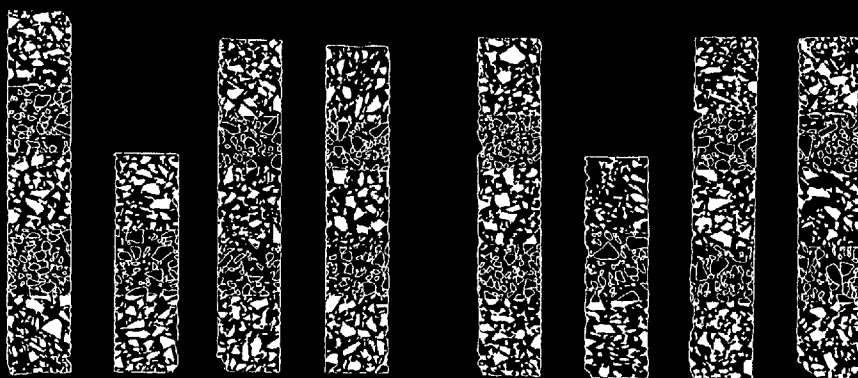
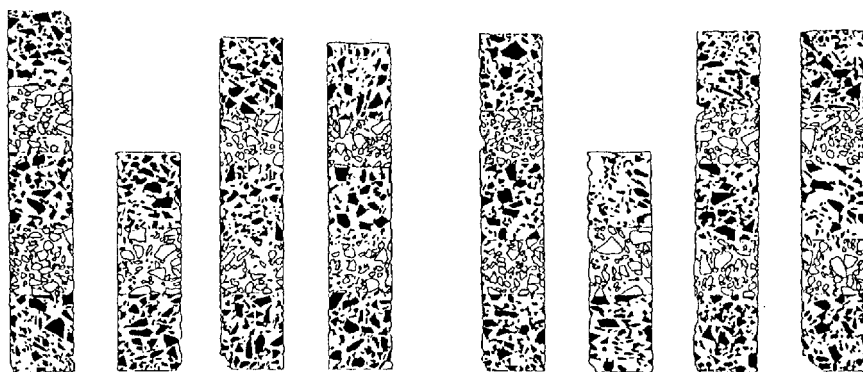


High Performance Concrete in Severe Environments



Paul Zia
Editor

High Performance Concrete in Severe Environments



Paul Zia
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PREFACE

Many recent innovations in advanced concrete materials technology have made it possible to produce concrete with exceptional performance characteristics. Recognizing the need to encourage the development of such high performance concrete technology and to expedite its transfer into practice, the ACI Technical Activities Committee formed a Subcommittee on High Performance Concrete (THPC) in 1992.

High performance concrete is defined by THPC as concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and normal mixing, placing, and curing practices. The requirements may involve enhancements of placement and compaction without segregation, long-term mechanical properties, early-age strength, toughness, volume stability, or service life in severe environments.

The Symposium on High Performance Concrete in Severe Environments held at the ACI Fall Convention in Minneapolis, Minnesota on November 9, 1993, is the first formal activity organized by THPC. Cosponsored by RILEM, the symposium emphasizes field applications rather than laboratory studies of high performance concrete.

This volume contains 14 papers, of which 13 have been scheduled for presentation at the symposium. The wide variety of topics includes long-span bridges, highway pavements, high-rise building structures, dam rehabilitation, underwater constructions, nuclear facilities, and mixture design methodology, all illustrating useful and successful applications of high performance concrete in severe environments.

I would like to thank all authors for their enthusiastic support of the symposium and for their cooperation in meeting a very tight publication schedule. Many members of the THPC also responded promptly to my requests for help in reviewing the manuscripts. Without such cooperation and the dedication of the ACI editorial staff, it would not have been possible to schedule the publication of this volume concurrently with the symposium presentations.

Finally, I extend my sincere appreciation to H.S. Lew and Henry G. Russell who served with me as the organizing committee for this symposium. It is our hope that the success of this symposium will help encourage more use of high performance concrete.

Paul Zia
Chairman, ACI TAC Subcommittee
on High Performance Concrete

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High Performance Concrete in Florida Bridges

by J. Armaghani, D. Romano,
M. Bergin, and J. Moxley

Synopsis: A high performance concrete (HPC) mixture was developed in the laboratory and later used in a bridge construction project. The HPC mixture was designed based on 752 lbs (341 kg) of cement with 0.33 water to cement ratio. The weight of the cement was partially replaced by fly ash (20%) and silica fume (8%). The concrete mixture incorporated 4.5 gal/yd³ (22.3 L/m³) of calcium nitrite corrosion inhibiting admixture. Other chemical admixtures included air entraining agent, and/or standard and high range water reducing/retarding admixtures. A wide range of field and laboratory tests were performed on fabricated concrete specimens, as well as on cores from field models and newly cast bridge members. The main tests included field and laboratory testing of permeability, and compressive strength. Results of tests on laboratory and field concrete were very close. The chloride permeability (AASHTO T277) of the HPC was very low, ranging between 618 to 1055 coulombs. The compressive strength was high, ranging between 8600 to 10670 psi (59 to 74 MPa). This study shows that laboratory produced HPC with multiple cementitious materials and chemical admixtures can be successfully implemented in construction without compromising its durability. It is also demonstrated that sacrificial concrete models cast and cured at the job site can provide accurate evaluation of the durability and performance of newly cast structures. The study also emphasizes the need to test the permeability as well as strength for more precise assessment of concrete durability.

Keywords: Admixtures; bridges (structures); compressive strength; cores; durability; field tests; high performance concretes; mix proportioning; models; permeability; strength; tests.

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INTRODUCTION

There are over 3000 bridges along the 1200-mile coastline of Florida. They are exposed to extremely aggressive environment of the ocean water (1). With 17,000 ppm chloride content along the coastline, corrosion of the reinforcing steel in concrete is the primary concern in the substructure of these bridges. Corrosion of the steel is a result of poor quality concrete and insufficient concrete cover. In 1989, the annual cost of repairing corrosion related damage in Florida was estimated at 30 to 35 million dollars. In the Keys bridges alone, the repair costs have reached approximately 25% of the original cost of construction.

The challenge to engineers at the Florida Department of Transportation (FDOT) is to build durable bridges that can resist the adverse environment of ocean water. To meet this challenge, major emphasis is placed on building bridges with high quality concrete. The durability aspect is addressed in structural design, concrete-mixture selection and construction practices. Elements of design

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and construction that promote good durability and long term performance include adequate concrete cover and proper placement of reinforcing steel, and sufficient compaction and curing of the concrete.

Quality of the concrete mixture has a major impact on corrosion resistance of bridge structures. Concrete placed in severely aggressive environments should not only meet or exceed the specified strength, but also maintain high durability. Optimum strength and high durability are the two main characteristics of high-performance concrete (HPC) mixtures. HPC mixtures are designed with stronger emphasis on durability than in conventional concrete mixtures (2,3).

Permeability of concrete is considered a direct indicator of concrete durability. High permeability is the main contributor to poor durability and premature corrosion of bridge substructure. Based on this fact, research in Florida has strongly focused on concrete permeability. The research in Florida has set the following two objectives: to develop low-permeable HPC mixtures (4), and to develop laboratory and field test methods to measure permeability (5,6). The ultimate goal is to develop concrete durability specification and ratings based on permeability and strength requirements (7).

This paper addresses the development, specification requirement, research and utilization of HPC mixtures in Florida. A case study of a specific mixture is presented. The mixture has low water to cementitious materials ratio (W/CT). The cementitious materials consist of type II cement, silica fume (slurry form) and Class F fly ash. Chemical admixtures in the mixture include air entraining admixture, and/or ordinary water reducer/retarder, superplasticizer and calcium nitrite corrosion-inhibiting admixture. The concrete was tested for strength and permeability in the laboratory, and then used experimentally in a bridge widening project. Various tests were performed on field-produced concrete, including field and laboratory permeability tests, and compressive strength tests. A description of various permeability and strength tests is presented. The main laboratory and field test results are also discussed.

HPC SPECIFICATION IN FLORIDA

Research to develop HPC mixtures in Florida started in the mid 1970s. Compared to normal concrete, HPC mixtures have been designed with higher cement content and lower water to cement ratio. The HPC also include fly ash as a replacement of the cement to enhance

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concrete durability. The fly ash has been used in rates between 20 to 50 percent by weight of the cement.

The HPC mixtures were utilized in the construction of the largest bridge project in Florida, the Sunshine Skyway Bridge (8). In the bridge substructure, fly ash was used to replace 50% of the cement in the concrete mixture. The use of high fly ash content was intended to satisfy two major objectives. First, to reduce concrete permeability for greater durability, and second, to reduce heat of hydration in the mass concrete elements to minimize thermal cracking.

Based on the experience from the Sunshine Skyway bridge and from results of numerous laboratory studies, a new concrete specification was derived for severely aggressive environments such as ocean water. The current FDOT specification requires the concrete mixture to have a maximum W/CT of 0.37, and a minimum total cementitious materials (including cement and pozzolans) content of 752 lb (341 kg) (9). For design purposes and calculation of ingredients (including those in this paper), the total cementitious content is initially assumed to be Portland cement. Fly ash is allowed to replace Between 20% to 50% of the weight of cement. Concrete mixtures with 50% fly ash replacement are used in mass concrete members. The minimum strength requirement for concrete at 28 days is 6500 psi (45 MPa).

The concrete specification also allows the replacement of between 50% to 70% of the cement with granulated blast furnace slag. The 50/50 slag/cement mixture is being used with good results in the construction of a major bridge in Jacksonville, Florida.

Despite greater emphasis on durability, the present FDOT specification contains no requirements for concrete permeability. Research efforts are underway to develop concrete durability specification and ratings based on both permeability and strength of concrete (7).

