STATE-OF-THE-ART REPORT ON HIGH-STRENGTH CONCRETE IN JAPAN
－RECENT DEVELOPMENTS AND APPLICATIONS－

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SUMMARY

Research and development on high-strength concrete have continuously been done for more than 40 years. This paper describes the past successful technology developments on materials to obtain the workable high-strength concrete and introduces recent enhanced performances as to strength, durability and fire resistance of high-strength concrete. Furthermore, this paper reports some applications of high-strength concrete to structural columns and CFT structures of high-rise buildings and an application of high-strength steel fiber reinforced concrete to a pre-stressed concrete bridge.

Keywords: *High-strength concrete; superplasticizer; silicafume; durability; water-binder ratio; high-rise building; fire resistance; spalling; steel fiber; synthetic fiber; fiber reinforced concrete; CFT; precast block*

INTRODUCTION

Realizing higher strength concrete has been a target or a dream for researchers and engineers engaged in construction industry. In the early 1960's, a superplasticizer was invented in Japan. By the inclusion of the superplasticizer, high-strength concrete could be realized by reducing W/C to under 30%. The high-strength concrete was however applied only to the factory products because it had a large loss in slump. Recent successful researches and developments on materials and construction methods have led to the cast-in place high-strength concrete with good workability, the strength of more than 150 MPa and higher durability. The high-strength concretes have been applied to a lot of high-rise buildings or diaphragm walls. The high-strength concrete however has two defects. One is the occurrence of thermal cracks due to the heat of hydration of a large amount of cement content. To overcome this, many types of low heat cements were developed and utilized. The other is the poor resistance to spalling during fire attack. Inclusion of some synthetic fibers is much effective for reducing the spalling of high-strength concretes.

Furthermore, high-strength steel fiber reinforced concrete (referred to as "RPC") based on a densest packing theory with heat curing was investigated to exhibit compressive strength of more than 200 MPa with great ductility.

Including above mentioned, this report describes recent developments and applications of high-strength concrete in Japan.

DEFINITIONS OF HIGH STRENGTH CONCRETE

ACI committee presents [1] that in the 1960's, 7500 psi (52 MPa) concrete was considered high-strength concrete and in the 1970's, 9000 psi (62 MPa) concrete was considered the same. The committee also recognized that the definition of the high-strength concrete varies on a geographical basis. In regions where 9000 psi (62 MPa) concrete is already being produced commercially, high-strength concrete might be in the range of 12,000 to 15,000psi (83 to 103 MPa) strength concrete.

Meanwhile, Japan Society of Civil Engineers [2] presents that the high-strength concrete is defined as the concrete which has the design strength of 60 – 100 MPa. Architectural Institute of Japan [3] presents that the high strength concrete is defined as the concrete which has the design strength of more than 36 MPa. JIS A 5308 "Ready-mixed concrete" prescribes that the high strength concrete is defined as the concrete which has the nominal strength of 50 or 60 MPa. Definition of the high-strength concrete has changed over the years and has depended on the country and the organization as mentioned above.

According to a lot of results from the research and the technical reports on high-strength concrete, the characteristics of the concrete in the fresh state and hardened state have a tendency to change on the boundary where the strength is around 60-80 MPa. In this paper, taking above mentioned into account, high-strength concrete is tentatively defined as the concrete having the strength of more than 60 MPa.

TECHNOLOGY   DEVELOPMENT

A lot of technology developments which have been done to realize the high strength concrete in terms of material, mix proportion and construction method are introduced here.

Two major remarkable developments of admixtures for high strength concrete are an invention of superplasticizer and a use of silicafume[4,5]. Dr. Hattori developed formaldehyde condensates of beta-naphthalene sulfonates with the primary aim of significantly reducing the water demand of concrete to produce high-strength concrete[6]. Water reductions of up to 30 percent were achieved with the use of this superplasticizer called Mighty 150. This admixture was introduced into the Japanese concrete industry as a nominal name of "high-range water-reducing admixture" in the early 1960's. Since then, it has considerably contributed to produce the high-strength concrete. In Germany, Dr. Aignesberger and his colleagues

developed the melamine based superplasticizer having nealy the same performance as the beta-naphthalene based one[7]. These two chemical admixtures however have one common defect that the loss in slump is considerably large. To solve this problem, new technology of slump control with a reactive polymeric dispersant[8] and a steric hinderance theory were studied. As a result, "an air-entraining and high-range water-reducing admixture" was also developed in Japan. This admixture is mixed in the concrete at the ready-mixed concrete plant and the concrete mixture is transported to the job-site to be placed because the loss in slump is relatively small. Since its introduction, this admixture has dramatically increased in use for achieving high-strength concrete and self-compacting concrete.

Under the circumstances, air–entraining and high-range water-reducing admixture was prescribed into JIS A 6204 (Chemical admixtures for concrete). High-strength concrete shows a small yield stress by the inclusion of the chemical admixture but it shows a high plastic viscosity due to a low water-cement (binder) ratio in terms of rheological aspect. This high plastic viscosity generally makes it difficult to achieve the easy placement. A new type of polycarboxylate based air-entraining and high-range water-reducing admixture has been developed. The admixture imparts the high-strength concrete with high deformability and reduces its plastic viscosity in the period immediately after initial mixing until placement, even when the water-binder ratio is 20% or below.

Silicafume is a by-product from the ferro alloys industry. It consists of extremely fine amorphous silica particles. It must be always used to achieve the concrete with the strength of more than 80 MPa. Replacement of the cement by silicafume increases the strength of the concrete and enhances the durability of the concrete[9]. The reasons for this interesting property may be attributed to a microfiller effect and a pozzolanic reaction of silicafume in the cement based products. The particles of silicafume are a 100 times smaller than the cement grains. A mean diameter is approximately 0.1 μ m. Threfore, it is said that the particle of silicafume is smaller than that of smoke of cigarette. The microfiller effect means that silicafume particles are easily introduced into the space between cement grains, thus reducing the space available for water and producing dense structure of hydration products. The pozzolanic reaction means that silicafume particles react chemically with calcium hydoxide to produce well crystalliszed CSH gel and to enhance durability.

Cement content of mix proportions of high-strength concrete is extremely higher compared with normal strength concrete. Binary cement and trinary cement which contain cement and mineral admixtures are commonly used to prevent the thermal cracks due to heat of hydration. Ground granulated blast furnace slag and flyash are sometimes utilized as mineral admixtures. Also, low-heat or moderate-heat portland cement containing relatively high amount of belite is often used to prevent thermal cracks and to reduce an autogenous shrinkage. These properties are desirable for the massive high-strength concrete.

