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Development of High-Performance Concrete Having High Resistance to Chloride Penetration

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ABSTRACT : The purpose of the present study is to investigate very low-permeable and highly durable concrete which has very high resistance to corrosion. Many series of concretes have been tested. Major test variables include the level of concrete strength, water to cement ratios, and use of other cementitious materials including silica fume, fly ash, and blast-furnace slag. The test method is found to be very efficient in determining low penetration of chloride ion for high performance concrete. The present study indicates that the concrete with an optimum amount of silica fume shows very high resistance to chloride ion penetration.

INTRODUCTION

Recently, the construction of highway bridges, dams, nuclear power plants, and offshore structures has been actively constructed in many countries. A number of structures constructed during past decades have suffered from safety and serviceability problems due to deterioration and many engineers are increasingly concerned about durability of concrete.

Although it is generally known that concrete is a very durable material, as a result of environmental interactions such as weathering action, chemical attack, abrasion, and other process of deterioration, the properties of concrete change with time and finally the structures reach the end of service life because of lack of safety and serviceability.

Therefore, one has great concern about durability and service life of concrete structures. The chloride ion penetration is one of the most important factors that affect the rate of deterioration of reinforced concrete structures. In porous solids, water is known to be the cause of many types of physical processes of degradation. As a vehicle for the transport of aggressive ions, water can be a source of chemical degradation. The physical-chemical phenomena associated with water movements and transport of aggressive ions in concrete are controlled by the microstructure of the concrete.(1)

In this paper, In order to study the influence of mixture proportions of high-performance concrete on the chloride ion penetrability, comprehensive tests have been conducted and major test variables include the level of concrete strengths, water to cement ratios, types and amount of cements, types and amount of mineral admixtures or blast-furnace slag, and the size of aggregates.

The conventional test method for permeability is very difficult to apply to high-performance concrete because of very dense nature and very low permeability of high-performance concrete.(2,3) This study shows that a reasonable and realistic test method for the measurement of chloride ion penetrability for the high-performance concrete can be used. The present study also proposes very low permeable high-performance concrete whose penetrability is less than 1 percent of that of conventional normal concrete.

RESEARCH SIGNIFICANCE

Many structures are increasingly constructed in severe environments, especially sea environment. The chloride permeability is one of the most important factors that affect the durability of the concrete structures under such sea environments The recent development of high-performance concrete may contribute to solve such durability problem. Therefore, present study focuses on the developments of high-performance concrete which has very low chloride permeability. This is very important because durability will be a major concern in the next decades.

CHLORIDE ION PERMEABILITY TEST OF HIGH-PERFORMANCE CONCRETE

Materials and Test Variables

Comprehensive tests have been conducted to study the influence of mixture proportions of high-performance concrete on chloride ion penetrability.The mixture proportions of concrete according to above test variables are given in Table.1, and physical and chemical properties of binders including cement, silica fume, fly ash, and blast-furnace slag are shown in Table.2-6.

The test program was scheduled as follows: first, preliminary tests were conducted to obtain flowability, strength, and durability requirements for various high-performance concretes. Secondly, the main test was conducted according to the mixture proportions determined from the preliminary test. The strength characteristics of various mixtures including compressive, splitting tensile, and flexural strengths are given in Table.7

The symbol and number for the identification of each test series is explained in Fig.1

Test Method

The permeability of concrete has an influence on durability such as corrosion of steel, sulfate attack, etc. Water infiltration due to high permeability is a vehicle for transport of aggressive ions that causes concrete in severe environment to be gradually degraded. Besides, the permeability is closely associated with microstructure of concrete and the high-permeable concrete exhibits a tendency to be more deteriorated.(4)

The conventional test method for permeability of concrete uses water under high pressure to determine a coefficient of permeability, K, given by Dairy's equation. In the case of dense concrete, this method has a defect that the amount of permeated water is very small and thus the required time for the test is very long and sometimes this method cannot give any permeability for very low-permeable concrete. On the contrary, the chloride ion penetration test by a potential difference shows a relative permeability index even for the extremely low permeable concrete.