FLORIDA RESEARCH IN HPC

The emergence of silica fume and more advanced superplasticizers in 1980s brought about new opportunities for further improvements in the durability and strength of concrete. In 1989 the FDOT started a major research program in HPC (4). This followed a successful cooperative research effort between the FDOT and the University of Florida to develop field and laboratory tests for water permeability of concrete (5,6).

The FDOT research has three main objectives: To develop HPC mixtures with low permeability and moderately high compressive strengths (more than 6000 psi or 41 MPa); to implement the laboratory and field permeability tests in the evaluation of concrete durability; and to implement HPC mixtures and assure their durability in field. The ultimate goal is to develop durability specification and ratings for concrete based on permeability and strength.

Since the start of this research, a wide range of HPC mixtures have been produced and tested for strength and durability (4). These mixtures are designed with multiple cementitious materials, different water to cementitious materials ratio (W/CT) and a variety of chemical admixtures. Materials incorporated in the mixtures include, type I, II, and III cements, limestone and granite aggregates, Class F fly ash and silica fume, ASTM C494 Types D and F admixtures, and corrosion inhibiting admixtures. The testing program is designed to evaluate strength, elastic modulus, water and chloride permeability, corrosion and sulfate resistance of HPC.

In addition to laboratory testing of small concrete samples, six research models in the shape of 2.5 X 2.5 X 5.0 ft. (0.76 X 0.76 X 1.5 m) columns, have been cast outside the laboratory. The objective is to verify that mixtures proven under laboratory environment maintain their durability and strength properties in simulated field conditions. Two laboratory-proven concrete mixtures were prepared in a commercial mix plant. The concrete was transported by ready truck mixers and placed in the models. Cores were extracted from the models at various ages, and tested for strength and permeability in the laboratory. Field permeability tests were also performed on these models. Figure 1 shows the extensively cored research models. Results of the permeability and strength test on laboratory samples and research models are compiled in a large database file. From this database, criteria will be derived for the evaluation and classification of durability in concrete mixtures and structures. This will lead ultimately to the development of durability specification and rating system for concrete.

CORROSION-INHIBITING HPC IN BRIDGE CONSTRUCTION

A decision by the FDOT to stop the use of epoxy-coated reinforcing bars in new bridges prompted an urgent need to develop alternatives with effective corrosion protection systems. The ongoing research in Florida has shown that concrete mixtures with type II cement, 20% Class F fly ash, 5 to 10 percent silica fume (slurry

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form), superplasticizers and a maximum W/CT of 0.35 produce concrete with low permeability, high strength and excellent corrosion resistance (4). These HPC mixtures were considered as obvious alternates to the epoxy-coating of the reinforcing bars. In addition, calcium nitrite corrosion inhibiting admixture was also selected for the HPC mixtures to further enhance the corrosion protection of the reinforcing steel.

However, there was little information on the use and performance of concrete with corrosion inhibitors in Florida. Therefore it was necessary to develop performance data from laboratory and field evaluation of this concrete. A plan was developed by which the HPC mixture would first be evaluated in the laboratory, and a preliminary materials specification would then be developed. The mixture would then be utilized and its properties verified in the field. Once this task has been accomplished the specification would then be finalized for application in bridge construction projects.

Scope of Testing Program

Table 1 shows the designs and plastic properties of all laboratory and field mixture. Two concrete mixtures were designed, batched and tested in the laboratory. The first mixture included fly ash and 5.5 gal/yd³ (27.3 L/m³) of calcium nitrite. The second included fly ash, silica fume and 4.5 gal/yd³ (22.3 L/m³) calcium nitrite. Field mixtures were designed with similar ingredients as in laboratory mix 2. Field mixtures were batched in concrete and prestress plants. The jobsite mixture was almost identical to the concrete plant mix.

An extensive testing program was developed to evaluate properties of the laboratory and field produced concrete. Laboratory specimens and field models were fabricated and tested to evaluate properties of the concrete. A wide range of laboratory tests were performed, including compressive strength, rapid chloride permeability (AASHTO T277), and laboratory water-permeability.

Large scale models were cast at the concrete plant, jobsite and prestress yard. A full-scale 15-foot (4.6 m) pile cap was cast at the concrete plant to evaluate general properties and handling of concrete in a large member. At the jobsite, a 2.5 X 2.5 X 4.0 ft (0.76 X 0.76 X 1.22 m) model of a column was cast from the same concrete that was used in casting the actual structural members. A one foot (300 mm) cube test-block was also prepared at the prestress plant. Cores were obtained from the model at the concrete plant and jobsite, as well as

from the actual structural members. The cores were subsequently tested for strength and laboratory permeability. In addition, field permeability tests were performed on all three models and on some structural members.

Courtney Campbell Bridge

The corrosion inhibiting HPC mixture was implemented in the field on an experimental bases. The mixture was used to cast piles and pile caps to widen a small bridge on the Courtney Campbell Causeway in Clearwater, Florida. This was the first field application of a concrete mixture containing silica fume, fly ash and corrosion inhibitor in Florida. The bridge is 473 ft. (144 m) long with eleven 43-foot (13 m) spans. It allowed traffic in both directions. In this project, each side of the bridge was to be widened by approximately 18 feet (5.5 m). The additional width, will provide two 10-foot (3 m) outside shoulders, two 8-foot (2.4 m) inside shoulders and two 12-foot (3.7 m) lanes in each direction. Figure 2 shows a view of the construction site.

Project specifications called for the use of corrosion inhibiting HPC mixture in the substructure. The concrete was used in all piles, pile caps and end walls. The piles were 18-inch (0.46 m) square prestressed members with 3 in (75 mm) concrete cover. Each pile cap was extended an additional 15 feet (4.6 m), and was supported by two piles. The pile caps were cast-in-place. A total of 2550 linear feet (777 m) of prestress piles were cast. The total amount of HPC placed in the pile caps and end walls was 121 yd³ (92.5 m³).

Laboratory Mixtures

Two laboratory trial mixtures were batched and tested. Table 1 shows mixture designs and plastic properties for the two mixtures. The total cementitious material content for each mix was 752 lb (341 kg). Mix 1 contained 20% of Class F fly ash and 5.5 gal/yd³ (27.3) of calcium nitrite, with no silica fume. Mix 2 had 8% silica fume (slurry form), 20% fly ash and 4.5 gal/yd³ (22.3 L/m³) of calcium nitrite. Type II cement was used in both mixtures. Tables 2 and 3 show the chemical and physical properties of cement and Class F fly ash. The aggregates consisted of Florida crushed limestone aggregates (grade 67) and silica sand. The ordinary water reducer (LRWR) and the high range water reducer (HRWR) were ASTM C494 Types D and F, respectively. The calcium nitrite was the non-accelerating type (contained a set retarder) formulated to prevent premature stiffening of the mixtures.

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Both mixtures had good workability as indicated by high slump. In mix 2, the air content was lower and the unit weight was higher than in mix 1. This is may be attributed to the silica fume which has the tendency to reduce the air content and increase the density of concrete. The concrete specimens were cast in plastic molds. After 24 hours, the specimens were demolded and placed in lime water for curing until test date.

Field Mixtures

Three mixture designs were implemented in the field, as shown in Table 1. The concrete-plant mixture was batched in the plant to verify the mixture design for acceptance purposes. In this mixture, grade 57 aggregate (1 in. or 25 mm maximum aggregate size) was used. The concrete was used to cast the pile-cap model at the plant.

The prestress plant mixture was used to cast all the piles for the widening project, as well as the one-foot cube test block. Only air and HRWR were used in the prestress plant mixture.

The jobsite mixture is a modification of the concrete plant mixture. The difference is that the jobsite mixture was designed with grade 67 aggregate (3/4 in. or 20 mm maximum aggregate size). The jobsite concrete was used to cast the pile caps and end walls of the bridge, and the column-model at the jobsite.

The three field mixtures are almost identical to laboratory mix 2, except for two distinct differences. Field mixtures used 69 oz. (2 L) of ASTM C 494 Type G HRWR which is also a set retarder, as compared to 5 oz. (0.15 L) of ASTM Type F regular set HRWR in laboratory Mix 2. The second difference is that the field mixtures included air entraining agent. The modifications in type and dosages of admixtures were necessary to offset any early stiffening of the concrete form the use of calcium nitrite, and also to maintain the target slump for at least 90 minutes after mixing.

Construction

The work at the concrete plant, prestress plant and jobsite was closely monitored. There were no problems with workability or early stiffening of the concrete. Even at the jobsite, when the truck mixers were discharging concrete in a timely manner, no workability problems were encountered. However, the concrete slump did drop from 4.5 to 2.5 inches (114 to 64) during a 60 minute period while a truck was waiting to discharge.

The pile caps and wing walls were cast-in-place. Wood forms were used for casting. The piles were fabricated in metal forms in a prestress plant. During concrete placement, fine mist was sprayed above the cast area. After placement, the finished concrete surface was wet cured under a curing blanket/burlap for 7 days. After 7 days, curing compound was applied to the finished surface. No cracking was observed on the prestress piles or on the cast-in-place pile caps/wing walls.

The concrete specimens in the field were cast in plastic molds, covered, and were left at the jobsite for 24 hours. Then they were transported to the laboratory to be cured in lime water until test time. The column-model at the jobsite was cast in a metal form unlike the wood forms of the pile caps and wing walls. The form was removed after 48 hours. The model was then wrapped with burlap and kept wet for 7 days. The pile-cap model was cast at the concrete plant using a wood form. The casting and curing were similar to those used at the jobsite. The concrete block at the prestress plant was cast in a wood form, and was cured similar to the prestress piles.

Compressive Strength

Table 4 shows the compressive strength of concrete at ages 1, 3, 7, 14, 28, and 91. At each age, three 6 X 12-inch (150 X 300 mm) samples were tested. Each value in Table 4 represents the average of three test results. The rate of strength development for lab mix 2 was significantly higher than mix 1. Silica fume contributed to the increase in the strength of concrete. The increase in compressive strength ranged between 14% at 7 days to 24% at 28 days.