High-strength concrete is not able to be mixed up by the tilting mixer because of the relatively high plastic viscosity. Long mixing for 2 to 4 min. with the revolving-paddle mixer   is needed to get the workable high-strength concrete.

HIGH STRENGTH CONCRETE FOR CAST IN- PLACEMENT

Information on principal performances such as compressive and tensile strengths, Young's modulus, rate of carbonation, drying shrinkage and freeze-thaw durability of high-strength concrete with the strength up to around 100 MPa have already been published[10,11].   For these several years, a lot of progressive researches and developments have been conducted to the stage that we can use the high-strength concrete with a water-binder ratio of 20％ or below and a design strength of 120 MPa or greater. In this section, principal performances of high-strength concrete with the water-binder ratios down to 12% are shown[12].

Strength

The mix design of the concrete is firstly outlined. Table 1 shows the mix proportions. The binding material was low-heat portland cement as specified in JIS R 5201 with 10% (by mass) replacement by silicafume powder. The water content and the designed air content were 150kg/m^3 and 2.0% respectively in all high-strength concretes. The water binder ratio was varied, with values of 12, 15, 18 and 22%.(These mixtures are referred to as LS12, LS15, LS18 and LS22, respectively.) Two kinds of air-entraining and high-range water-reducing admixtures were used: One was a conventional admixture SPC based on a polycarboxylate polymer with polyethylene oxide and the other was a new admixture SPN based on a polycarboxylate polymer with a new monomer. SPN was developed to impart higher deformability and reduce plastic viscosity of the high strength concrete compared with SPC even if water-binder ratios are under 20％. For comparison, normal strength concrete made from ordinary portland cement, containing an AE water-reducing agent, was prepared (OP55).

Table　1　Mix proportions

No	W/B (%)	s/a (%)	Unit content (kg/m^3)						SP	AEA	Slump-flow (mm)	Slump (cm)	Air (%)
			W	C	LC	SF	S	G	Dosage (B×%)				
LS12	12.0	23.8			1125	125	254		4.0		430		2.4
LS15	15.0	35.7	150	0	900	100	463	836	2.0	0	700	-	1.7
LS18	18.0	41.9			750	83	603		1.5		700		1.8
LS22	22.0	46.6			614	68	729		1.2		675		2.2
OP55	55.0	47.0	176	320	320	0	836	948	0	0.25	-	19.0	4.5

Figure 1 shows the relationship between W/B and the dosages of SPN and SPC to attain the required flowability. Flowability is expressed by slumpflow instead of slump because high flowability (low yield stress) is indispensable for high-strength concrete to achieve the easy placement. The difference between the dosages becomes greater as W/B ratio becomes lower. Even at the concrete with W/B =14％, an SPN dosage of 3.0% was just sufficient. This result pointed out that SPN exhibits much higher dispersibility than SPC and that SPN is more suitable for high strength concrete.

Figure 2 shows the compressive strength. Test specimens were cured not only by standard curing but also by simple adiabatic curing. A simple adiabatic curing means that specimen were formed and cured under sealed conditions in a heat-insulation formwork described in Fig. 3 for 7 days and then were continued to be cured under the condition of in air at 20 ℃ and RH of 60%. The specimens by simple adiabatic curing showed higher strength than those by standard curing at the age of 7 days. Figure 4 shows the temperature hysteresis of

specimens cured by simple adiabatic curing. Compared with standard curing, temperatures of the specimens cured were considerably higher during 7days. These date explain the difference of the strengths at the age of 7days. On the other hand, the specimens by standard curing and those by the simple adiabatic curing showed nearly the same strength at the age of 56 days. This corresponds to the common understanding that the higher the early curing temperature, the lower the increase in compressive strength later on. The highest compressive strength of the standard cured specimen reached 170 MPa by LS18. LS 15 and LS12 exhibited only a little bit lower strengths. From these results, compressive strength of the concrete with water-binder ratios of under 20% can reach more than 150 MPa.

Durability

Figure 5 shows the result of freeze-thaw tests up to 300 cycles. Any drastic reduction in relative dynamic modulus of elasticity could not be measured in the specimens of the high strength concrete. It can be concluded that in the high strength range, even if the air content is approximately 2%, excellent freeze-thaw resistance is achieved. The OP55 specimens exhibited good freeze-thaw resistance because it contained 4.5% air entrainment. The mass change was smaller for every W/B compared with OP55. No scaling occurred in the specimens.

Figure 6 shows the changes in length and mass up to the age of 1 year in the drying shrinkage tests. Both of change ratios of high-strength concretes were much lower than those of OP55. As W/B ratio reduces, both of changes become smaller at all ages. These are explained by the fact that the free water content in the hardened concrete reduces, as W/B ratio reduces.

Figure 7 shows the test results of the chloride ion permeation into LS15 and OP55. At depths between 0 to 2 cm from the surface, chloride ion permeation in LS15 is considerably lower than that in OP55. Chloride ion permeation in OP55 is increasing, but that in LS15 is rarely increasing as the number of cycles increases. JSCE [2] introduces the equations for the prediction of the diffusion coefficient of the concrete which are depending on the water-cement ratios. From these results and considerations, durability of high strength concrete is enhanced in terms of permeability.

Figure 8 shows the total pore volume calculated from the measurement of distribution of pore diameters in specimens. The total pore volumes at all ages are noticeably less in high-strength concrete than in OP55. It is natural to understand that the high-strength concretes have much denser structures in the hardened state than the normal strength concrete. Almost no change in total pore volume of high-strength concrete was seen in the period between 28 days and 6 months. This means that the most of the hydration of cement occurs in the high-strength concrete during the early age. Because all of the water-binder ratios of the high-strength concretes discussed here are below 23% which is the ratio theoretically required for complete hydration of cement.   On the other hand, total pore volume of OP55 decreases in the period between 28 days and 6 months. The hydration of cement gradually occurs after 28 days in the normal strength concrete.

Fire resistance[13]

Figure 9 shows RC specimens with four different strengths after fire resistance test. The degree of the spalling becomes severer, as the design strength becomes higher. It is generally thought from the tests that spalling during fire attack frequently occurs in the high-strength

concrete with strength of more than 60 MPa. **I**t becomes serious problems for building structures and sometimes for concrete linings of shield tunnel. Figure 10 shows RC columns made from high-strength concrete after fire resistance tests. The RC column made from plain high-strength concrete was heavily damaged by spalling as shown in Fig.10 (a). On the other hand, the RC column made from high-strength concrete containing polypropylene (hereafter, referred to as "PP") fibers of 0.33% by volume had no spalling as shown in Fig.10 (b). Effectiveness of PP fibers for reduction in spalling was confirmed by this test. PP fibers are known as effective material for the reduction in spalling. The mechanism of spalling reduction is explained on the assumption that PP fibers in concrete disappear at high temperature leaving tubular pores in the concrete through which the high-pressure vapor in the high temperature concrete flows out easily. According to this assumption, in order to clarify the effect of the diameter and length of PP fibers on the reduction in spalling, fire resistance tests on concrete specimens were carried out. Table 2 shows the mix proportion and Table 3 shows experimental specifications.