Therefore, the accelerated chloride ion penetration test by a potential difference is adopted in this study,(5,6) to study the permeability characteristics of high performance concrete.

This test method consists of monitoring the amount of electrical current passed through 50mm thick slices of 100mm nominal diameter cylinders during a 6-hour period. After 28day curing, test specimens are made by cutting cylinders into slices of 50mm thick using a circular saw, and fitted in at each end of voltage cell and the whole assemblage is bolted together. Fig.2 shows the test configuration during the test, a potential difference of 60V DC is maintained across the ends of the specimen, one of which is immersed in a 3% sodium chloride solution, and the other in a 0.3N sodium hydroxides solution. Fig.3 shows the applied voltage cell in detail.

A data logger monitors the current value across each cell by recording oltage applied to 0.2 Ω resistor at every 30 min. interval. The total charge passed during the 6hour test period is calculated by the following formula based on the trapezoidal rule.

$$Q = 900 \times (I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{330} + 2I_{630}) \qquad (1)$$

where, Q = charge passed (in coulomb)

I_n = current(in amperes) at n min after voltage is applied

The total charge passed has been found to be related to the resistance of the specimen to chloride ion penetration and test result can be evaluated by Table 8 given in ASTM Standard

TEST RESULT AND DISCUSSION

Chloride Ion Permeability Characteristics According to Use of Mineral Admixtures

The concrete containing silica fume showed the best performance in the chloride permeability test because it has very dense pore structure due to finer particles of silica fume than the other cementitious materials. In particular, the chloride-ion penetration of high strength concrete test series(H series) containing silica fume is almost negligible Fig.4 and Fig.5 show the chloride permeability of concrete containing silica fume The silica-fume concrete has low permeability in addition to remarkable strength improvement. The optimum mixture proportion for permeability and strength may be obtained from present experimental study.

As shown in Fig.6 and Fig.7, the concrete containing fly ash also showed good performance in permeability test. In normal strength concrete series, the 28-day compressive strengths containing 0%, 15%, and 30% fly ashes were 43.1MPa, 433MPa, and 33.5MPa respectively, and their total chloride-ion charges passed were 2766C(Coulombs), 565C, and 597C, respectively. This indicates that the addition of fly ash into concrete decreases the permeability greatly, even though the strengths of fly ash concrete at 28-days are not enhanced.

Fig.8 shows the permeability characteristics of concrete added with blast-furnace slag The replacement of cement with blast-furnace slag also decreases the permeability. The permeability of concrete with 25% slag contents is about 1/3 of that of normal concrete, even though the strength is about the same at the test age. This fact comes from the dense nature of microstructure due to secondary chemical reaction The concrete with high volume slag contents will reduce the permeability much more.

In order to improve the resistance to permeability, it is also effective to decrease water to binder ratio, but it is more effective to use the appropriate type and amount of mineral admixtures or slag.

Chloride Ion Permeability Characteristics According to Water to Binder Ratio

As shown in Table.11, the chloride-ion permeability decreases as water to binder ratio decreases. It can be seen that the permeability of H series(low water to cement ratio) is much less than that of N series(higher water to cement ratio).

Chloride Ion Permeability Characteristics According to Cement Types, Size of Aggregate and Air Contents

Table.11 shows that the permeability of Type V (sulfate resisting) cement concrete is slightly higher than that of Type I cement(Ordinary Portland Cement). Therefore, normal portland cement has more resistance to permeability than sulfate resistant portland cement concrete

The variations of air contents and aggregate sizes do not seem to have a great influence on permeability, compared with replacement of mineral admixtures or slag Fig.9 shows the effect of the size of aggregate on permeability and Fig.1(shows the permeability according to air content It can be seen from this figure that the concrete with larger size aggregates shows a little bit less permeability(see Fig.9)