All field mixtures had lower compressive strength than lab mix 2. The reduction of strength at 28 days for concrete plant mixture, prestress mixture, and jobsite mixture was 20%, 6%, and 4%, respectively. However the compressive strengths of these mixtures were still above the 6500 psi requirement for concrete acceptance. Furthermore, strengths of concrete at the jobsite and prestress plant were very close to the strength of laboratory concrete. This shows that using HPC mixtures in the field will not result in significant decrease in the compressive strength. The key factor in duplicating laboratory properties of HPC in the field is to maintain a high quality control during production of concrete.

Laboratory Permeability Tests

Two permeability tests were performed on the laboratory and field mixtures. The tests were the Rapid

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Chloride Permeability Test (RCPT), and the Laboratory Water-Permeability Test (LWPT). The RCPT was performed according to AASHTO T277 and ASTM C1202-91. Figure 3 shows the test apparatus for the rapid chloride permeability test.

The LWPT is a water permeability test procedure developed in Florida. Reference 5 presents detailed information on the test. Figure 4 shows the test system. The test specimen is a 2 in. (50 mm) thick slice of concrete cut from a 4 in. (100 mm) diameter cylinder or core. The specimen is coated on its perimeter with 1 in. (25 mm) thick epoxy. It is then securely sealed in the permeameter cell and connected to a manometer tube, as shown in Figure 4.

The test begins by injecting water into the manometer tube and reservoir of the permeameter cell. This is followed by applying 100 psi (0.69 MPa) pressure inside the system to force the water into the concrete specimen. The amount of water flowing into the specimen is monitored on the manometer tube until a steady-state flow is reached. Experience has shown that the steady-state flow is reached after 14 to 21 days. The test is continued for additional 7 days, during which the flow of water is recorded at 24-hour intervals.

To obtain the coefficient of permeability, the cumulative amount of water is plotted versus elapsed time. Then, using statistical methods, the best fit linear-curve is established for the data points. This is followed by determining the slope of the curve. Finally, Darcy's formula is used to determine the water permeability of concrete. The test is normally completed between 28 and 31 days. Efforts are underway to reduce testing time in order to obtain the results in a shorter period of time.

All test samples were cured in water until time of testing. Table 5 shows the averages of results of water and chloride permeability tests. The tests were performed twice during the first 91 days. Each time, Two specimens were tested. In some cases, additional specimens were tested at ages beyond 91 days. The water/chloride permeability did not necessarily decrease after 28 days. In some cases, the results showed a slight increase in permeability. The variation in test results is not unusual for two main reasons. First, it can be hypothesized that HPC mixtures may develop very low levels of permeability at 28 days, and more or less maintains that plateau beyond this age. Second, according to ASTM C1202-91, a variation as high as 35% is expected in the chloride permeability test results. It

should be noted that the water-permeability test results are extremely small, which makes them very sensitive to variables between specimens from the same batch or between different batches. Therefore, for all practical purposes, the true permeability for an HPC can be considered as the average of all permeability results at and beyond 28 days.

The permeability results for all mixtures are very close, except for lab mix 1. The relatively higher permeability for lab mix 1 can be attributed to lack of silica fume in the mixture.

Another important observation is worth mentioning. The chloride permeability results for a mixture with calcium nitrite tend to be higher than permeability of the same mixture without calcium nitrite. This may be due to the fact that calcium nitrite is likely to increase the electric conductivity of concrete, resulting in a deceptively higher coulomb results.

Results of strength and permeability do not necessarily correlate. For example, in Table 4, the strengths at 28 days for laboratory mix 1 (7410 psi or 51 MPa) and the concrete plant mixture (7360 psi or 52 MPa) are almost identical. However, the permeability results for the two concretes are significantly different, as shown in Table 5. This inconsistency between strength and permeability agrees with findings of a separate study (4). These findings stress the fact that concrete mixtures with equal strengths do not necessarily have equal levels of permeability.

Field Water-Permeability Test

The field permeability test (FPT) measures permeability of concrete in structural elements. The test was developed at the University of Florida (6). The FPT is portable and is designed to measure the permeability of structural elements. Figure 5, shows various components of the system. The control panel, manometer loop for monitoring water flow, and the testing probe are housed inside an aluminum case. A pressure-regulated nitrogen gas provides the external pressure that is required to run the FPT test.

To run the test, a 7/8 in. (22 mm) diameter and 6 in. (150 mm) deep hole is drilled in the concrete. The test probe is inserted and securely sealed inside the hole. Depth of the test region inside the concrete is adjustable ranging between 1.5 and 6.5 in. (38 to 165 mm). The concrete area around the probe is saturated prior to the start of test. The test begins by vacuuming

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the system. Water under pressure is then injected through holes of the probe, and forced into the concrete. The pressure applied to the water may vary between 100 and 300 psi (0.69 and 2.0 MPa), depending on strength and permeability of the concrete. The water flow into the concrete is monitored on the manometer loop. The position of the water is marked on the manometer at equal time intervals ranging between 5 and 30 minutes.

The presaturation and testing are normally completed in 2 to 3 hours, depending on how early the steady-state flow is reached. The steady-state flow rate is measured and applied in the permeability formula (commonly referred to as the Packer/Lugeon equation) to compute the permeability coefficient of the concrete.

The FPT was performed on various models and bridge elements. The models included the 15-foot (4.5 m) long pile cap at concrete plant, a one-foot cube block from the prestress plant, and a 2.5 X 2.5 X 4.0 ft. (0.76 X 0.76 X 1.22 m) column-model (block) at the jobsite. The tested members of the bridge included a prestress pile, and a cast-in-place pile cap and wing wall. Figures 6, 7, and 8 show field permeability testing of the pile-cap model (concrete plant), column-model (jobsite) and a prestress pile (bridge), respectively. The FPT was performed on at least two positions in each model/member. The test was performed at 28 and 91 days. Four-inch diameter cores were obtained from each model/member after completing the FPT. Every effort was made to extract the cores from positions close to the FPT point. The cores were later tested in the laboratory for compressive strength, water permeability and chloride permeability. It should be noted that cores from the bridge members were obtained from the 3 inch concrete cover. This provided an excellent opportunity to evaluate the permeability of this important region which forms the only barrier between the chlorides and the reinforcing steel.

Table 6 shows average values of field permeability test results for various models and elements, and of laboratory permeability tests on the core samples. Past experience has shown that the values of FPT are less than those for LWPT by more than one order of magnitude. The trends for both test results are similar.

Results of FPT indicate very close permeability values among the three models, and between the models and actual structural elements. The term "very close" describes the values as being within the same order of magnitude, considering the fact that the permeability values are very small. The LWPT and the chloride

permeability of the models are close to those of the mixtures used in casting the models. For example, the K-water results of the core from the pile-cap model and of the cylinder from the concrete-plant mixture are 1.0 E-12 and 0.59 E-12 in/sec (2.54 E-12 and 1.5 E-12 cm/sec), respectively. The K-chloride results are even closer, showing 1066 coulombs for the model-core and 862 coulomb for the mixture-cylinder.

Permeability Classification and Ratings

Table 7 shows the permeability classifications for concrete. The different classifications are basically those listed in AASHTO T277, with the exception of one class called "very high". The range of chloride permeability values per classification follows the AASHTO/ASTM criteria. The ranges for laboratory-water permeability (K-Water) and field permeability (K-Field) were derived from a database of over 100 test results. The database represents field and laboratory tests, including test results from the research models shown in Figure 1. In these models, FPT was first performed. Then cores were extracted and subsequently tested for LWPT and chloride permeability test (RCPT). At the same time LWPT and RCPT were performed on cylinders fabricated from the same mixture used in casting the models.

The range of permeability per class in Table 7 may be modified in the future as more field results are added to the database. The ultimate goal is to develop durability specification and ratings for concrete mixtures and structures in Florida.

Based on the classifications in Table 7, permeability ratings for the mixtures, models and structural elements were established. Table 8 shows the ratings based on chloride permeability (K-Chloride), laboratory water permeability (K-Water) and field water-permeability (K-Field). In all cases the permeability was rated very low to low, with the exception of K-chloride for lab mix 1 (moderate). This suggests that an HPC laboratory mixture can be designed in the laboratory to have a very low permeability. The mixture can then be successfully implemented in construction without altering its intended permeability and long term durability. This complements similar remark made earlier with respect to compressive strength of laboratory and field mixtures.

Another important fact has emerged from this study. Concrete models cast and cured at the jobsite simulate very closely the properties of the actual structural members. These models can be used as sacrificial testing elements to evaluate properties and predict future

performance of newly placed structural members. In this respect, the use of the jobsite models provides the project engineer with an excellent tool to evaluate the quality of construction.

Summary and Conclusions

This paper presents the development and successful implementation of high-performance concrete in Florida specifications and bridges. Details of a major research effort in HPC is outlined. A description of the various permeability tests utilized in the research is included. The paper also discusses in detail the development and field use of a corrosion inhibiting HPC mixture. Based on the information and test results in this study the following conclusions are drawn.

1. Corrosion inhibiting HPC mixtures have been used successfully in Florida bridges subjected to extremely aggressive environment. Properties of the concrete in the plastic and hardened stages are not significantly altered between laboratory and field environments.
2. The compressive strength and permeability of HPC in the field can be comparable to those observed in the laboratory. This can be accomplished by following an effective quality control program for concrete production.
3. Durability and performance of concrete would be properly and more accurately evaluated if both strength and permeability of concrete are tested.
4. A useful chart for permeability classification has been developed. Concrete permeability can now be rated according to the results of the rapid chloride permeability test (AASHTO T277/ASTM C1202-91), the laboratory-water permeability test, or the field-water permeability test.
5. Field and laboratory tests for measuring concrete permeability have been very effective in durability evaluation of concrete mixtures and structures.
6. Concrete models cast and cured at the jobsite can be used to obtain accurate information on properties of concrete in newly cast structural members. The models can be sacrificed by extensive coring, instrumentation and testing to evaluate strength, permeability and temperature development of the actual structure.