Table 2　　Mix proportion and properties of concrete for small specimens

W/C (%)	s/a (%)	Water (kg/m^3)	Cement (kg/m^3)	Compressive strength (MPa)	Moisture content (%)
25.0	42.1	165	660	113	4.5

Table 3　　　Experimental specifications

Fiber			Dimensions of specimen (mm)	Heating condition
Diameter(mm)	Length(mm)	Volume (%)		
12, 18, 30, 48	5, 10, 20	0.10	Rectangular prism 100×100×400	
100	12	0.10		
-	-	0		
48	10	0.05, 0.10, 0.30		
100	12	0.05, 0.10, 0.30		← :heat flow

The results are shown in Fig.11. According to the figure, PP fibers with smaller diameter and longer length are desirable for the reduction in spalling. It can be seen from Fig.12 that the higher the volume of fibers in concrete, the less the spalling. Moreover, it is confirmed from Fig.12 that the smaller diameter and the longer length are advantageous for reducing the spalling.

Next, a lot of fire resistance tests on high-strength concrete containing PP fibers were also carried out to identify the relationships between water-cement ratio and degree of spalling using reinforced concrete elements with different configurations. According to the results, 'spalling reduction ratio' α which is an index of the reduction in spalling by PP fibers was calculated. Figure 13 shows the relationship between calculated spalling reduction ratio and volume percentage of fibers in concrete, and Figure 14 shows the relationship between calculated spalling reduction ratio and W/C ratio of concrete. Each relationship seems to have a linear relation and a regression equation is defined as Eq.1.

$$\alpha = V_f \times \left(43.9 \times \frac{W}{C} - 7.43 \right)$$ (1)

where　　　　　　α : spalling reduction ratio

V_f: volume percentage of fibers in unit volume of concrete, (vol%)

From the equation (1), it is pointed out that the degree of spalling depends on volume of PP fibers and water-cement ratio of the concrete.

Applications To High-Rise Buildings

Applications of high strength concrete to RC columns

The application of high-strength concrete with strength of more than 60 MPa to columns of high-rise buildings started in North America in 1970's[14]. Meanwhile, the application of the concrete that possesses a design strength of 100 MPa or more to columns of high-rise buildings is increasing in Japan and now we have more than 20 applications. Through the use of high-strength concrete floor areas can be increased because it allows the sectional area of building columns to be reduced. In this section, one of the construction records of high-strength concrete applied to a high-rise building with the strength exceeding 150 MPa is reported[15].

The building was a 45-story apartment building in Tokyo as shown in Fig.15. High-strength concrete was applied to the columns from the first to the third floors. Total volume of the high-strength concrete was 700 m^3. Table 4 shows the mix proportions. The compressive strength required from the structural design was 130 MPa and the W/B ratio was 18%. The mix proportion was determined from a lot of results of the field tests conducted in winter and in summer using mock-up columns. The binder consisted of 70% ordinary portland cement, 20% blast-furnace slag and 10% silica fume, and it had been premixed at the cement factory as a trinary cement for high-strength concrete. Compressive strength of cores taken from the mock-up column (800×800mm) made with the concrete using the same binder is described in Fig.16. This binder was proven to develop a high compressive strength up to an age of 10 years. Crushed andesite stone and sand were selected as aggregates for high-strength. A polycarboxylate-type air-entraining and high-range water-reducing admixture was used. Synthetic fibers for preventing spalling in case of a fire were added.

Table 4 Mix proportions

Fc (MPa)	W/B (%)	Unit content(kg/m^3)						Slumpflow (mm)	Air (%)
		W	B	S	G	Fiber(vol%)	SP		
130	18	150	834	647	835	0.22	12.9	650	1.0

(Note)Requirements: Water content (Not more than 169kg/m^3), Slumpflow(600-700mm), Air content(0.5-2.0%)

The concrete was primarily conveyed with a concrete bucket within the construction site as shown in Fig.17 while being partially pumped. At the jobsite, quality control tests were carried out as to air content, slumpflow, water content and compressive strength as shown in Fig. 18. All the results of water content, slumpflow and air content satisfied the requirements. The test results of compressive strength are shown in Fig. 19. The average compressive strength of standard-cured specimens at the age of 56 days exceeded 150 MPa, with the coefficient of variation being as low as 2.0%. During construction, two mock-up columns were constructed with the same high-strength concrete on different days. The top and bottom ends were insulated to correspond the temperature conditions of the mock-up columns to those of the actual columns. The temperature histories near the center of the mock-up columns are shown in Fig. 20. The maximum temperatures of the first and second mock-up columns were 57°C and 62°C, respectively. Fig. 21 shows the compressive strength of the drilled cores. The strengths in both columns satisfied the requirement of 150 MPa at the age of 56 days.

Application of high strength concrete to CFT

Concrete-filled tubular (referred to as "CFT") structure was firstly adopted in 1990's in Japan. The development of the high-strength self-compacting concrete made it possible to fill the concrete completely into a steel tubular column having a number of diaphragms inside. CFT structure has rapidly been prevailing in Japan with the strength requirements for concrete becoming more demanding. In this section, an application record of CFT structure with high-strength concrete to a high-rise building is reported[16].

Building B is a 36-story high-rise office building located in Tokyo as shown in Fig.22. Columns up to 90m above ground were designed in CFT structure. The main columns were square with a cross-sectional size of 800 by 800 mm as shown in Fig.23. Square columns were strengthened with internal diaphragms, each having a round opening in the center with a diameter of 200 to 400mm, through which concrete passed. Concrete was pumped from the ground (see Fig.24) to the allowable level at which the lateral pressure was expected to reach the permissible stress of the welds. Concrete buckets were used for filling concrete in the upper parts of square columns above the pumped level (see Fig. 25).
Circular columns with a diameter of 800 mm were partially used. Since circular columns were found resistant to the lateral pressure by calculation, concrete was placed into circular columns by pumping from the ground to a height of 90 m in a single lift.

Building C is a 47-story high-rise condominium located in Tokyo as shown in Fig.26. The columns at from the first to twelfth floor were designed in CFT structure using concrete with a design strength of 100 MPa. The cross-section of the main columns was a square measuring 900 by 900 mm. Table 5 shows the mix proportions of the high-strength concrete with water binder ratio of about 20% and slumpflow of 650mm. The binder was 70% ordinary portland cement, 20% blast-furnace slag and 10% silica fume.

