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STUDY ON PROPERTIES OF HARDENED HIGH-PERFORMANCE CONCRETE STRIPPED AT AN EARLY AGE

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High-Performance Concrete, which was developed by a group of the University of Tokyo, was originally designed with a low water-cement ratio to ensure self-compactability. Consequently, this concrete can be expected to offer adequate performance in the hardened state for ordinary concrete structures, even if it is not well cured. In this study, systematic experiments are carried out in order to evaluate the durability of hardened High-Performance Concrete when it is stripped early. Its applicability in situations where early form-removal is required is discussed based on the experimental results.

Keywords : High-Performance Concrete, avoidance of curing, durability of concrete

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1. INTRODUCTION

High-Performance Concrete (HPC), which was developed for the purpose of improving the reliability of concrete structures, requires no vibrating operation because it is self compacting. Consequently, this concrete is not affected by the quality of the concreting work. HPC is highly resistant to initial defects arising as a result of heat generation by the cement and drying shrinkage. Its oxygen permeability is also low, as is that of water which causes corrosion of reinforcing bars embedded in the concrete[1]. In terms of mix proportion, HPC is characterized by low water-cement ratio and a large amount of powder material; both characteristics are necessary for self-compactability, which is the most important virtue of this concrete. As a result, its properties as regards heat generation and shrinkage must be strictly controlled as compared with conventional concrete[1][2]. Nevertheless, if cured by ordinary methods used with conventional concrete under normal environmental conditions, this concrete can be expected to have better-than-required performance in areas such as strength and permeability because of its dense pore structure.

The properties of hardened concrete generally depend not only on the mix but also on curing conditions. Since formwork protects most of the concrete — aside from the cast surface — against drying, the time of form-removal is a substantial factor in the curing conditions of actual structures. If the formwork is removed at an early age, the performance of the hardened concrete cannot fully developed to the level obtained under good curing conditions. On the other hand, it is also true that hardened concrete retains a certain potential if cured under less than ideal curing conditions. Even in a case where the potential of the concrete is only partly developed, it is possible to make practical use of it as long as its qualities exceed the required level. A concrete with good potential may make this possible.

HPC has high potentiality after hardening. If it could be shown possible to remove formwork earlier and simplify the curing operation, construction process would be further rationalized; for instance, less labor would be needed from casting to curing and the costruction period could be reduced.

In order to realize a construction method in which the curing process is simplified or even eliminated altogether, it is necessary to establish a technology capable of predicting the properties of hardened concrete from a given set of concrete materials, the mix proportion, and the curing conditions. It must be possible to judge in advance whether these properties satisfy the requirements[1]. Since the quality of the concrete at the surface of a structure is greatly affected by curing conditions, an investigation of durability properties is particularly important. Although some investigations of individual properties have been reported as regards the quantitative relationship between concrete materials, mix proportions, curing conditions, and concrete properties[3], there have been few efforts so far in which the various properties are systematically investigated and durability is synthetically discussed.

The purpose of this research is to synthetically investigate the possibility of early form-removal and simplified curing operations using HPC, mainly from the viewpoint of durability. In this paper, strength, drying shrinkage, drying shrinkage cracks, carbonation, chloride penetration, and freezing and thawing are examined. The behavior of these properties when formwork is removed at an early age is discussed based on the results of systematic experiments.

2. OUTLINE OF EXPERIMENTS

1.1 Concrete Used in Experiments

Two types of HPC and one conventional concrete with a water-cement ratio of 55% were used in the experiments. The two HPCs were MS, whose powder phase comprises mainly moderate-heat portland cement, and S6, in which 60% of the powder phase is replaced by blast furnace slag. These two HPCs are self-compacting. They are designed, in this study, with equal water-powder ratios in volume, and equal unit water, unit sand, and unit gravel contents so as to allow

Table 1 Mix Proportion and Properties of Fresh Concrete Used in the Experiments

Name of Mix Prop.	Water Cement Ratio [%]	Max. Agg. Size [mm]	Air Content [%]	Unit Weight [kg/m³] W	C	MC	L18	S6	S	G	Ad.1	Ad.2	Slump [cm]	Slump -Flow [cm]	Funnel Test[1]	Initial Set [hr-m]	Final Set [hr-m]
MS	35.5	20	3.5	172	–	513	28	–	828	827	8.12	0.03	–	56.5	1.58	9-11	11-09
S6	55.8	20	3.5	172	–	308	17	200	828	827	7.88	0.02	–	51.0	1.28	–	–
OP	55.0	20	4.5	165	200	–	–	–	927	924	0.75	0.0099	8.5	–	–	–	–

Note) Ad.1 : superplasticizer in MS and S6 and AE admixture in OP, Ad.2 : air adjustment admixture.