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TABLE 1 — DESIGN AND PLASTIC PROPERTIES OF LABORATORY AND FIELD MIXTURES

Material /yd ³ of concrete & plastic properties	Lab mixtures		Field mixtures		
	mix 1	mix 2	Concrete	Prestress	Jobsite
Cement, lb	602	542	542	542	542
Fly ash, lb	150	150	150	150	150
Silica fume, lb	0	60.2	60.2	60.2	60.2
Total cementitious materials (CT), lb	752	752	752	752	752
Water (W), lb	263	263	263	257	263
W/CT	0.35	0.35	0.35	0.34	0.35
Coarse agg., lb	1668	1668	1690	1690	1720
Fine agg., lb	1193	1133	1085	1160	1117
Air entraining admixture, oz	0	0	10	2	10
LRWR, oz	20	27	21	0	21
HRWR, oz	5	5	69	69	69
Calcium nitrite, gal	5.5	4.5	4.5	4.5	4.5
Slump, in	9.75	7.0	4.5	4.5	4.25
Air content, %	2.4	1.4	2.0	2.2	2.0
Unit weight, lb/ft ³	140.5	142.2	140.2	142.9	142.4

1 yd³ = 0.765 m³; 1 lb = 0.454 kg; 1 fl. oz = 0.0296 L; 1 gal = 3.785 L; 1 in = 25.4 mm; 1 lb/ft³ = 0.0624 kg/m³.

TABLE 2 — CHEMICAL COMPOSITION OF CEMENT AND FLY ASH

Element percent	Type II cement	Class F fly ash
CaO	63.23	4.71
SiO ₂	20.21	
Al ₂ O ₃	5.53	
Fe ₂ O ₃	4.32	
(SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃)		86.53
MgO	0.62	
SO ₃	2.67	1.24
LOI	1.69	2.88
Insoluble Residue	0.33	
Alkalies (Na ₂ O + 0.658 K ₂ O)	0.48	
C ₃ S	52.84	
C ₂ S	18.07	
C ₃ A	7.34	
C ₄ AF	13.16	

TABLE 3 — PHYSICAL TEST RESULTS

Test	Type II cement	Fly ash
Fineness -		
Blaine, m ² /kg	383	
Retained on mesh 325, %		23.63
Soundness	0.02	0.01
Pozzolanic activity index @ 28 Days		84.90
Specific gravity	3.15	2.47
Gillmore setting time -		
Initial set, minutes	120	
Final set, minutes	245	
Compressive strength, psi -		
1 Day	2038	
3 Day	3188	
7 Day	4319	

1 psi = 0.0069 MPa

TABLE 4 — COMPRESSIVE STRENGTHS (psi)

Mixture	Age - days					
	1	3	7	14	28	91
Lab mix 1	3320	4780	6225	6675	7410	8730
Lab mix 2	3945	5680	7120	8250	9180	10675
Concrete plant	NA	NA	5770	6900	7360	NA
Prestress plant	NA	5185	7095	8025	8615	8640
Jobsite	2825	4760	6899	7835	8775	9325

1 psi = 0.0069 MPa.

TABLE 5 — AVERAGE RESULTS OF LABORATORY-WATER AND RAPID CHLORIDE PERMEABILITY TESTS

Mixture	K-Water (in/sec)	K-Chloride coulomb
Lab mix 1	3.18 E-12	2511
Lab mix 2	0.81 E-12	618
Concrete plant	0.59 E-12	862
prestress plant	0.46 E-12	893
Jobsite	1.72 E-12	1055

K-Water: water permeability Test
 K-Chloride: Chloride permeability
 in/sec = 2.54 cm/sec or 25.4 mm/sec.

TABLE 6 — AVERAGE RESULTS OF FIELD PERMEABILITY TEST AND CORE TESTING

Model/structural element	K-Field in/sec	Core Testing	
		K-Water, in/sec	K-Chloride coulomb
Pile-cap model	66 E-12	1.0 E-12	1066
Prestress plant model	49 E-12	N/A	N/A
Prestress Pile	67 E-12	1.7 E-12	N/A
Jobsite model	43 E-12	2.26 E-12	N/A
Cast-in-place element	57 E-12	2.94 E-12	N/A

K-Field : field permeability

TABLE 7 — PERMEABILITY CLASSIFICATIONS

Permeability Classification	Classification criteria		
	K-Chloride, coulombs *	K-Water, (in/sec) $\times 10^{-12}$ **	K-Field, (in/sec) $\times 10^{-12}$ **
Negligible	< 100	< 0.1	< 10
Very low	100 - 1000	0.1 - 1.0	10 - 50
Low	1000 - 2000	1 - 10	50 - 250
Moderate	2000 - 4000	10 - 100	250 - 500
High	> 4000	100 - 1000	500 - 1000
Very high	N/A	> 1000	> 1000

* According to AASHTO T277 classification

** According to FDOT classification

TABLE 8 — PERMEABILITY RATINGS FOR MIXTURES, MODELS AND STRUCTURAL MEMBERS

Type	K-Chloride	K-Water	K-Field
Lab mix 1	Moderate	Low	N/A
Lab mix 2	Very low	Very low	N/A
Concrete plant mix	Very low	Very low	N/A
Pile-cap model	Low	Low	Low
Prestress plant mix	Very low	Very low	N/A
Prestress block-model	N/A	N/A	Very low
Prestress pile	N/A	Low	Low
Jobsite mix	Low	Low	N/A
Jobsite column-model	Low	Low	Very low
Cast-in-place pile cap	N/A	Low	Low



Fig. 1—Research models cast outside FDOT laboratories

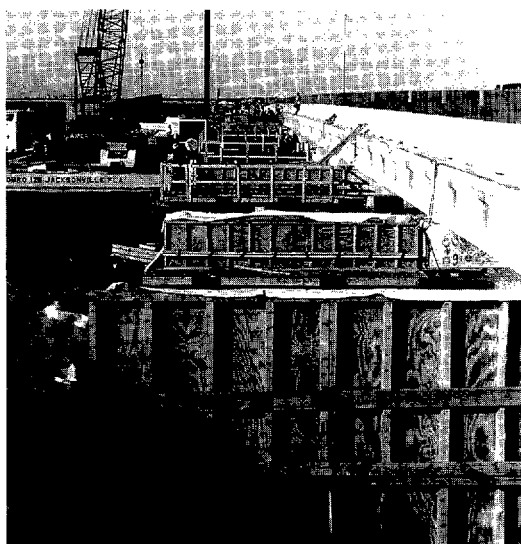


Fig. 2—View from the Courtney Campbell Bridge project



Fig. 3—Chloride permeability test apparatus

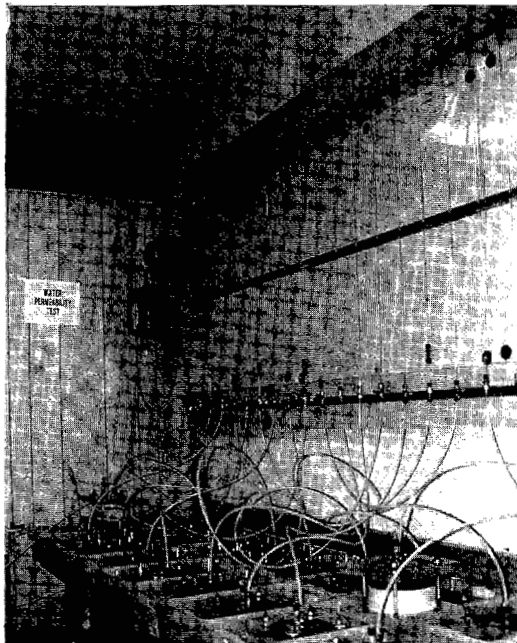


Fig. 4—Laboratory water-permeability test system

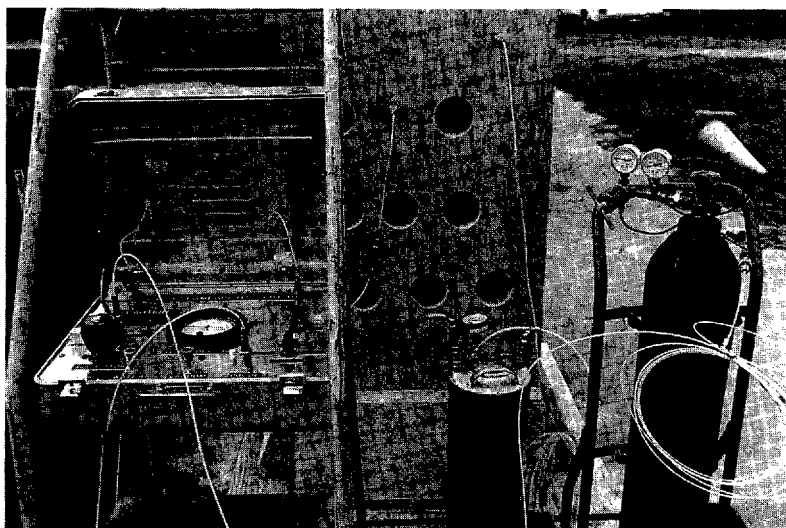


Fig. 5—Field water-permeability test system



Fig. 6—Field permeability testing of pile-cap model

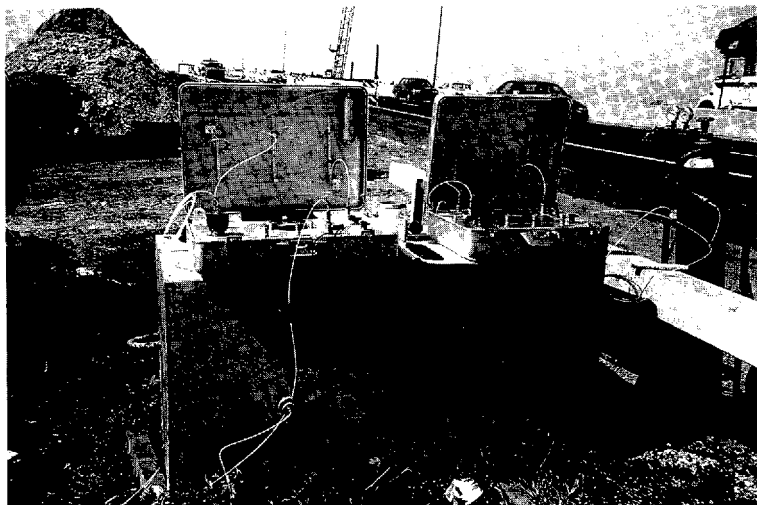


Fig. 7—Field permeability testing of column-model at jobsite



Fig. 8—Field permeability testing of bridge pile

SP 140-2

Development and Utilization of High Performance Concrete for the Construction of the Akashi Kaikyo Bridge