Table 5 Mix proportions

Plant	Fc (MPa)	W/B (%)	Unit content (kg/m³)					Slumpflow (mm)	Air (%)
			W	B	S	G	SP		
A	100	20	155	775	634	862	13.6	650	2.0
B	100	21	150	714	676	894	14.2	650	2.0

In advance of an actual construction, a trial placement of the concrete into a mock-up column of the actual size was conducted. The concrete was placed with a bucket. Sections of the mock-up column are shown in Fig. 27. The mock-up column was successfully filled with concrete. Figure 28 shows a section of the mock-up column cut by a wire saw. This experiment revealed that the high strength concrete with a high viscosity was filled in all corners of the column to the bottom, including those under diaphragms, without any problem. Figure 29 shows the results of quality control. The average of the compressive strengths of specimens by standard curing was 135 MPa, exceeding the required strength.

Application of fire resistance concrete

PP fibers are known as effective material for the reduction in spalling. Newly developed polyacetal fibers (referred to as "PA"), which are more effective to resistance to spalling, are being used instead of PP fibers. An application of PA fibers is introduced here.

Building D is a 40-story high-rise condominium located in Tokyo as shown in Fig.30.

High-strength concrete was applied to the columns from the first to the eighth floor and the number of the columns was 294. The compressive strength required from the structural design was 80-120 MPa. High-strength concrete with a strength of 120 MPa was applied to columns at the first floor. The cross-section of the columns was a square measuring 1000 by 1000 mm. Table 6 shows the mix proportions of the high strength concrete with a water binder ratio of 15.6% and slumpflow of 650mm. The binder was 90% low-heat portland cement and 10% silica fume.

Table　6　Mix proportions

Fc (MPa)	W/B (%)	Unit　content(kg/m^3)						Slumpflow (mm)	Air (%)
		W	B	S	G	Fiber(vol%)	SP		
120	15.6	145	929	541	875	0.267	12.9	650	2.0

PA fibers (see Fig.31) have been used instead of PP fibers at this project. Figure 32 shows the melting performance of PP and PA fibers. PA fibers melt away at lower temperatures than PP fibers. In advance of an actual construction, fire resistance tests based on mock-up RC columns made with high-strength concrete were conducted to confirm the anti-spalling performance of the two fibers. Figure 33 shows the appearances of the RC columns after fire resistance test. The column containing no fiber suffered heavy damage from spalling. On the other hand, the columns containing fibers had resistance to spalling. But the degree of resistance depended on the kind of fiber and the dosage of the fiber. According to the result, the column containing PA fibers had higher resistance to spalling than that containing PP fibers even if the dosage of PA fibers was smaller than that of PP fibers.

As the strength of concrete increases, the degree of spalling during fire attack becomes severe. Therefore, PP fibers are applied to the concrete with strength of 80-100 MPa and PA fibers are applied to the concrete with strength of 120 MPa or more. Required qualities of the high-strength concrete have been confirmed and the work is now being successfully conducted (see Figs. 34 and 35).

HIGH STRENGTH STEEL FIBER REINFORCED CONCRETE

In Europe, high-performance steel fiber reinforced cementitious composite referred to as Reactive Powder Concrete (RPC) was developed[18]. Steam curing at 90℃ and densest packing design enable to produce precast concrete having high-performance and ultra high-strength of around 200 MPa. The actual applications of RPC have been done by around 35 projects in the world. Recently some applications have been done in Japan and Recommendations for the concrete[19] was established by JSCE. In this section, main features as to mix proportion, properties in fresh and hardened states, mechanical properties, durability and construction method of the first application to pre-stressing concrete bridge in Japan is reported.

Table 7 shows the mix proportions. Water-cement ratio is around 23% and water-binder ratio is 12%. Cement, quartz and silicafume particles are well balanced to obtain the densest packing described in Fig.36. This packing design achieves high-strength and high durability. RPC shows good flowability (self-leveling property) to be cast into the thin mold or into the

complicated shaped mold. It takes 8-14min. to be mixed to get the specified flowability even by the revolving-blade mixer.

Table 7　Mix proportions

Steel fiber			Unit　content(kg/m^3)					Flow value (mm)
Diameter (mm)	Length (mm)	Volume (%)	W	C	Grain (quartz, sand etc.)	Steel fiber	SP	
0.2	15	2	180	774	1523	157	22(liquid)	240-260

The compressive strength of RPC is 200-240 MPa and the tensile strength is around 9 MPa after 90℃ heat curing for 48 hours. Figure 37 shows a relationship between typical load bending stress and deflection of a beam. The first initial crack stress (25-30 MPa) mainly depends on the flexural toughness of mortar matrix and the ultimate flexural stress (40-45 MPa) depends on the bridging effect of steel fibers. RPC has very high energy absorption capabilities. The high tensile strength combined with enough ductility makes conventional reinforcement unnecessary. The 15mm long steel fibers inside of the mortar matrix act as reinforcement to resist for tensile stress.

RPC forms a dense matrix structure due to the densest packing design and pozzolanic reaction. Test results present that RPC has an excellent freeze-thaw resistance and an excellent abrasion resistance. The microstructure of the RPC is so dense that it is difficult to determine the diffusion coefficient of chloride ion. The diffusion coefficient determined by special methods by the use of EPMA analysis or electrical permeation test method ranged between 1.9 and 2.2 $\times 10^{-10}$ cm^2/sec. This value is approximately 1/100 of that of conventional high-strength concrete. Figure 38 compares the calculated chloride profiles within the specimens exposed to a surface chloride content of 3.0kg/m^3. In the case of RPC, the depth at which the chloride concentration reaches the threshold value for corrosion (1.2kg/m^3) is approximately 1/10 of that of conventional high-strength concrete.

RPC premix, water and a chemical admixture were mixed as a primary mixing. After checking the flow value, steel fibers were added to the mixture and it was mixed as a secondary mixing for 7 min. The flow value was checked again (see Fig.39). Mixed RPC was placed through a tremie attached to the hopper outlet to manufacture the precast blocks described in Fig.40. After placing, the block was cured by sheets to prevent water evaporation as a primary curing. For secondary curing, 90℃ steam curing was conducted for 48 hours in a house. The rate of rising and dropping temperature were controlled to15℃/h and 7 to10℃/h, respectively to prevent the cracks due to temperature difference in the blocks. Transverse wet jointing of blocks was conducted in the plant prior to installation(see Fig.41). After blocks were fixed on both sides, RPC was poured from the bottom slab to the top slab. The joints were heat-cured by electrical heaters and insulation. The specified strength was achieved as temperature between 70 and 90℃ was maintained at joints.