Very Low Permeable High-Performance Concrete

The study on the water permeability of concrete had been mainly conducted in 1930's to 1940's and the coefficient of permeability of concrete has the range as follows: typically, the permeability coefficients for moderate-strength concrete (containing nominal 38-mm maximum size aggregate, 365 kg/m^3 cement content and 0.5 water to cement ratio), and low-strength concrete (75-mm size aggregate 148 kg/m^3 cement content, and 0.75 water to cement ratio) are of the order of 1×10^{-12} and 30×10^{-12} m/sec, respectively.(7) Also, from the permeability data of some natural rocks and cement pastes, the coefficient of permeability of most marble, traprock, diorite, basalt, and dense granite may range from 1 to 1×10^{-14}m/sec, as illustrated in Table.9.(8) The permeability of mortar or concrete is higher than that of the corresponding cement paste because of the microcracks that are present in the interface zone between the aggregate and cement paste.(9)

Therefore, from other researchers' results, the permeability coefficient of low permeable concrete has the range of 1 to 1×10^{-14} m/sec and it is thought that this is a limited value which conventional permeability test method can estimate. A illustrated in Table.10(10) that compares the chloride-ion penetration test result with the coefficients of permeability, the concrete which has total charge passed Less than 1000C can be classified as very low permeabilily concrete.

The test results of present study are summarized in Table.11 and the order of permeability is arranged in sequence The present study proposes very low permeable high-performance concrete whose permeability is about 1/100 of conventional normal concrete, as shown in Table.11. Therefore, this paper provides a firm base for the use of very low permeable and hence high-durable concrete in actual structures

CONCLUSION

The principal findings from the results of this paper with respect to permeability of high performance concrete may be summarized as follows.

1) The conventional lest method can not be directly applied to measure the permeability of high-performance concrete which has dense microstructure and very low permeability Therefore, the chloride-ion penetration test has been conducted in this study that is simple and realistic to apply to high-strength and high-performance concrete.

2) It is found that chloride-ion permeability decreases as water to binder ratio decreases

3) The concrete containing silica fume showed the best performance in permeability test because it has very dense microstructure due to finer particles of silica fume than any other cementitious materials. In particular, the chloride permeability of high-strength concrete containing silica fume is almost negligible.

4) The chloride permeability of Type I (ordinary portland) cement is found to be slightly less than that of Type V (sulfate-resisting) cement

5) The concrete containing fly ash also shows good performance in permeability test. The chloride permeability of concrete with 15% fly ash contents is about 20% of that of normal concrete without fly ash addition.

6) The replacement of cement with blast-furnace slag also decreases permeability. The chloride permeability of the concrete with 25% slag contents is about 1/3 of that of normal concrete, even though the strength is about the same at 28 days

7) The variations of air content and size of aggregates do not have a great influence on permeability. The concrete with larger size aggregates shows slightly less permeability.

8) In order to improve the resistance to chloride permeability, it is effective to decrease water to binder ratio, but it is more effective to determine and use the appropriate type and amount of mineral admixtures.

9) Finally, the present study proposes very low permeable high performance concrete whose permeability is about 1/100 of that of conventional normal concrete. This paper provides a firm base for the use of very low permeable and hence high durable concrete in severe environments.

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Table 1. Mixture Properties of Concrete