by K. Tanaka, K. Sato, S. Watanabe,
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Synopsis: We developed an enhanced flowable concrete using both a binary low heat cement and coarse aggregate of 40 mm maximum size, usable in large-scale mass concrete structures (this concrete is provided with a high flowability and an excellent resistance to segregation, and is able to be placed densely without compaction). We verified that its fundamental performance surpasses that of existing types of concrete. Further, we also verified that it possesses superior workability when compared with conventional concrete. Next, we established production, quality control, and construction methods for super-workable concrete through experiments at a large scale construction site, and utilized it in a large-scale structure. We were able to verify the following results: superior workability of the concrete because it can be spread and compacted easily; effective control over thermal cracking because concrete temperature rose very little. Furthermore, the hardened concrete is confirmed, from the core samples, to be very compact and has excellent strength.

Keywords: Bridges (structures); coarse aggregates; compacting; cracking (fracturing); durability; flowability; high performance concretes; mass concrete; mixing time; moisture; segregation; strength; temperature; workability.

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INTRODUCTION

Akashi Kaikyo Bridge linking the city of Kobe with Awaji Island in Japan (Figure 1) is scheduled to be completed in 1998. When completed it will be the longest suspension bridge in the world (Figure 2), 580 m longer than the longest currently in the world, the Humber Bridge. Approximately 240,000 cu m of concrete is planned to be placed in the 4A anchorage and in the substructure above water level on the Awaji side of the Akashi Kaikyo Bridge. Because it is such a massive structure, attention to the following items is essential: utilization of a concrete with extremely small temperature increase; control of concrete thermal cracking due to heat of hydration; and control of drops in the strength. Furthermore, because it is a marine structure, a densely compacted concrete must be used, and it must be a concrete of superior durability. However, in structures where there are a large number of obstructions, consisting of a varied mixture of cable anchor frames, and temporary steel structures as seen on anchorages, using conventional intensive labor construction methods or mechanized construction methods with a distributor, it has been difficult to compact sufficiently to achieve proper concrete fill. With such methods, the planned quantity of concrete was 1,900 cu m per day, so it was determined that completing 240,000 cu m of concrete within the time period would be formidable.

At this point we developed and used a concrete with extremely small temperature rise, that was flowable even without compacting, had no segregation of ingredients, and was able to be filled densely (hereinafter called super-workable concrete). We would like to report on the study results in the development of this concrete, and the knowledge obtained in implementation.

THE CONCEPT OF SUPER-WORKABLE CONCRETE

Currently in Japan, as shown in references (1), a lot of research is being conducted for a super-workable concrete, which provides improved flowability and ingredient segregation resistance in the concrete, while being capable of reducing compacting work without sacrificing concrete quality. As a means of providing enhanced flowability and ingredient segregation resistance, some measures are taken such as use of superplasticizer for flowability, addition of a large quantity of fine powder, and use of a viscosity increasing agent for segregation resistance, or use of both methods together.

For the development of the super-workable concrete, our basic strategy is to use the same concrete as the 110 mm slump concrete with binary low heat cement and 40 mm aggregate, which is studied in various aspects by Honshu-Shikoku Bridge Authority for its use for the Honshu-Shikoku Bridge (hereinafter called reference concrete) (2). The expected segregation resistance of ingredients is given by substituting fine highly pure limestone powder for one part of the aggregate, and flowability by using an appropriate amount of superplasticizer with low slump loss. Thus, the type of cement, the type of aggregate, the unit water amount, the unit cement amount, and the water-cement ratio were all consistent with the reference concrete. In addition the thermal generation characteristic, and product quality targets in the hardened concrete equaled or surpassed those of the reference concrete. The result of the test mixing was that the slump flow was 550 mm (+/-50 mm). Indicators of ingredient segregation, such as segregation of mortar from aggregate, or mortar surge on the slump flow edge, were not apparent. "Slump flow" is an index of the consistency of flowable concrete. The conical spread of concrete is measured to determine the arithmetic mean of the maximum diameter and the diameter normal to it. This mean is called slump flow.

EXPERIMENTAL GOALS

Figure 3 shows the flow of the experiment. In Phase I, we were able to deduce the fundamental characteristics of the super-workable concrete that we determined through experimental mixing. At the same time, the effect of mixing time, which becomes crucial in investigation of actual productivity, and the effect of fluctuation in the proportion of surface moisture on the fine aggregate as projected for a concrete plant in site, were quantitatively clarified. In Phase II, flowability and placing experiments were conducted using small scale simulation components. The flowability of the super-workable concrete enabled it to flow around obstructions. The strength characteristic, coarse aggregate distribution, and lateral stress distribution were investigated.

In Phase III, a mock-up test using the components of actual size was used, and experiments were conducted for concrete production, pumpability, placing method, in order to determine the optimum execution method for super-workable concrete. In Phase IV, the construction method, concrete production method, quality control method, and execution method determined based on the results of Phases I-III were employed. The material properties of super-workable concrete were studied both when the concrete was first mixed and after setting.

PHASE I

Blending Experiments

The water–cement ratio and the quantity of limestone powder were varied, and the mix proportions were studied in the fresh concrete state. Table 1 shows the various bases of ingredients used in the experiment. Table 2 shows the preparation of the concrete. Mixing was conducted according to the methods shown in Figure 4.

Figure 5 shows the amount of superplasticizer used in the different mix proportions in cases where there was a 550–millimeter slump flow. The amount of superplasticizer used was increased as the water–cement ratio was reduced and the amount of limestone powder additive was increased. The amount used was 2.0 – 2.4 times the standard amount which is used ordinarily in concrete.

Figure 6 shows the slump flow against time for a 51.8% water to cement ratio. Slump flow for super-workable concrete reaches its peak about five minutes after mixing of the concrete is finished. Subsequently for about 60 minutes thereafter no variation in the slump flow is observed. The conditions of the different mix proportions were as follows. For the case of 100 kg/cu m of limestone powder, a tendency for the coarse aggregate to be conspicuous because of a low level of viscosity in the mortar was observed. At 200 kg/cu m, a tendency for the flow velocity to decline was observed. Figure 7 shows the slump condition five minutes after completion of mixing.

Figure 8 shows the bleeding percentage for the various mix proportions. For super-workable concrete, from the observation that ingredient segregation is prevented, it is desirable that bleeding be extremely small. In this experiment, bleeding reached a maximum level of 0.51%, obtaining a result that is nearly satisfactory. As an overall trend, the smaller the water–cement ratio and the greater the amount of limestone powder, the less bleeding occurs. For a water–cement ratio of 51.8% and a 200 kg/cu m quantity of limestone powder, bleeding was very close to zero.

The setting times for the various mix proportions are shown in Figure 9. Because the amount of clinker contained in the cement is low, concrete using low heat cement has a tendency to extended setting times. For the reference concrete (W/C=55.8%) initial setting was at 11 hours and final setting at around twenty hours. On the other hand, because the quantity of superplasticizer used was added to the super-workable concrete, both initial and final settings were both delayed around five hours compared to the reference concrete.

Physical Properties and Durability Experiments

In order to study the fundamental characteristics of the super-workable concrete, various tests were conducted with the mix proportions shown in Table 3. However, based on the results of blending experiments, the range of the amount of additive was adjusted. Mix proportion No. 10 was the reference concrete.

Figure 10 shows the relationship between the cement–water ratio and compressive strength. Both graphs were very nearly a linear relationship, the same as for ordinary concrete.

Figure 11 shows the relationship between the quantity of limestone powder additive, and compressive strength for a 55.8% water–cement ratio. The compressive strength at all ages increased as the quantity of limestone powder increased. For the case when the quantity of limestone powder was 180 kg/cu m, an increase in strength was demonstrated on the order of 20% greater than for the 30 kg/cu m case. It is believed that two principles promoted this kind of increase in compressive strength in direct proportional to the amount of limestone powder additive. The first was a chemical principle originating in a chemical reaction of the limestone powder, and the second was a physical principle arising as voids in the hardened cement were reduced because they were effectively filled as a result of adding fine powder. With regard to the limestone powder reaction, simple cement paste and cement paste with limestone powder added were observed with an electron microscope, and the differences were noted. Furthermore, in the adiabatic temperature rise test, for the same cement unit amount, no difference occurred in the amount of temperature rise. From these facts we can infer that the increase of compressive strength from the limestone powder additive originated primarily in the fill effectiveness due to the addition of fine particles, plus the internal defect reduction in the concrete matrix due to a decrease in bleeding.