CONCLUDING REMARKS

More than 40 years have passed since a high-strength concrete was realized. The high-strength concrete itself has been enhanced in terms of performance and placeability

through a lot of useful developments to the stage that now many applications have been done in north America, Europe, Japan and other countries. In the near future, the high-strength concrete will be prevailing and increasing in use all over the world.

Meanwhile, the fact is that to acquire the much higher strength of the concrete has been one of the dreams and is also one of the incentives to research and development for researchers and engineers. Many reliable data as to the relationship between the total pore volume and compressive strength exist. Extrapolating the date, the compressive strength can theoretically reach 700 MPa as the total pore volume of the concrete will be reduced to be in the vicinity of zero. Research and development on high-strength concrete making full use of more advanced technologies will continue until the strength of the concrete reaches this limit.

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(19) Japan Society of Civil Engineers, "Recommendations for Design and Construction of Ultra High Strength Fiber Reinforced Concrete Structures – Draft, " September, 2004.

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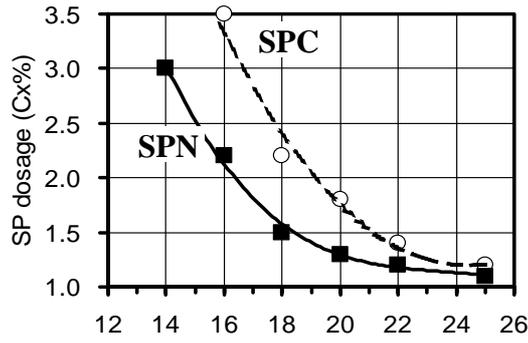
Fig. 1   Comparison of SP dosage

