4).

(2) The factors of positive correlation to the degree of scaling are the content of Al_2O_3 in the cement, the water cement ratio and the salt content in the curing water. Those of negative correlation are air content, the strength at site curing and the height from ground level of the measured part which related to the degree of supplied sea water (Table 4).

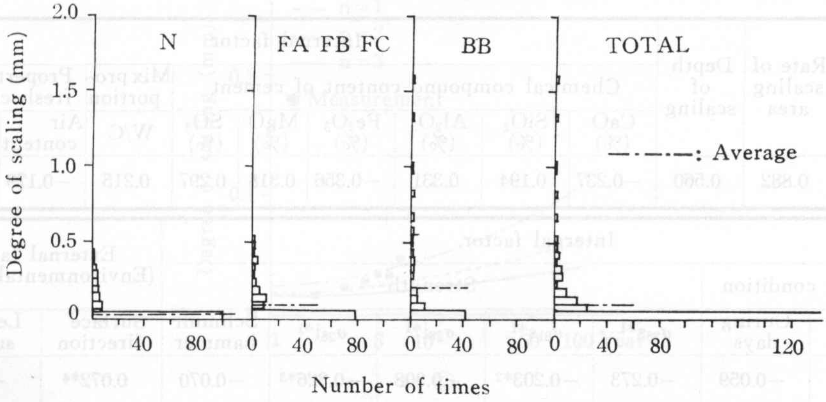


Fig. 2. Number of distribution and degree of scaling.

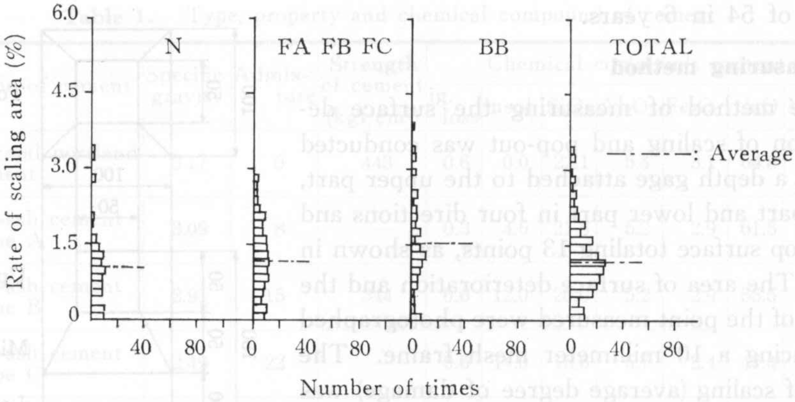


Fig. 3. Number of distribution and scaling area.

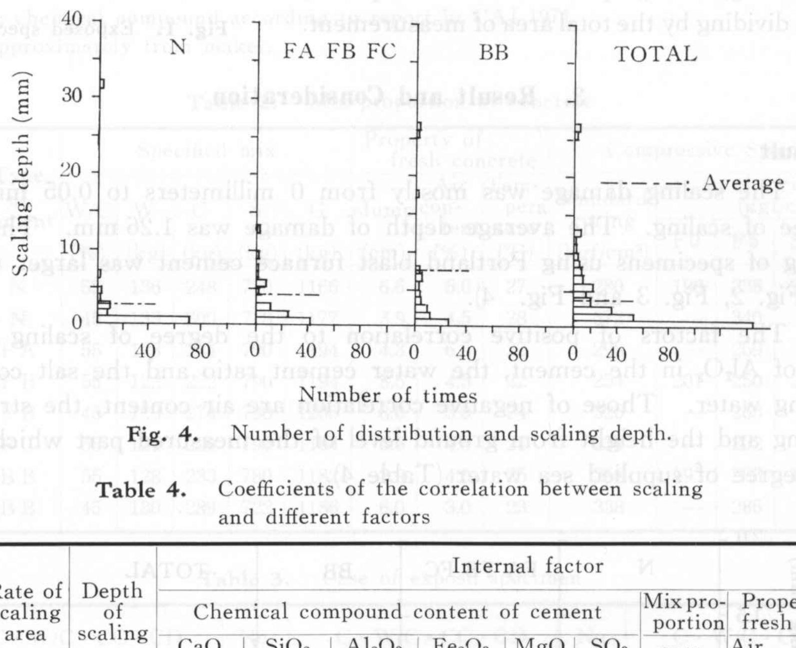


Fig. 4. Number of distribution and scaling depth.