Figure 12 shows the results of the accelerated carbonization test. The smaller the water–cement ratio, and the greater the quantity of limestone powder, the smaller is the depth at which carbonization occurred. No ill effects were noticed from increasing the additive amounts of limestone powder and superplasticizer. In contrast, with 150 kg/cu m of limestone powder there was about a 10% delay in carbonization over the 30 kg/cu m reference concrete. This is considered to be given from the result that the texture of the hardened concrete become more compact, because of the excellent filling effect of limestone powder above mentioned.

Figure 13 shows the test results of the length variation ratio caused by drying shrinkage. The length variation ratio was approximately the same for both super-workable concrete and the reference concrete, $4.6 - 4.8 \times 10^{-4}$ at age 26 weeks.

Figure 14 shows the results of the adiabatic temperature rise. Looking at the differences in adiabatic temperature rise by unit amounts of cement, we see that it was 20.4 C for a cement amount of 240 kg/cu m (mix proportion No. 2), 22.0 C for 260 kg/cu m (mix proportion No. 5), 24.3 C for 280 kg/cu m (mix proportion No. 2). For each 10 kg of cement amount, the temperature rises by approximately 1 C. Furthermore, against a 22.2 C adiabatic temperature rise in the reference concrete (mix proportion No. 10), the amount of temperature rise in super-workable concrete was 22.0 C. No difference was noticeable between the two types, but for the super-workable concrete, since setting was delayed, a tendency toward moderation of the initial temperature rise was seen. Based on the above results, mix proportion No. 5 was selected as the mix proportion for the super-workable concrete, and was used in the following experiments. Mix proportion No. 10 was used as the reference concrete.

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Mixing Time Experiments

Four mixing times of 30, 60, 90, and 120 seconds were taken. The characteristics of concrete were examined while the concrete was fresh, and strength properties determined after the concrete had hardened.

Figure 15 shows the relationship between mixing time and slump flow, and mixing time and amount of air. Slump flow had a tendency to decrease as mixing time increased. For a mixing time of 30 seconds or shorter, the concrete exhibited a tendency to segregate. The cause can be that because of inadequate dispersion in the cement particles and limestone powder, the quantity of free water increases due to a decrease in the amount of water retained in the fine particle component. With regard to the amount of air, there was no clear tendency, because fluctuations with mixing time were too small.

Figure 16 shows the relationship between mixing time, setting time, and bleeding ratio. The setting time tends to become shorter with increased mixing time. This also is thought to result from improvement in the fine particle variance. Furthermore, bleeding occurred only for a mixing time of 30 seconds, but it was quantitatively insignificant, and is affected by the mixing time only to a small extent.

Figure 17 shows the compressive strength test results. The trend was that the longer the mixing time the greater the compressive strength. In particular, strength deterioration for a mixing time of 30 seconds was striking. At all ages the strength only reached 85%, compared with a mixing time of 120 seconds. Therefore, since the mixing time has such a strong impact on the physical properties (compressive strength) in both the fresh and hardened states of super-workable concrete, when production is done at a concrete plant in site, it is essential that sufficient prior study of the mixing time as well as mixer capability be conducted.

Experiment to Vary Surface Moisture

Five values for surface moisture variation, -2, -1, 0, +1, +2% were taken, and characteristics of concrete were examined while the concrete was fresh, and strength properties determined after the concrete had hardened.

Figure 18 shows the relationship between fine aggregate surface moisture variation, slump flow, and amount of air. For slump flow, when surface moisture was on the plus side (when the actual amount of surface moisture on the sand was greater than the compensating factor), fluctuation was great. At a variation of 1%, a slight segregating tendency was apparent, and at 2%, it was completely segregated. The amount of air tended to increase on the plus side and decrease on the minus.

Figure 19 shows the relationship between surface moisture, setting time, and bleeding. The setting time was delayed five hours at 2% compared to the time for 0%, but it was two hours earlier at -2%. Both initial and final setting times tended to change tremendously when surface moisture moved to the plus side. The percentage of bleeding was 1.26% at +2%, but was extremely small in the +1 to -2% range. As above, excluding air amounts, the fresh concrete state tended to change tremendously when surface moisture moved to the plus side.

Figure 20 shows the relationship between surface moisture variation, and compressive strength. Compressive strength also declines considerably when surface moisture moved to the plus side. It is thought that when surface moisture moves to the plus side, not only does the unit amount of moisture increase qualitatively, but also the ingredients tend to segregate.

PHASE II

Flowability Experiment

Super-workable concrete was placed into the form shown in Figure 21 from the edge of the form in two layers. The first layer was 0.7 cu m and the second 0.8 cu m. Observations were made of the flowability and fill in the vicinity of obstacles, and at the same time, the flowing gradient of the concrete top for each layer was measured at the time of placement. Furthermore, core samples were taken at the locations shown in Figure 21, consolidation in the vicinity of obstacles was verified, and measurements were made of the concrete core compressive strength, and the concrete core coarse aggregate distribution. In addition, reference concrete was placed by conventional methods and a comparison was made of compressive strength, and aggregate distribution. A forty-millimeter dia. high frequency vibrator was used to compact the reference concrete. Each layer (two layers) was compacted by vibration at 22 locations for 10 seconds each.

As shown in Figure 22, even though the super-workable concrete was not compacted, it flowed into the corners of the steel frames, steel bars, and other obstacles placed inside the form, and filled without leaving any gaps. Furthermore, even for projections of the beams placed in a horizontal direction, the concrete flowed around gaps in the lower parts of the obstacles and filled into the corners of the form. Therefore, it is evident that the super-workable concrete possesses sufficient flowability and ingredient segregation resistance to fill around even obstacles placed in the hypothetical massive structure for this experiment.

Figure 23 shows the concrete top flow gradient which is an index of flowability and easiness of finishing of concrete. It is equal to the difference of height at two points of the top of placed concrete over the distance between the two points (the fraction is adjusted to make the numerator be an unity). For the first layer, the gradient from the vicinity of the point of placement to the leading edge averaged 1/40. For the second layer, in front of the beam-shaped horizontal projections it was 1/85, and even on the back surface was 1/30. The level differential for the upper edge of the concrete in front of and behind obstacles was 44 mm. Thus, for the obstacle of this type, even if there is a considerable distance from the point of placing, we found that irregularities on the upper edge of the concrete were kept small.

With regard to the fill characteristic in the vicinity of steel bars, core samples were taken in six locations, and observations were made of the concrete fill. As shown in Figure 24, the fill characteristic was extremely good in all locations.

Figure 25 shows the compressive strength at age 28 days for core samples. The average compressive strength for super-workable concrete was 27.8 MPa, with

a standard deviation of 0.87 MPa. For the reference concrete the average compressive strength was 23.8 MPa, and the standard deviation was 0.98 MPa. When we compare the two, we find that the super-workable concrete was approximately 16% stronger than the reference concrete. There was some fluctuation, but it was small. Thus we see that this super-workable concrete, even without compaction, was held within strength fluctuation of concrete placed with conventional placing methods.

Figure 26 shows coarse aggregate distribution for core samples. In the super-workable concrete, almost no segregation of aggregate was observed, whereas for the reference concrete, in the core sample of the section simulating a horizontal frame, an area was found where the amount of coarse aggregate was reduced. It is believed that lateral flow occurred when filling the section simulating the horizontal beam. Furthermore, in corners of the form, and perpendicular to the vicinity of the steel frame, formation of rock pockets is likely, but for super-workable concrete, even in those sections, it was apparent that it flowed and filled into the corners without segregation of coarse aggregate.

Measurement of Lateral Pressure Distribution

Super-workable concrete was poured into the form shown in Figure 27 at a rate of 1.5 m/h continuously and in layers. Lateral pressure against formwork was measured with an earth pressure gauge attached to the form, and lateral pressure was studied against placement height.

Figure 28 shows the results of the measurements of lateral pressure by the earth pressure gauge. For continuous placement, the lateral pressure against formwork was largest up to a placement height of around 1 m, when the lateral pressure was on the order of 0.015 MPa. Furthermore, at the point placement was completed, the lateral pressure in the lower sections began to drop. The cause of this is believed to be due to occlusion of the hardened particles, whereas the lateral pressure is a fluid pressure figure calculated taking the concrete as a fluid, up to a placement height of around 0.75 m. The lateral pressure against formwork that occurs when the concrete is placed, drops to nearly zero after two hours and thirty minutes.

For layered placement, the lateral pressure in the first layer had dropped to about 28% of the value at placement just before placing the second layer two hours later. However, when placement of the second layer commenced, the lateral pressure against formwork in the lower sections increased. By the time placement was completed, it had risen to 61%.

PHASE III

The concrete placement plan was to partition the 4A anchorage of the Akashi Kaikyo Bridge (Figure-29) into five blocks horizontally. A pump and a conveying pipe were used to convey the concrete. A suitable valve was attached to the conveying pipe, and distribution and placement of the concrete was performed by the opening and closing of this valve.

A one cubic meter capacity two-axle forced action mixer was used for the experimental concrete plant. All ingredients were put in at the same time. Further, an experiment (3) was conducted, with the result that a mixing time of 75 seconds was selected.

Pumpability

There were three factors in the experiment, the mixture, pipe diameter, and theoretical discharge rate. A study was conducted of the two standard mix proportions, super-workable concrete, and the reference concrete. For the super-workable concrete, a six-inch and an eight-inch pipe were used, but for the reference concrete only a six-inch one was used. The three standards for the theoretical discharge rate were 30, 45, and 60 cu m/h. The set up for the piping is shown in Figure 30. The total length of the pipe was approximately 120 m. Table 4 shows the items measured, and Table 5 pumper specifications.