Standard curing
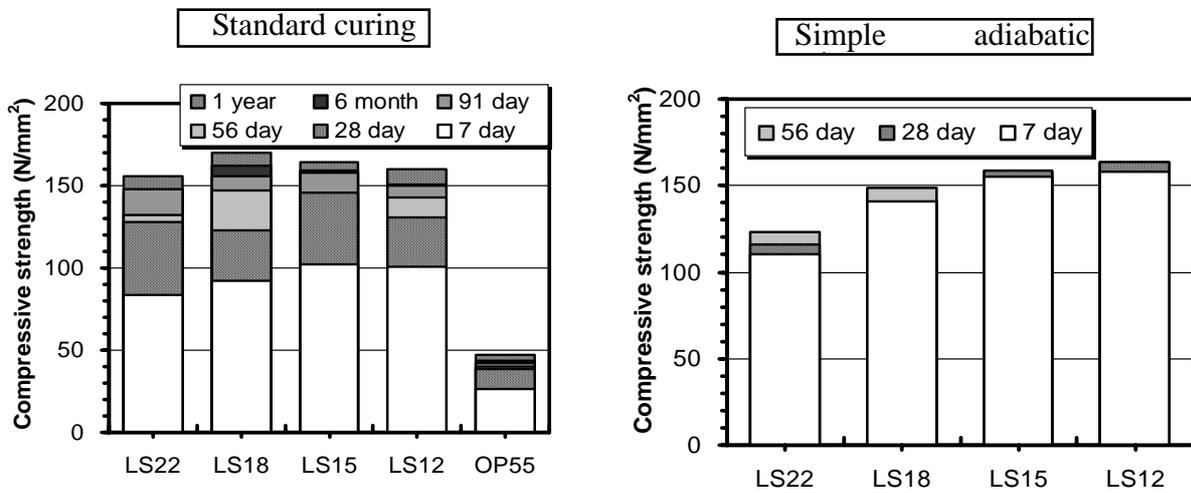
Simple   adiabatic

Fig. 2   Compressive strength
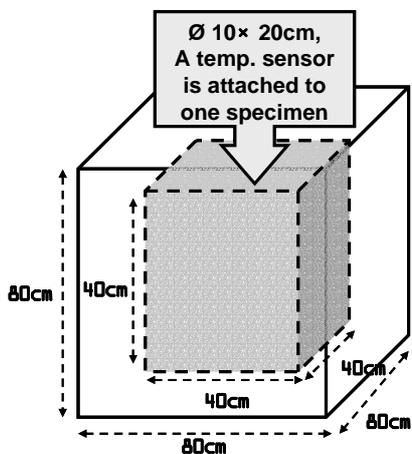
Fig. 3 Diagram of simple adiabatic curing method
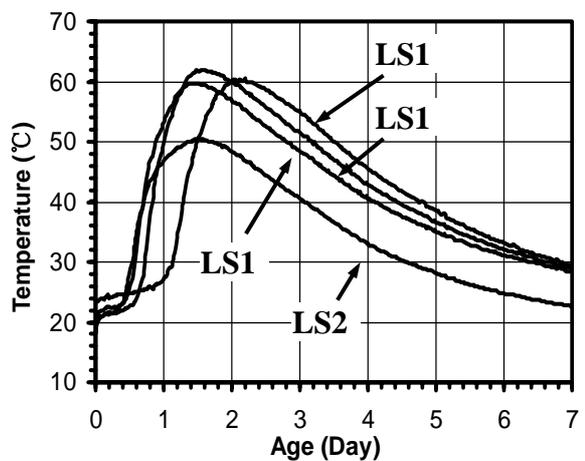
Fig. 4   Temperature hysteresis of specimens cured by simple adiabatic curing
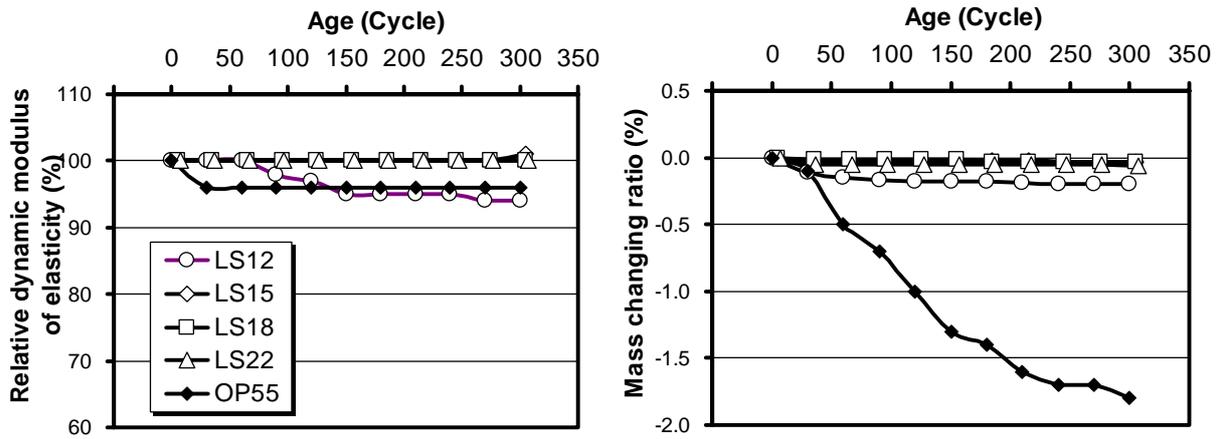
Fig. 5   Freeze-thaw test
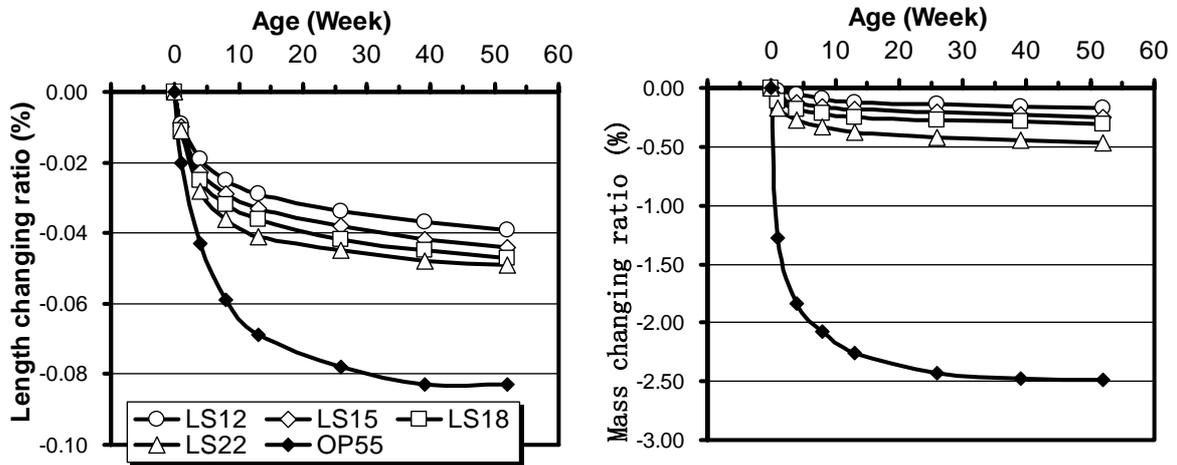
Fig. 6   Changes in length and mass
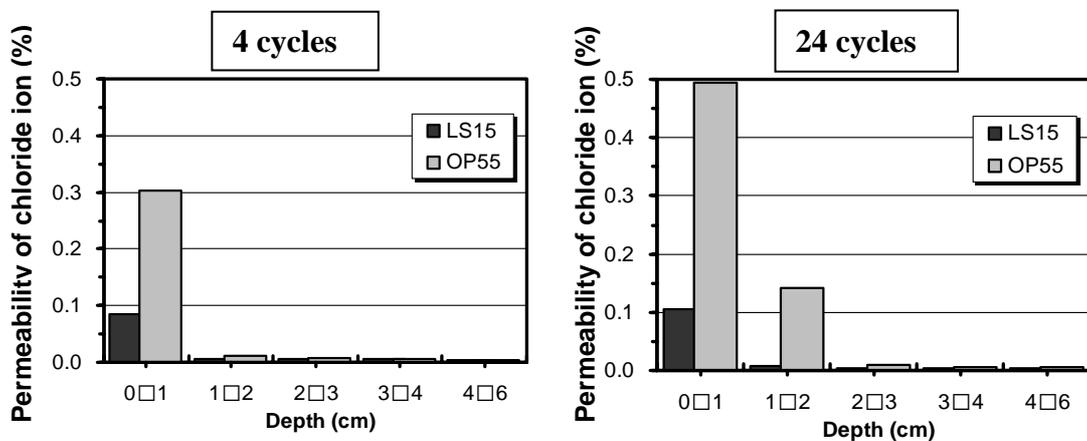
Fig. 7   Chloride ion permeability

Fig. 8　　Total pore volume

Fc=48 MPa　　　　Fc=60 MPa　　　　Fc=80 MPa　　　　Fc=120 MPa
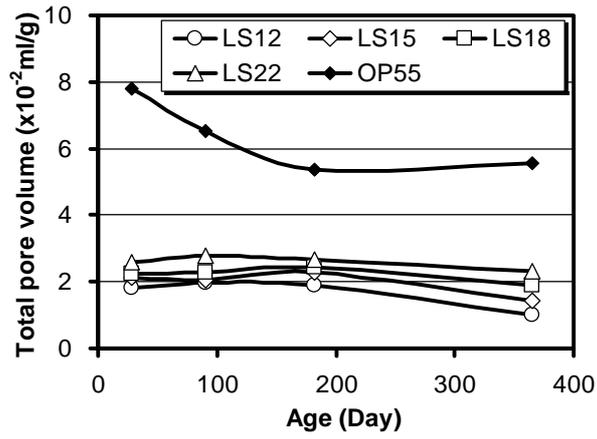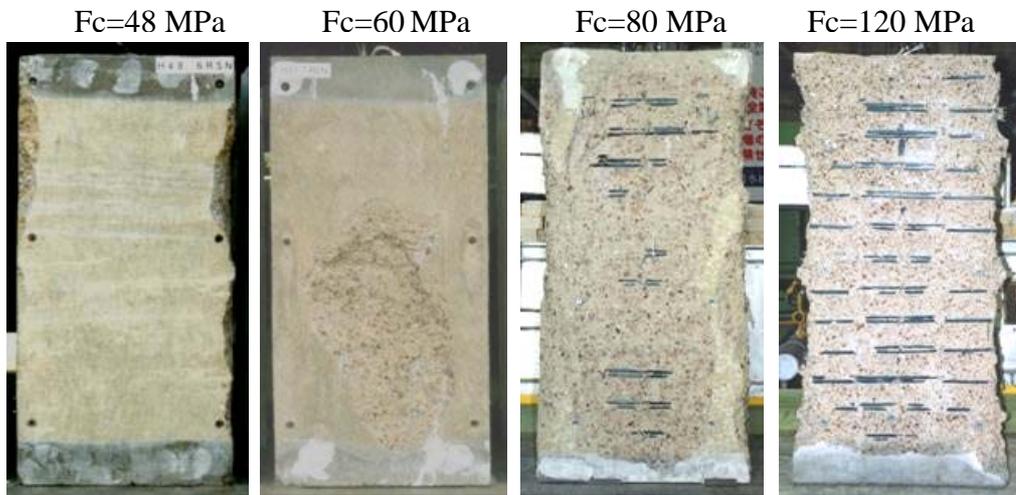
Fig. 9　　RC specimens after fire resistance test

(a)　　　　　　　(b)