Teat Series		Cement (kg/m³)	Admixture			Water (kg/m³)	Sand (kg/m³)	Gravel (kg/m³)	AE Admixture (C×%)	HRWR (C×%)
			fly ash	silica fume	slag					
Gravel size 19mm	N1-0-0	380	-	-	-	164	850	1040	-	1.7
	N1-F15-0	323	57	-	-	164	850	1040	-	1.5
	N1-F30-0	266	114	-	-	164	850	1040	-	1.2
	N1-F15-0.04	323	57	-	-	164	850	1040	0.04	1.3
	N1-S10-0	342	-	38	-	164	850	1040	-	1.4
	N1-S20-0	304	-	76	-	164	850	1040	-	1.5
	N1-S10-0.04	342	-	38	-	164	850	1040	0.04	1.5
	N1-B12.5-0	332.5	-	-	47.5	164	850	1040	-	1.8
	N1-B25-0	285	-	-	95	164	850	1040	-	1.7
	N1-F15,S10-0.04	285	57	38	-	164	850	1040	0.04	1.6
Gravel size 25mm	N1-0-0	380	-	-	-	164	850	1040	-	1.9
	N1-F15-0.04	323	57	-	-	164	850	1040	0.04	1.4
	N1-S10-0.04	342	-	38	-	164	850	1040	0.04	1.5
	N1-F15,S10-0.04	285	57	38	-	164	850	1040	0.04	1.5
Gravel size 19mm	H1-0-0	550	-	-	-	154	609	1142	-	1.8
	H1-F15-0.04	467.5	82.5	-	-	154	609	1142	0.04	1.7
	H1-S10-0.04	495	-	55	-	154	609	1142	0.04	1.7
	H1-F15,S10-0.04	412.5	82.5	55	-	154	609	1142	0.04	1.6
	N5-0-0	380	-	-	-	164	850	1040	-	1.2
	N5-F15-0.04	323	57	-	-	164	850	1040	0.04	0.6
	N5-S10-0.04	342	-	38	-	164	850	1040	0.04	0.8
	N5-B12.5-0	332.5	-	-	47.5	164	850	1040	-	1.0

Table 2. Chemical Properties of Cement

Cement Type	Chemical Properties (%)											
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_4	Ig. loss	Na_2O	K_2O	F-CaO	T-Alkali	Cl
I	21.0	6.4	3.1	61.3	3.0	2.1	1.6	0.12	0.78	1.1	0.63	0.0120
V	22.7	4.1	4.4	62.7	2.7	1.9	0.9	0.11	0.55	0.5	0.48	0.0065

Table 3. Physical Properties of Cement

Cement Type	Finess		Setting Time		Heat of Hydration (cal/g)		Compressive strength (kg/cm²)				Specific gravity	Autoclave expansion (%)
	Blaine (cm²/g)	44μ (%)	Initial (min)	Final (hr)	3day	7day	1day	3day	7day	28day		
I	3228	9.7	254	6:40	70	80	98	211	281	375	3.15	0.11
V	3169	4.0	285	7:37	55	65	74	182	259	364	3.15	0.03

Table 4. Properties of Blast-Furnace Slag

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Blaine
34.4 %	15.9 %	0.6 %	41.3 %	6.2 %	3886 cm²/g

Table 5. Properties of Fly ash

SiO_2	Moisture	Ig. loss	Specific gravity	Blaine (cm²/g)	Water requirement	Strength activity index % of control (28day)
63 %	0.06 %	3.5 %	2.15	3166	100 %	92

Table 6. Chemical Properties of Silica Fume

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	C	K_2	N_2
97 %	0.3 %	0.07 %	0.23 %	0.7 %	0.9 %	0.1 %	0.4 %

Table 7. Strength Properties for Various Mixtures

Test Series \ Strength(MPa)	Compressive Strength		Splitting Tensile Strength	Flexural Strength	Remarks
	7days	28days	28days	28days	
N1-0-0	337	431	44	51	Gravel size 19mm
N1-F15-0	270	433	48	48	
N1-F30-0	262	335	34	48	
N1-F15-0.04	305	430	38	55	
N1-S10-0	449	525	68	80	
N1-S20-0	550	630	50	63	
N1-S10-0.04	403	511	69	79	
N1-B12.5-0	292	429	46	61	
N1-B25-0	327	426	48	59	
N1-F15.S10-0.04	399	539	54	78	
N1-0-0	301	420	32	43	Gravel size 25mm
N1-F15-0.04	308	360	37	49	
N1-S10-0.04	378	503	50	71	
N1-F15.S10-0.04	340	515	48	67	
H1-0-0	372	590	50	67	Gravel size 19mm
H1-F15-0.04	341	645	49	74	
H1-S10-0.04	516	724	64	87	
H1-F15.S10-0.04	415	593	54	81	
N5-0-0	285	389	56	62	
N5-F15-0.04	236	331	52	59	
N5-S10-0.04	307	443	54	69	
N5-B12.5-0	270	383	45	49	