Table 2 Properties of Materials

Notation	Name	Specific Gravity	Blaine Value etc.
MC	Moderate-Heat Cement	3.17	Blaine 3200[cm²/g]
C	Ordinary Portland Cement	3.15	Blaine 3300[cm²/g]
L18	Limestone Powder	2.68	Blaine 18000[cm²/g]
S6	Blast Furnace Slag	2.91	Blaine 6000[cm²/g]
S	Sand	2.62	River Sand, Absorption 1.54[%], Solid Volume 70[%], F.M. 3.01
G	Gravel	2.71	Crushed Stone, Absorption 0.6[%], Solid Volume 61[%], F.M. 6.85

Table 3 Test Subjects and Curing Conditions

Mix Form-Removal	MS 16th hr	MS 2nd day	MS 7th day	S6 2nd day	S6 7th day	OP –
Compressive Strength	○	○	–	○	–	◎
Drying Shrinkage	○	○	○	○	○	△
Drying Shrinkage Crack	○	○	○	○	○	△
Carbonation	○	○	○	○	○	△
Chloride Penetration	○	○	○	○	○	△
Freezing and Thawing	–	○	–	○	–	▽

Note) ◎: Curing in Water, △: Stripped at the 7th day, ▽: Stripped at the 2nd day.

investigations of the effect of mix proportion and curing conditions on the concrete properties. Conventional OP concrete was used for the purpose of comparison. Mix proportions and test results for the fresh concrete are shown in Table 1. The properties of the materials used are shown in Table 2.

2.2 Curing Conditions

The curing conditions were controlled by altering the age at which the formwork was removed. After casting and up till form-removal, the concrete was protected from both drying and wetting by polyethylene sheeting. The concrete age at form-removal was basically 16 hours, 2 days, and 7 days for MS concrete, whose base cementitious material is moderate-heat cement, and 2 days and 7 days for S6 concrete, which contains blast furnace slag. After form-removal, specimens were kept in a room at a temperature of about 20℃ and a relative humidity of about 60%. These conditions were chosen based on a consideration of the mean climate of Japan. For conventional OP concrete, which was tested for comparison purposes, the formwork was in principle removed at 7 days. The various combinations of test subjects and curing conditions are shown in Table 3.

2.3 Test Subjescts and Procedure

a) Compressive Strength
Specimen size was ϕ 10x20cm. The compressive strength of concrete is not only representative mechanical property but also provides an index for the time of formwork removal. Besides tests to investigate the effects of curing conditions on compressive strength, strength development within the formworks was also examined[4].

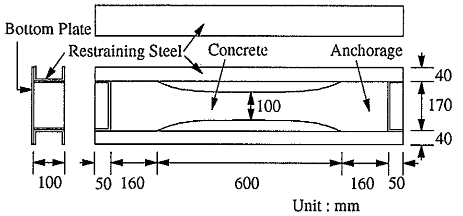

Fig.1 Testing Apparatus of Restrained Shrinkage Crack

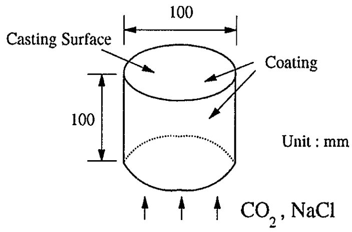

Fig.2 Specimen for Carbonation and Chloride Penetration

b) Drying Shrinkage
Specimen size was 10x10x40cm. After form-removal at the designated age, specimens were exposed to drying conditions in the temperature-controlled room with a temperature of about 20℃ and a relative humidity of about 60%. Time-dependent weight changes and shrinkage strain were measured. Strain was measured using contact gages.

c) Characteristics of Drying Shrinkage Cracks
A test apparatus for drying shrinkage cracks as proposed by JIS was used (Fig.1)[5][6][7]. After form-removal (removal of the bottom plate) at the designated age, specimens were dried in the temperature-controlled room. Strain on the restraining steel plate was measured until cracking.