Figure 31 shows the relationship between discharge rate and pressure loss in the horizontal pipe. For the six-inch pipe, the percentage of increase in pressure loss against discharge was considerable. When compared to the reference concrete, the gradient was sharply rising. For example, looking at the pressure loss for a discharge rate of 40 cu m/hr, the figure for super-workable concrete is approximately 0.012 MPa/m, as against a figure of 0.008 MPa/m for the reference concrete, nearly 1.5 times the amount. On the other hand, for the eight-inch pipe at a discharge rate of 40 cu m/h, the figure for the pipe pressure loss dropped to approximately 0.006 MPa/m. This was about 3/4 of the pressure loss for the reference concrete (using a six-inch pipe).

Figure 32 shows slump flow variation before and after pumping. Slump flow variation before and after pumping was striking for super-workable concrete using a six-inch pipe. In particular, the super-workable concrete exhibited a significant loss of 250 mm when the discharge rate was set to 60 cu m/h. On the other hand hardly any loss was observed for an eight-inch pipe.

A six-inch pipe is feasible for the super-workable concrete pump if the exchanged horizontal conveying distance is relatively short, but when variations in concrete quality are considered, it would be desirable to use an eight-inch pipe to convey super-workable concrete using 40 mm coarse aggregate.

Placing Methods

The planned placing method is a layered placement which used the opening and closing of a series of gate valves to distribute the concrete evenly in layers.

Figure 33 shows the shape of the member by the layered placement. After concrete has hardened, core sampling was implemented at the points shown in the figure, to measure the 7-day compressive strength and coarse aggregate area ratio for cross-section of the core. In addition, adjusting the superplasticizer content, three levels of slump flow were obtained, that is, 510, 570, and 620 mm and the gradient of the concrete top was measured.

Figure 34 shows the concrete gradient. Compared with a gradient of about 1/20 for a slump flow of 510 mm, the value for 570 mm and 620 mm was about 1/30.

The gradient decreases as slump flow increases. However, a visual examination revealed that concrete flow was optimal for a slump flow of 570 mm. At 620 mm, settling of the aggregate could be seen, and it is believed that this exhibits a slight tendency toward segregation. In addition, Figures 35 and 36 show the compressive strength of core samples taken from the concrete, and the coarse aggregate area ratio. For both compressive strength and coarse aggregate area ratio, there was almost no unevenness, meaning an even-quality concrete was placed.

Therefore, by achieving a flow distance of about 5 m, good quality of concrete and adequately level surface could be achieved in concrete placement.

PHASE IV

Figure 37 shows the placement block shape for the 4A anchorage of the Akashi Kaikyo Bridge. The slotted construction method was employed (the construction method of setting a three-meter-wide opening in the gap between each of the blocks that were placed), and the surface was divided into five blocks. The maximum block surface area was approximately 1,200 sq m, lift height was 1.5 to 2.5 m, and the maximum concrete that could be placed in a single day was 1,900 cu m. Figure 38 shows the current situation with excavation completed and concrete construction underway.

Concrete Work Method

The method of concrete construction was to have seven fixed type pumps (one of which was held in reserve) each pumping directly to each of the placement locations through separate pipes (six systems). For the conveying pipe, eight-inch diameter pipes were used.

Within all placement blocks, each system, (arranged at approximately five-meter intervals) for temporary spacing gates valves that automatically open and close, was set up at approximately five-meter intervals. Within the blocks at the same level, the layered placement method was used. Figure 39 and 40 show the pipe arrangement and concrete placement situation.

By choosing the layered placement method, the following results were achieved: (a) since the flow distance is short, almost no ingredient separation occurred, so an extremely even-quality concrete was produced; (b) a sufficiently flat upper concrete edge (gradient less than 1/20) was obtained so leveling work was greatly reduced.

Concrete Production and Quality Control

Two four-cubic-meter capacity dual-axis forced action mixers were used for concrete production. Below these units, in order to distribute the concrete to the concrete pumps, a 12 cubic meter capacity agitator was installed. Maximum concrete production capacity was 288 cu m/h. In the control room adjacent to the batcher plant, all processes relating to production and conveyance were controlled, from conveying of materials, aggregate cooling, ingredient batching, mixing, to distribution and conveyance between agitator and pump. It was set

up to enable regular monitor supervision. Ingredients were injected into the mixer all at once for mixing the concrete. Based on the results of a mixing capacity test, mixing each time was set to 60 seconds. Concerning the concrete quality, by control of surface moisture rate on the aggregate, the unit water amount could be kept constant at a predetermined level. Flowability was fine-tuned by use of superplasticizer. Table 6 lists concrete quality controls.

In order to stabilize the aggregate surface moisture which has such a major effect on concrete flowability and strength, water was drained using two 1.6 cubic-meter capacity sand stabilizer units for the fine aggregate. The coarse aggregate was first soaked and cooled, then passed through a vibrating sieve.

Figure 41 gives one example of the variation in surface moisture rate, but consistency was obtained by application of the above countermeasures.

With regard to strategies to prevent thermal cracking, we attempted to achieve better than the thermal cracking index of 1.2 of Honshu-Shikoku Authority's specifications, but an analysis of the actual execution plan revealed that concreting temperature combined with artificial cooling was less than 18 C. For that reason, particularly in the summer, the following pre-cooling measures were taken. (a) Water cooled to 2 C was used. (b) The fine aggregate in the sand stabilizer was cooled by spraying it with chilled water. (c) The coarse aggregate, after being sprayed with chilled water in the storage tank, was conveyed in cool water on the belt conveyor, and soaked and cooled. Through these kinds of measures, the initial concrete temperature was held below 13 C.

"Thermal cracking index" represents the probability of cracking, obtained by dividing the tensile strength of concrete by the thermal stress due to heat of hydration.

Fresh Concrete Quality

Figure 42 shows slump flow test results, for the point in time when the concrete is produced and for when it comes out of the pipe for the period from October to December 1992. When produced, the slump flow value was in the 550 $\pm$ 50 mm range, the same as for ordinary concrete, but after conveying, at the end of the pipe, it had declined somewhat, and there was a tendency toward a slight increase in irregularities. However, in execution, even for slump flow of less than 500 mm, a degree of flowability was maintained. By adopting strategies such as extending the flow distance through a slight increase above the usual interval for the opening and closing of the gate valve, and utilization of a supplementary vibrator, no particular problem arose during execution. Furthermore, the air content at both time of production and coming out of the pipe was kept within the range of 4 $\pm$ 1%.

Hardened Concrete Quality

Figure 43 shows compressive strength of standard samples of concrete at age 7, 28 and 91 days that had been placed in the period between October and December. The variance index was small, on the order of 6.5 to 8.1%.

For structural concrete quality, a core boring was made in three places in each of the completed blocks, and used in a test to verify coarse aggregate distribution and compressive strength. The locations where the samples were taken from the blocks that had been placed is shown in Figure 44. Figure 45 shows a

comparative graph of the compressive strength at age 7 days by location in the poured block from where the sample was taken, and by location in the sample. No variance by location of the sample or position in the sample could be observed in the compressive strength of the core sample. The finished concrete quality was extremely even. A cross-sectional sketch of a core sample is shown in Figure 46. The coarse aggregate ratio per cross-sectional area in the core cross-section had a value close to the 43.1% in the concrete as a whole. The coarse aggregate was very evenly distributed throughout the core with no dependence on whether it was upper, middle, or lower section. From this data, we are able to determine even quality of the placed concrete.

Figure 47 shows temperature measurements for lift numbers 4 to 6 of the L1 block. The amount of temperature rise was held to 22 – 23 C, and no damaging cracks were observed in approximately 60 lifts that have been completed. Thus we can conclude that temperature control measures in this construction project were adequate, and that thermal cracking resistance for super-workable concrete is improving.

CONCLUSION

The super-workable concrete using a binary low heat cement and limestone powder that we have developed, possesses superior flowability, will not segregate, and has the capability to completely fill narrow gaps created with steel members. In addition, with regard to the quality of the hardened concrete, it possesses properties equal to or better when compared with the reference concrete. Furthermore, since newly employed material is just limestone powder which is easily obtainable, current plants have adequate production potential. Thus it would be excellent for regular use.

The following areas need further consideration regarding super-workable concrete. (a) Since aggregate surface moisture relatively easily affects the condition of the fresh concrete, it is important that adequate aggregate quality control be implemented in concrete production. (b) Because bleeding is extremely low, pipe pressure loss during pumping is comparatively large. It is essential to employ a high pressure pipe of larger diameter than conventionally used. (c) Setting time is delayed due to the use of a large amount of superplasticizer, but since bleeding is small, if the surface is dried for an extended period of time, plastic shrinkage cracking may occur. It is essential that appropriate initial curing of the upper placement surface be performed. (d) Lateral pressure against formwork at the time of placement is larger than conventional concrete. Thus in cases where placement speed is high, or in cases where the placed concrete is vibrated, a liquid pressure acts on the form, so that it is essential to adequately observe actual placement work, and design formwork that will be sufficiently safe.

Currently approximately 120,000 cu m of super-workable concrete have been employed with favorable results.