Table 8. Chloride-ion Penetrability Based on Charge Passed

Charge Passed (Coulombs)	Chloride Ion Penetrability
> 4000	High
2000 ~ 4000	Moderate
1000 ~ 2000	Low
100 ~ 1000	Very Low
100 >	Negligible

Table 9. Comparison between Pemeabilities of Rocks and Cement Pastes

Type of Rock	Coefficients of permeability (m/sec)	W/C ratio of matyre paste of the same permeability
Dense Trap	2.47×10^{-14}	3
Quartz diorite	8.24×10^{-14}	42
Mable 1	2.39×10^{-13}	48
Mable 2	5.77×10^{-12}	66
Granite 1	5.35×10^{-11}	70
Sandstone	1.23×10^{-10}	71
Granite 2	1.56×10^{-10}	71

Table 10. Comparison of Chloride-ion Penetration Test Results with Permeability Coefficients

Permeabilituy characteristics	Other researcher's permeability test	Chloride-ion penetration test	Test series in this study
W/C ratio Cement content Permeability	30 % 550 kg/m^3 2.8×10^{-14} m/sec	28 % 550 kg/m^3 1891 C	H1-0-0
W/C ratio Cement content Permeability	40~50 % - $1\sim2\times10^{-13}$ m/sec	43 % 380 kg/m^3 2312 C	N1-0-0

Table 11. Grading of Chloride-ion Penetration

ASTM Specification		Test Series	Currents (Coulomb)
Chloride-ion Penetrability	Currents (C)		
Negligible	< 100	H1-F15,S10-0.04 H1-S10-0.04	79 95
Very Low	100~1000	N1-S20-0 N1-S10-0.04(25*) N1-F15,S10-0.04(25*) N1-S10-0 N1-S10-0.04 N1-F15-0.04(25*) N1-F15,S10-0.04 N1-F15-0 N1-F30-0 N1-F15-0.04 N1-B25-0	144 297 302 465 503 535 544 565 597 707 967
Low	1000~2000	H1-F15-0.04 N1-B12.5-0 H1-0-0	1048 1572 1891
Moderate	2000~4000	N5-S10-0.04 N1-0-0(25*) N1-0-0 N5-B12.5-0 N5-F15-0.04 N5-0-0	2048 2312 2766 2897 2919 3453
High	4000 <	N21**	7960

* : Size of aggregate is 25mm(other specimen : 19mm)
**:Normal concrete mixture(design strength 21MPa)