d) Carbonation
Specimen size was ϕ 10x10cm (Fig.2). After form-removal at the designated age, specimens were coated with a rubber-type bonding material on all except their bottom surfaces. They were cured in the temperature-controlled room until the 28th day and then in a temperature-and humidity-controlled chamber at a temperature of 40℃ and a relative humidity of 40% from the 28th day until the 42nd day. From the 42nd day on, specimens were exposed on environment of 40℃ temperature, 40% relative humidity, and 10% carbon dioxide in the chamber for a further 28 days. Finally, they were taken from the chamber and cut along the casting direction using a concrete cutter. 1% phenol phthalein solution was sprayed onto the cut surface. The width of the portion which did not turn red was measured[8].

e) Chloride Penetration
Specimen size, the method of coating, and the curing conditions until the 42nd day were common with the carbonation test (Fig.2). From the 42nd day on, specimens were exposed to a salt-water spray at 35℃ and 5% sodium chloride and, in turn, to an atmosphere of 40℃ and 40% relative humidity, for 7 days each until the 70th day. After that, the samples were cut along the casting direction. Fluorescein and silver nitrate were sprayed onto the cut surface. The width of the portion which turned white was measured.

f) Freezing and Thawing
Specimen size was 10x10x40cm. The test method conformed to the JIS method. The arrangement of test cases differed from other the other tests[9]. The amount of air entrained in the MS and S6 concrete was varied using an admixture. Formwork was removed 2 days after casting in all cases. Specimens were cured in a room at a temperature of about 20℃ and a relative humidity of about 60% until the 28th day. Some were cured in water. The measured air content of the fresh concrete was 2.8% and 5.2% in MS, 2.9% in S6, and 4.5% in OP.

3. STRENGTH DEVELOPMENT

3.1 Strength at Form-Removal

Before the formwork can be removed, the concrete must be at least be strong enough to support

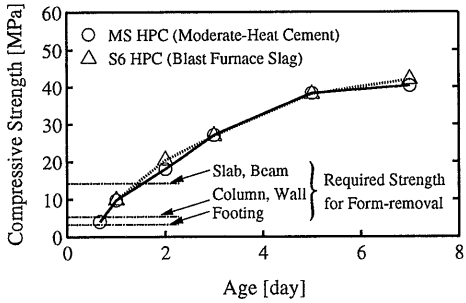

Fig.3 Strength Development of Concrete in Mold

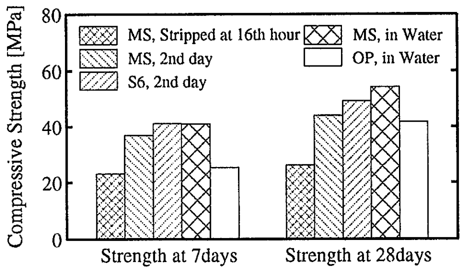

Fig.4 Strength of Concrete Stripped at an Early Age

the dead load of the structure and any applied load resulting from construction work[10]. Strength development at an early age was investigated first. Figure 3 shows the development of compressive strength of MS and S6 concrete until the 7th day while in the mold[4]. The strength development of these two concretes is almost identical. If we consider the age at which formwork can be removed from the viewpoint of dead load and load applied during construction, based on the design specifications for concrete structures[10], it is possible to remove the formwork after 16 hours (in the case of MS concrete) at the surfaces of footings, after one day for columns and walls, and after two days for slabs.

3.2 Strength after Form-Removal

The compressive strength of MS and S6 concrete at the 7th day and the 28th day in the case of early stripping is shown in Fig.4. For comparison, the compressive strength of MS and OP concrete cured in water is also shown in the figure. HPCs are designed with a low water-powder ratio to comply with the requirement for self-compactability. Consequently, when hydration of the cement ideally proceed in water, 54.1 MPa of compressive strength at the 28th day was obtained for MS concrete. When formwork was removed on the 2nd day, the compressive strength on the 28th day was 43.8 MPa for MS concrete and 49.1 MPa for S6 concrete. Thus, if formwork is removed early, the compressive strength after hardening is lower compared with the case of curing in water. However, it is still possible to use these concretes in normal concrete structures. MS concrete stripped at 16 hours showed 26.3 MPa in compressive strength at the 28th day, which is a useable strength for some actual structures.

These compressive strength measurements were all obtained using ϕ 10x20cm specimens. In the case of an actual structure, water evaporates less rapidly from inside the structure as compared with the surface layer. Even if the formwork is removed at an early age, hydration of cement deep within the concrete can proceed without being affected by evaporation. Thus the strength of concrete inside the structure will develop better than indicated by the test results reported here. Therefore, there should be no serious concern in using these concretes after early form-removal taking into account the strength required to obtain adequate structural performance. More important are the properties relating to durability, which imperfections in hydration at the surface have a direct effect on. These are discussed in the next chapter and beyond.