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2. K.Kanazawa et al., "Applicability of Super Low-Heat Cement to Mass Concrete Structures," Concrete Journal, Vol. 27, No.5, May 1989, pp.31-37
Vol.14, No.1, 1992, pp.63-68
3. K.Suenaga et al.,"Study on the Workability of Binary Low Heat Super-Workable Concrete (Part 2 Properties of Concrete)," 47th Lecture Meeting of the Japan Society of Civil Engineers

TABLE 1 — MATERIALS USED

Material	Kind	Properties/components
Cement	Binary low heat cement	specific gravity 3.00, specific surface area 485000 sq mm/g low heat clinker 30 %, slug 70 %
Fine aggregate	Sea sand	specific gravity under saturated surface-dry 2.54 water absorption 2.36 % fineness modulus 2.39
Coarse aggregate	Crushed rhyolite	maximum size 40 mm specific gravity under saturated surface-dry 2.64 water absorption 0.57 % fineness modulus 7.21
Admixture	Limestone powder	specific gravity 2.71 lime purity 99.0 % specific surface area 750000 sq mm/g
Chemical admixture	Superplasticizer	naphthalene-based
	Air entraining agent	modified alkyl carboxyl oxide

TABLE 2 — MIX PROPORTIONS OF CONCRETE

Mixture No.	W/C (%)	s/a (%)	Unit content (kg/cu m)				
			Water	Cement	Limestone powder	Fine aggregate	Coarse aggregate
1	60.5	36.0	145	240	100	638	1179
2					150	621	1148
3					200	605	1117
4	55.8			260	100	632	1168
5					150	615	1137
6					200	599	1106
7	51.8			280	100	626	1157
8					150	609	1126
9					200	592	1095

TABLE 3 — MIX PROPORTIONS OF CONCRETE

Mixture No.	W/C (%)	s/a (%)	Unit content (kg/cu m)				
			Water	Cement	Limestone powder	Fine aggregate	Coarse aggregate
1	60.5	36.0	145	240	120	632	1167
2					150	621	1148
3					180	611	1130
4	55.8			260	120	625	1156
5					150	615	1137
6					180	605	1118
7	51.8			280	120	619	1145
8					150	609	1126
9					180	599	1107
10	55.8	36.0	145	260	30	656	1211

TABLE 4 — MEASUREMENT ITEMS

Items	Measurement method
Pressure in the piping	with pressure gauges
Pump main oil pressure	with pump hydraulic pressure gauge
Actual discharge volume	directly measured by a measuring device
Slump flow Air content Concrete temperature	measured before and after pumping

TABLE 5 — SPECIFICATIONS OF THE PUMP

Name	IPF110B-8E21
Maximum discharge rate (cu m/h)	68.0 (under high pressure)
Theoretical discharge rate (MPa)	8.26 (under high pressure)
Cylinder size (mm)	205 diam x 1600
Hopper capacity (cu m)	0.45

TABLE 6 — QUALITY CONTROL METHOD

Kind	Test item	Test method	Test frequency	Standard value
Aggregate	Sieving	JIS A 1102	once per day	Standard grain distribution of JSCE
	Chloride content of sand	Standard of JSCE	once in the morning and once in the afternoon	---
	Surface moisture of fine aggregate	JIS A 1111	before mixing start and once/30 min	---
	Surface moisture of coarse aggregate	JIS A 1803	ditto	---
Fresh concrete	Slump flow	Standard of JSCE	once/150 cu m after first 5 batches	500 +/- 50 mm
	Air content	JIS A 1128	ditto	4 +/- 1 %
	Temperature	Bar thermometer	ditto	¹
	Chloride content	Simplified instrument	once per day	less than 300 g/cu m
Hardened concrete	Compressive strength	JIS A 1108	the moment when pumping is stabilized (about 150 cu m) and once/300 cu m	$\sigma_{91} \geq 30$ (MPa)
	Mass per unit volume	²	ditto	2300 kg/cu m or more

Note : JIS is short for Japanese Industrial Standard

JSCE is short for Japan Society of Civil Engineers

¹ : 18 deg C or less at the pouring point

² : To be calculated from dimensions and mass of the standard specimen (at 7 days)

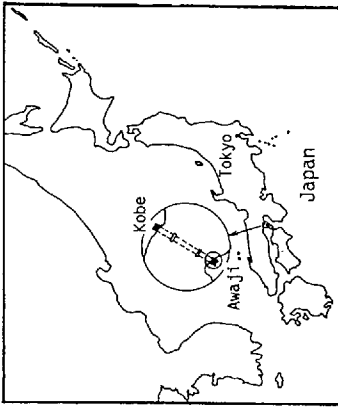


Fig. 1—Situation of Akashi Kaikyo Bridge

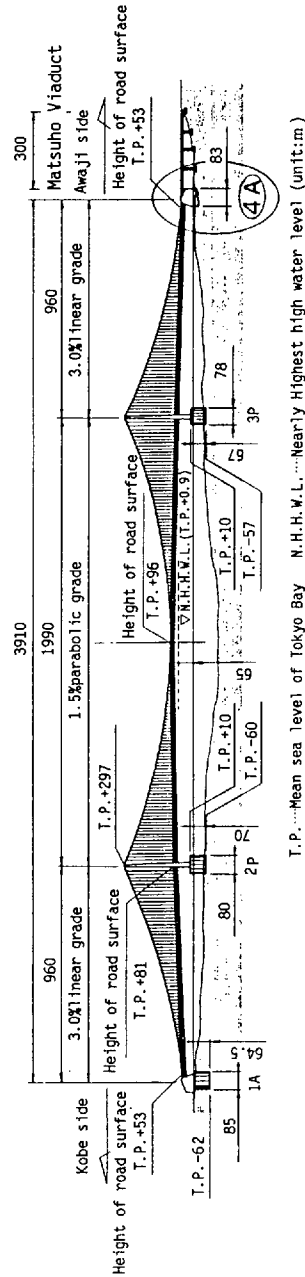


Fig. 2—Side view of Akashi Kaikyo Bridge

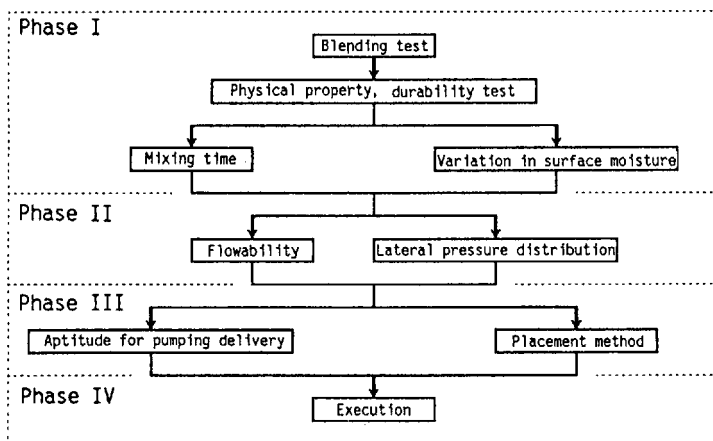


Fig. 3—Flow diagram of experiments

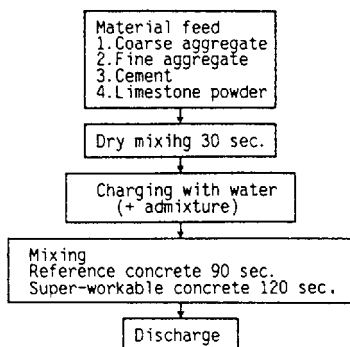


Fig. 4—Flow chart of concrete mixing

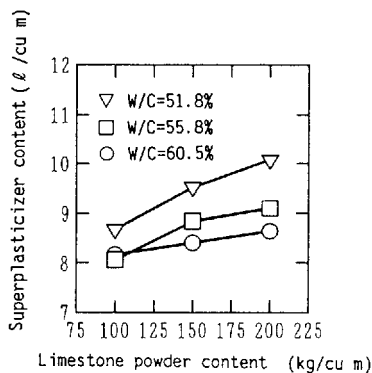


Fig. 5—Content of limestone powder and superplasticizer

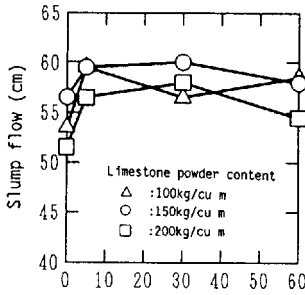


Fig. 6—Time-scale slump flow

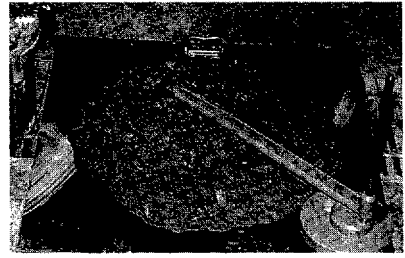


Fig. 7—Slump condition

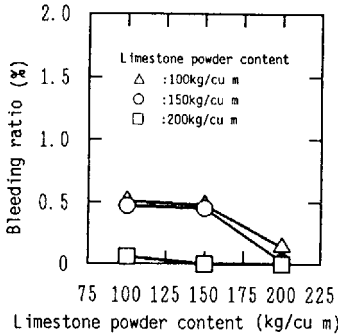


Fig. 8—Bleeding ratio versus limestone powder content

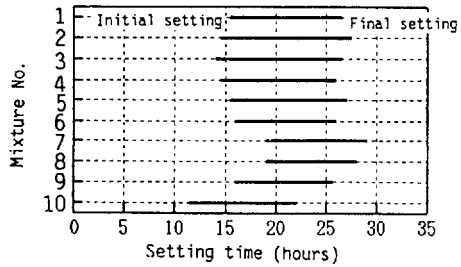


Fig. 9—Setting time of different mixtures

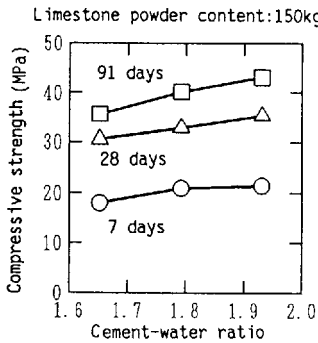


Fig. 10—Compressive strength versus water-cement ratio

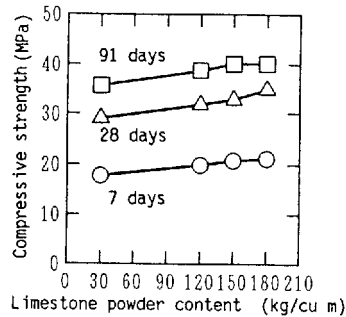


Fig. 11—Compressive strength versus limestone powder ratio