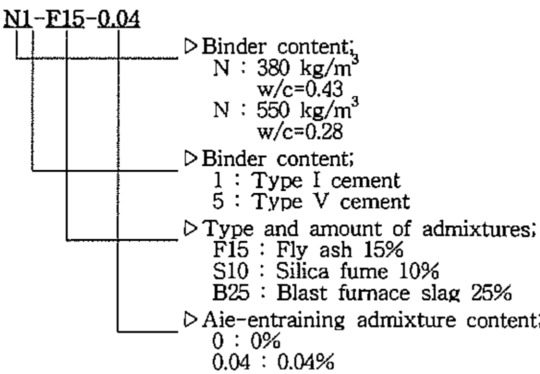

Fig 1. Explanation of Variables of Specimen

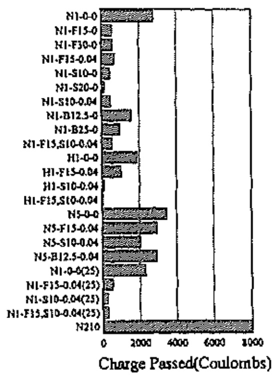

Fig. 10 Total Charges Passed for Various Test Series

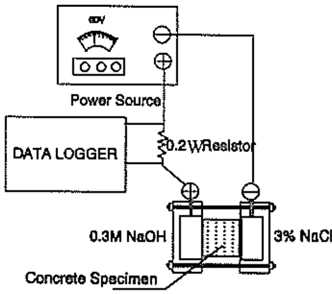

Fig. 2 Test Configuration

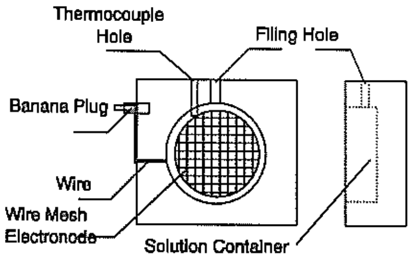

Fig. 3 Applied Voltage Cell

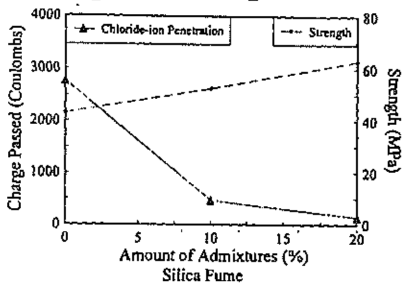

Fig. 4 Relationship between Strength and Penetrability According to Use of Silica Fume(cement contents:380kg/m^3)

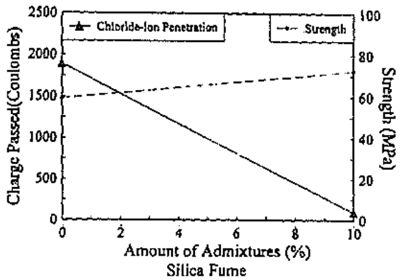

Fig. 5 Relationship between Strength and Penetrability According to Use of Silica Fume(cement contents:550kg/m^3)

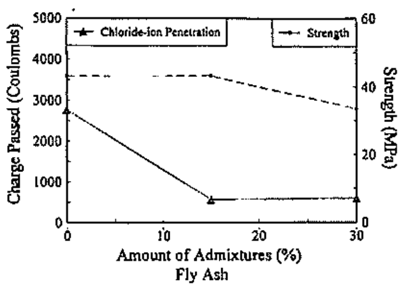

Fig. 6 Relationship between Strength and Penetrability According to Use of Fly Ash(cement contents:380kg/m^3)

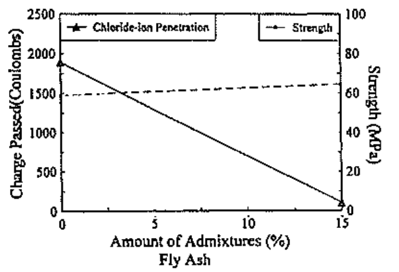

Fig. 7 Relationship between Strength and Penetrability According to Use of Fly Ash(cement contents:550kg/m^3)

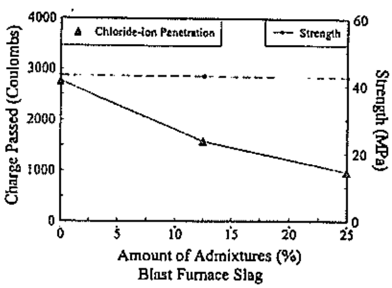

Fig. 8 Relationship between Strength and Penetrability According to Use of Blast-Furnace Slag(cement contents: 550kg/m^3)

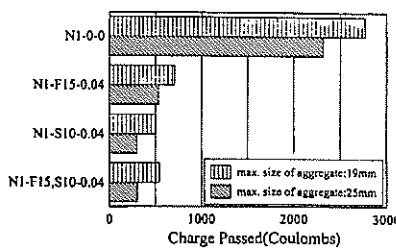

Fig. 9 Permeability According to Size of Aggregate