4. PROPERTIES RELATING TO DURABILITY

4.1 Drying Shrinkage

In order to discuss the quality of concrete as it relates to structure durability based on the test results, it is necessary to clarify the relation between the test results and the durability of actual concrete structures made of that concrete. In other words, it is essential to establish a general

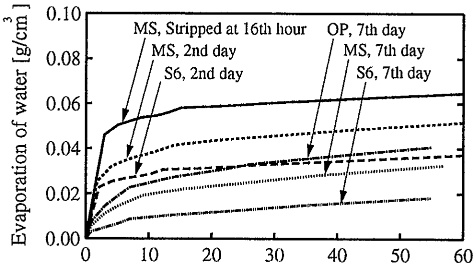

Fig.5 Relationship between Drying Time and Evaporation of Water

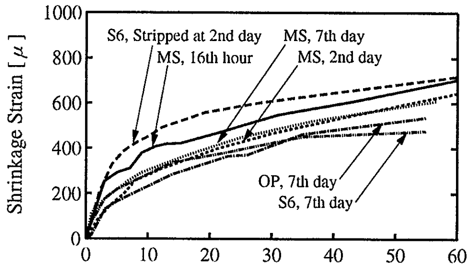

Fig.6 Relationship between Drying Time and Shrinkage Strain

estimation system for structure durability which takes into account the shape and size of the structure, boundary conditions, and environmental conditions; this will enable the test results of concrete specimens to be efficiently used[11]. However, such a generalized estimation system able to predict the occurrence of cracks and the penetration of deterioration has not been developed as yet. Thus, in this study, the quality of HPC stripped at an early age is compared with that of conventional concrete with a 55% water-cement ratio cured by standard curing conditions.

Figure 5 shows the relationship between drying time and amount of evaporated water. Figure 6 shows the relationship between drying time and shrinkage strain. In these figures, amount of evaporated water and shrinkage strain reach zero when the drying time is zero. The evaporation of water is more pronounced in cases where form-removal was earlier. Large shrinkage strain at an early stage was observed in the case of MS concrete stripped at 16 hours and S6 concrete stripped on the 2nd day. In other cases, including conventional OP concrete, the relationships between drying time and shrinkage strain were little different from each other. The observed shrinkage strain in S6 concrete, which contains blast furnace slag, varied remarkably with the age at form-removal. The authors believe that this is because of hardening shrinkage, which is a volumetric change independent of drying[2][12]. In this experiment, strain at the time of form-removal was defined as zero. Therefore, if there is any time-dependent deformation which is not directly due to drying, this will have a progressively greater effect on the observed shrinkage as form-removal takes place earlier. The behavior demonstrated in these experimental results can be understood if it is assumed that S6 concrete, which contains blast furnace slag, has a large hardening shrinkage.

4.2 Drying Shrinkage Cracks

Figure 7 shows the relationship between drying time and average stress in a concrete cross section induced by restraint plates. The points where the stress is released in the figure correspond to the occurrence of cracking. In this test, cracking occurs after about several days or weeks of drying in most cases[6]. The number of days until cracking occurs can be regarded as an the index representing the concrete's characteristic of drying shrinkage cracking under restraint conditions.

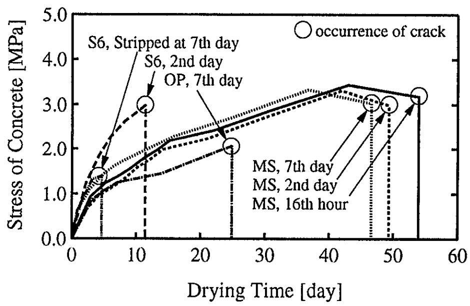

Fig.7 Results of Restrained Shrinkage Crack Test

An overview of these test results shows that the number of days until cracking occurred was more greatly affected by the materials used than by the difference in age of form-removal. In the case of MS concrete, cracks occurred after about 50 days of drying in spite of differences in age at form-removal. With S6 concrete, cracks occurred after about 10 days. Conventional OP concrete which was tested for the purpose of comparison, cracked at the 27th day — thus falling mid-way between MS concrete and S6 concrete under these experimental conditions.

As to the reason for S6 concrete, which contains blast furnace slag, cracking after less drying time, the authors are considering the possibility that either hardening shrinkage before drying was large[2][12] or that this concrete might have brittle characteristics under tensile stress due to crystallization of the slag.