Table 4. Coefficients of the correlation between scaling and different factors

Degree of scaling	Rate of scaling area	Depth of scaling	Internal factor								
			Chemical compound content of cement						Mix proportion	Property of fresh concrete	
			CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	W/C	Air content	Slump
1.000	0.882	0.560	−0.237	0.194	0.331	−0.356	0.318	0.297	0.215	−0.179	−0.294

Internal factor							External factor (Environmental factor)	
Curing condition		Strength						
Curing water	Curing days	σ_{28}S*1	σ_{91}S*1	σ_{28}i*1	σ_{28}i*1	Schmidt hammer	Surface direction	Level of surface
0.227	−0.059	−0.273	−0.203*2	−0.308	−0.326*3	−0.070	0.072*4	−0.313

*1 S: Standard curing, i: Insite curing

*2 without BB45 because of no experiment

*3 without 45F14, BB45F5, BB55F0, BB55S5 and BB45F14 because of no experiment

*4 without top surface

3.2 Consideration

When the degree of scaling is the objective variable, then the prediction of the change of the concrete's surface scaling by the statistical method may be assumed from the following equation,

$$Y=\frac{e^{\alpha_0}\times(\mathrm{Al_2O_3}\,(\mathrm{wt}\%))^{\alpha_1}\times\{(\text{number of freeze and thaw cycles})^{(\mathrm{W/C}(\%)/55)^{n}}\}^{\alpha_5}}{(\mathrm{CaO}\,(\mathrm{wt}\%))^{\alpha_2}\times(\text{surface strength of 28 days (kgf/cm}^2))^{\alpha_3}\times(\text{level to grand(cm)})^{\alpha_4}}$$

where α_0, α_1, α_2, α_3, α_4 and α_5 are constats and $1\leqq n\leqq 3$.

The results of multiple correlation analysis is shown in Table 5. By analysis of variance these results are adequate as shown in Fig. 5.

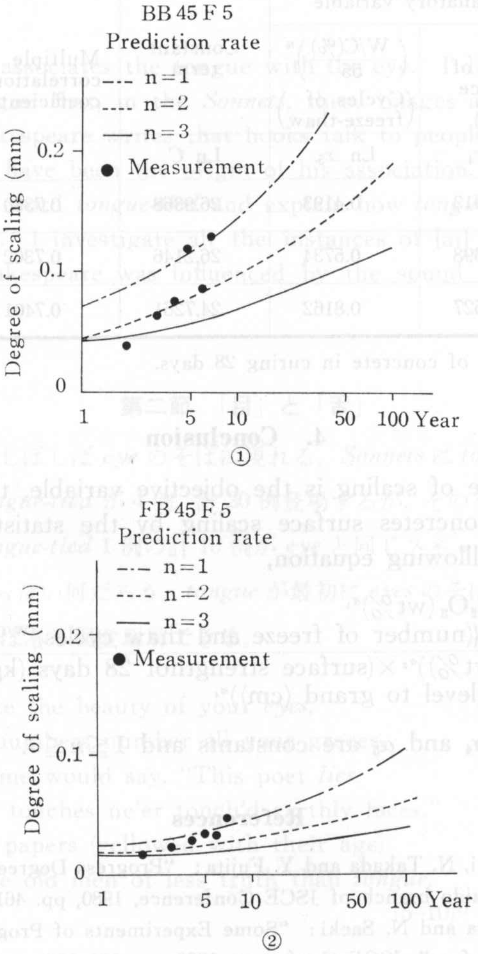


Fig. 5. Relation between the prediction rate from the model equation and measurement.

Table 5. The result of multiple correlation analysis

Case Exponential of $\left(\frac{W/C(\%)}{55}\right)$	Variable	Criterion variable	Explanatory variable		
		Degree of scaling	Al_2O_3 (wt%)	CaO (wt%)	$\sigma 28^*$ (kgf/cm^2)
	Natural logarithm	Ln y	Ln x_1	Ln x_2	Ln x_3
$n=3$	Regression coefficient (α)	—	2.0364	−6.0203	−1.5298
$n=2$	"	—	2.0731	−6.0342	−1.5395
$n=1$	"	—	2.0131	−5.4344	−2.1178

Case Exponential of $\left(\frac{W/C(\%)}{55}\right)$	Explanatory variable		Constant term	Multiple correlation coefficient	Analysis of variance (F-ratio)
	Level of surface (cm)	$\left(\frac{W/C(\%)}{55}\right)^n$ (Cycles of freeze-thaw)			
	Ln x_4	Ln x_5	Ln C		
$n=3$	−1.5313	0.4193	26.9368	0.7330	$271.5 \geqq F^5$ (0.005)
$n=2$	−1.5398	0.5734	26.2146	0.7362	$276.4 \geqq F^5$ (0.005)
$n=1$	−1.5527	0.8162	24.7261	0.7401	$283.2 \geqq F^5$ (0.005)

* Surface strength of concrete in curing 28 days.

4. Conclusion

When the degree of scaling is the objective variable, then the prediction of the change of the concretes surface scaling by the statistical method may be assumed from the folllowing equation,

$$Y=\frac{e^{\alpha_0}\times(\mathrm{Al_2O_3}\,(\mathrm{wt}\,\%))^{\alpha_1}\times\{(\text{number of freeze and thaw cycles})^{(\mathrm{W/C}(\%)/55)^n}\}^{\alpha_5}}{(\mathrm{CaO}\,(\mathrm{wt}\,\%))^{\alpha_2}\times(\text{surface strengthof 28 days }(\mathrm{kgf/cm^2}))^{\alpha_3}\times(\text{level to grand }(\mathrm{cm}))^{\alpha_4}}$$

where α_0, α_1, α_2, α_3, α_4 and α_5 are constants and $1 \leqq n \leqq 3$.

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