Fig. 10　　RC columns after fire resistance test
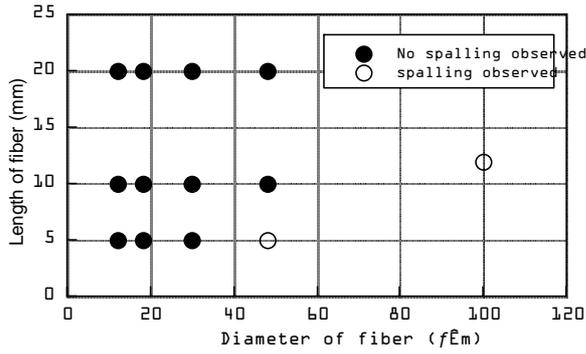
Fig. 11 Influence of diameter and lengths of synthetic fibers on spalling reduction
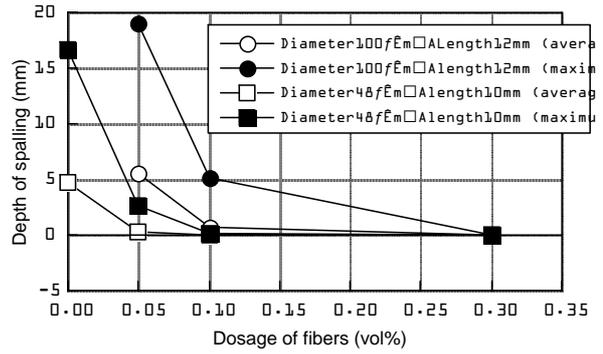
Fig.12 Relationships between volume of synthetic fibers in concrete and spalling reduction
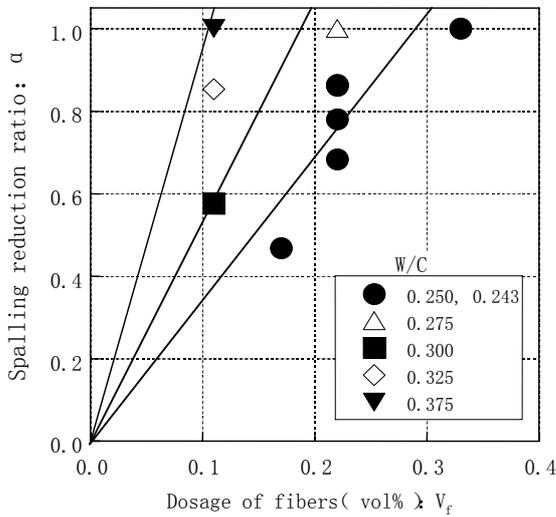
Fig. 13 Volume percentage of fibers. vs. spalling reduction ratio
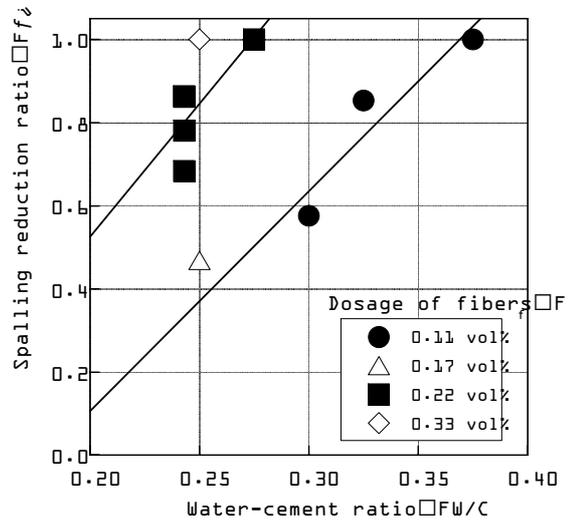
Fig. 14 W/C ratio vs. spalling reduction ratio

Fig. 15 The high-rise building
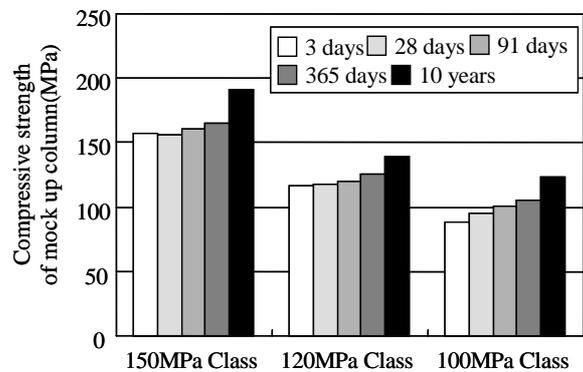
Fig. 16 Long-term compressive strength of mock-up columns using developing binder

Fig. 17   Placement with a bucket

Fig. 18   Quality control test

Average: 154MPa
Standard deviation: 3.1MPa
Coefficient of variation: 2.0%
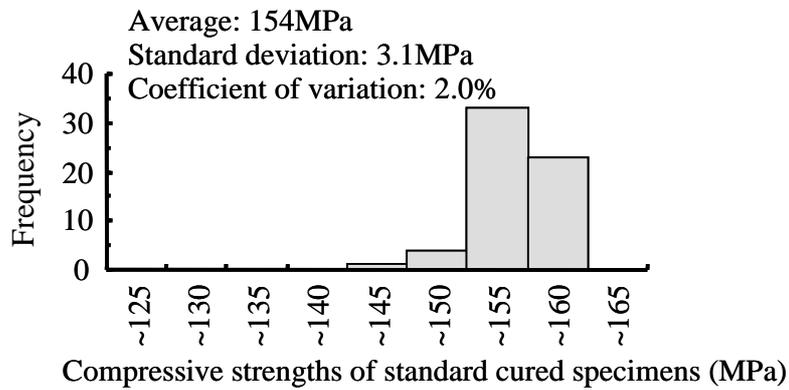
Fig. 19   Results of compressive strength
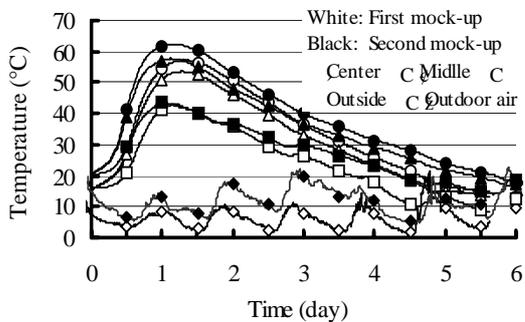
Fig. 20   The temperature histories of
the mock-up columns.
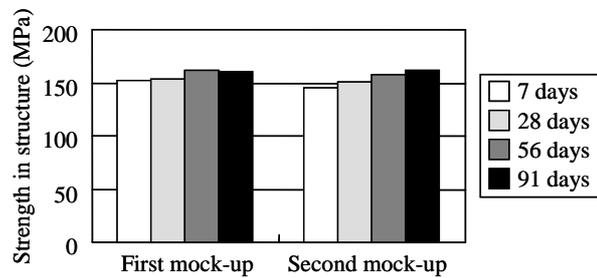
Fig. 21   Compressive strength of
concrete in structure.