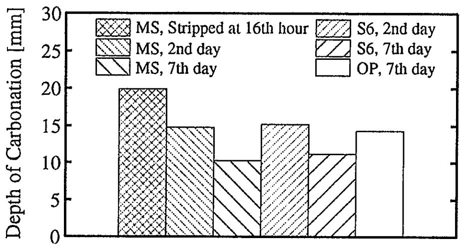

Fig.8 Results of Carbonation Test

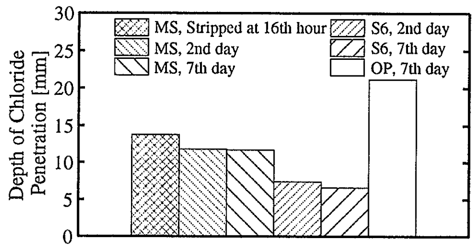

Fig.9 Results of Chloride Penetration Test

4.3 Carbonation

Figure 8 shows the depth of carbonation. The resistance to carbonation of MS and S6 concretes was similar. In both cases, the resistance fell as form-removal took place. The depth of carbonation of these concrete stripped at the 2nd day was almost equal to that of conventional OP concrete stripped at the 7th day.

4.4 Chloride Penetration

Figure 9 shows the depth of chloride penetration. It is clear as with the results for carbonation, that chlorides penetrate deeper as form-removal takes place earlier. However, the differences among the various cases are smaller compared with carbonation. Both MS and S6 concrete had higher resistance to chloride penetration than conventional OP concrete. Even when stripped at 16 hours, MS concrete had better resistance than conventional concrete stripped at the 7th day. As far as resistance to chloride penetration is concerned, S6 concrete, which contains blast furnace slag, is slightly superior to MS concrete.

4.5 Freezing and Thawing

Figure 10 shows the relationship between the number of freeze-thaw cycles and relative dynamic modulus of elasticity[9]. Where MS concrete containing a small amount of air (measured air content : 2.8%), S6 concrete containing a small amount of air (measured air content : 2.9%), and conventional OP concrete (measured air content : 4.5%), specimens which had been stripped at the 2nd day and cured in the air deteriorated within 100 cycles of freezing and thawing.

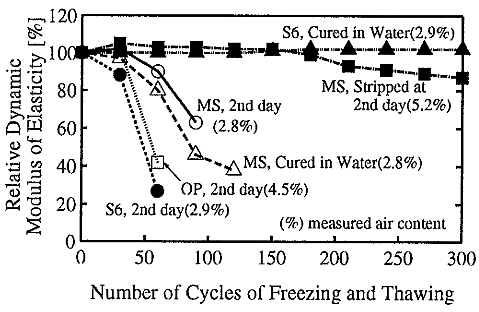

Fig.10 Results of Freeze-Thaw Test

In this series of MS and S6 concrete with a small amount of air, specimens which had been cured in water were also tested for comparison purposes. Resistance to freezing and thawing of MS concrete was not improved by changing the curing method. Results for MS concrete cured in water were little different from those for air curing. On the other hand, S6 concrete proved to have high resistance to freezing and thawing in spite of an air content of only 2.9%. Although the reason for this has been investigated in a previous paper[9] from the viewpoint of pore structure, void structure, and strength, it is still unresolved at this stage. However, this test result implies that some properties of concrete containing blast furnace slag are remarkably improved when it is cured under good conditions.

MS concrete cured in air and with a measured air content of 5.2% was also tested. If it contains an adequate amount of air, MS concrete proved to have adequate resistance to freezing and thawing even when stripped at the 2nd day and thereafter cured in air. Compressive strength in this case (measured air content : 5.2%) was 49.4 MPa, which is little different from that of MS concrete used in the other tests in this study (measured air content : 4.2%). Differences in air content within this range will, therefore, not degrade other qualities of the concrete.

5. DISCUSSION ON CONSTRUCTION USING HIGH-PERFORMANCE CONCRETE STRIPPED AT AN EARLY AGE

5.1 General Assessment of Qualities of Hardened Concrete

Figure 11 shows a comparison of the qualities of hardened MS and S6 HPCs stripped at an early age and conventional OP concrete cured under ideal conditions. Results for drying shrinkage, depth of chloride penetration, and depth of carbonation are given as reciprocals so that distance from the origin represents superiority in each property.

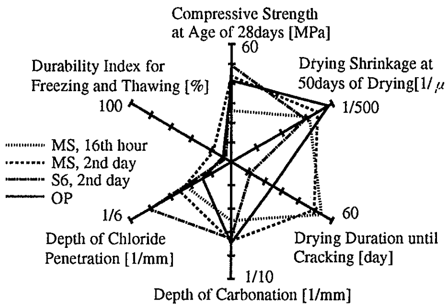

Fig.11 Performance of Concrete Stripped at an Early Age

MS HPC, whose base cementitious material is a moderate-heat cement, has similar or better qualities as regards compressive strength, drying shrinkage, drying shrinkage cracks, carbonations, and chloride penetration than conventional OP concrete cured under good conditions when stripped at the 2nd day and thereafter cured under non-ideal conditions. Although it is not shown in this figure, it was also proved that this concrete has adequate resistance to freezing and thawing, as a result of its air content, even when stripped at the 2nd day. When stripped 16 hours after casting, this concrete is inferior to conventional concrete in compressive strength and resistance to carbonation.

S6 HPC, which contains blast furnace slag, tends to suffer from drying shrinkage cracks whatever the age at form-removal. Even when stripped at the 2nd day, this concrete has the same level of quality as conventional concrete cured under good conditions as regards compressive strength, drying shrinkage, carbonation, and chloride penetration.

5.2 Discussion on Application to Actual Structures

HPC, through not requiring compaction, has a similar quality as properly compacted conventional concrete. On the contrary, if it is vibrated, it will sometimes segregate. In other words, not vibrating it is the best and most positive method of extracting the full potential of HPC. As far as curing is concerned, however, it is true that better curing can develop the potential of the concrete further and that worse curing degrades the qualities of the concrete. Therefore, curing must not be ignored without fully quantifying the performance of the concrete even if is a high-performance concrete under good curing conditions and skipping curing would be beneficial to the construction process. The authors consider, however, that this study should be taken as a first step toward quantification of the qualities of HPC when the curing conditions are varied.

All experiments in this study were carried out inside the laboratory. Specimens and the number of tests were also limited. Although a deeper and wider-ranging investigation is necessary in order to theoretically obtain a more general conclusion as regards application to actual structures, the results reported here suggest the following possibilities.

Structures with adequate durability if constructed with conventional concrete with water-cement ratio of 55% and cured under standard conditions, — normal concrete structures in other words, — would suffer from no problems of strength, drying shrinkage, drying shrinkage cracks, carbonations, chloride penetration or freezing and thawing if constructed with MS HPC, stripped 2 days after casting and not thereafter cured. If stripped 16 hours after casting, this concrete would be slightly inferior to conventional concrete as regards performance after hardening. Nevertheless, it can be applied to structures in which high durability is not required, since the loss is small.

S6 HPC, which contains blast furnace slag, can be used in structures which would be little affected by drying shrinkage cracks even if stripped at an early age. However, since one of the advantages of using blast furnace slag is its good resistance to freezing and thawing when well cured, this concrete should only be used where good curing can be expected so as to make full use of the advantages of the material.

In this study, experiments were carried out based on the assumption that curing was completely omitted after early form-removal. Instead of completely dropping curing, simplified methods, such as reducing the period of water spraying, could be applied in reality. It is obvious from the experimental results given here that higher quality could then be expected than in case where no curing tkes place. This would widen the range of application.

Further studies need to focus on deeper and wider-ranging investigations related to the quantification of concrete quality when the curing conditions are varied. On the other hand, it is essential to establish an estimation system which can predict the durability of structures from the properties of the concrete and the environmental and structural conditions.

6. CONCLUDING REMARKS

In this study, systematic experiments were carried out on properties of two types of HPC which were stripped at an early age and then not cured. The possibility of a construction procedure involving early form-removal and omission or simplification of curing was discussed based on the experimental results. The following conclusions can be drawn from this study.

(1) The two types of HPC used in this study are both of high enough strength for use in normal structures even if stripped 2 days after casting and then not cured further.

(2) An HPC based on moderate-heat cement, when stripped at the 2nd day, has similar or better qualities than conventional OP concrete with a water-cement ratio of 55% cured under good conditions as regards compressive strength, drying shrinkage, drying shrinkage cracks, carbonation, and chloride penetration. It also has adequate resistance to freezing and thawing since it contains enough amount of air even when stripped at the 2nd day.

(3) An HPC containing blast furnace slag tends to suffer from drying shrinkage cracks whatever the curing conditions. When stripped at an early age, its compressive strength, drying shrinkage, carbonation, and chloride penetration are similar to the HPC based on moderate heat cement. When cured under good conditions, its resistance to freezing and thawing is significantly improved.

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