Fig. 22   Office building

Fig. 23   Diaphragms in a steel tubular column

Fig. 24   Placing with a concrete pump

Fig. 25   Placing with a concrete bucket

Fig. 26   Condominium
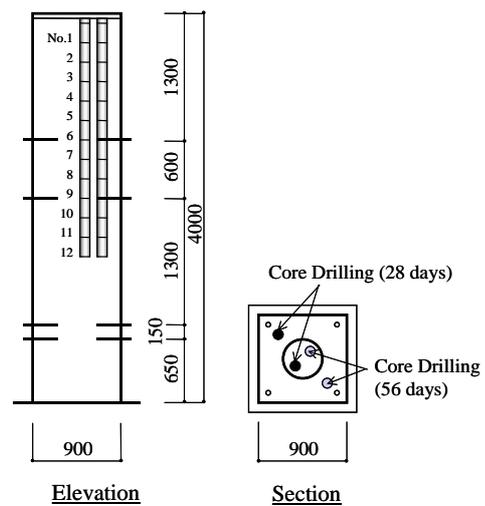
Fig. 27   Sections of mock-up column

Fig. 28   A cut section of mock-up column

Average: 135MPa

coefficient of variation: 3.2%
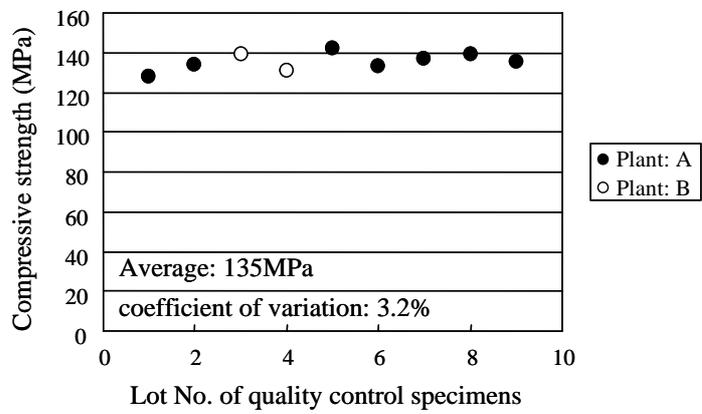
Fig. 29   Results of quality control
of 100 MPa concrete

Fig. 30   Condominium

Fig. 31   Polyacetal fibers
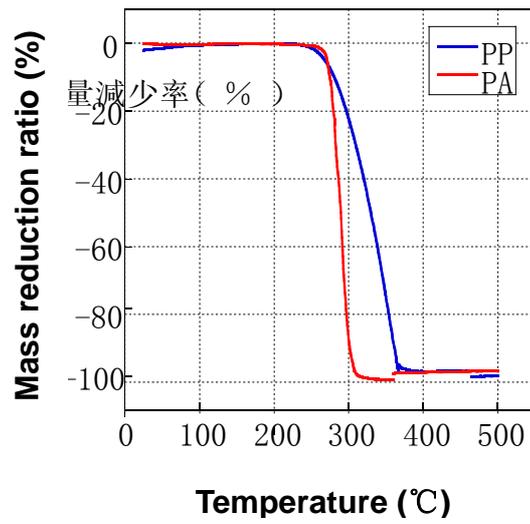
Fig. 32   Melting performance of fibers

Plain   PP 0.3vol%   PA 0.2 vol%

Fig. 33   Columns after fire resistance test

Fig. 34   Quality control tests

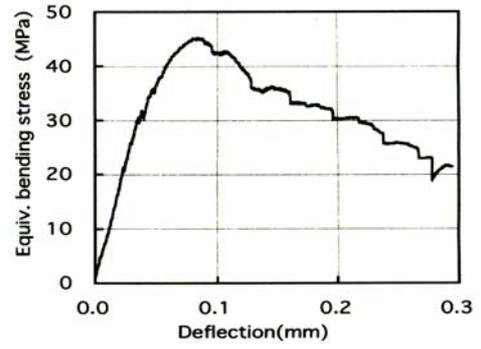Fig. 35   Placement with a bucket
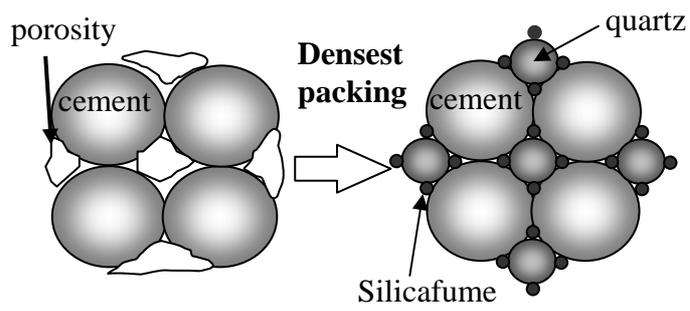
Fig. 36　Packing mix design
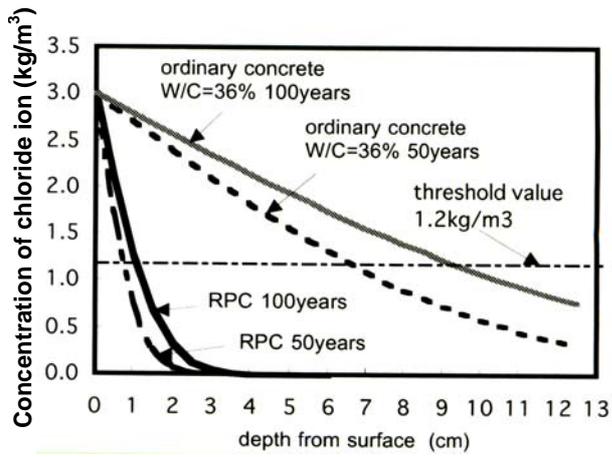

Fig. 37　Flexural behavior
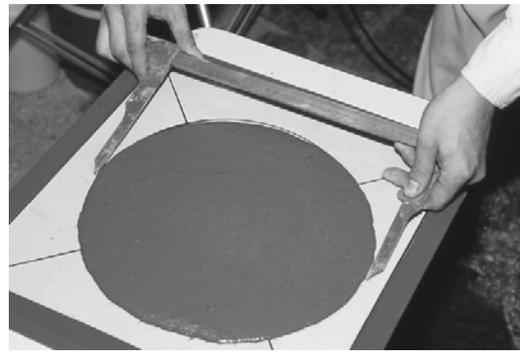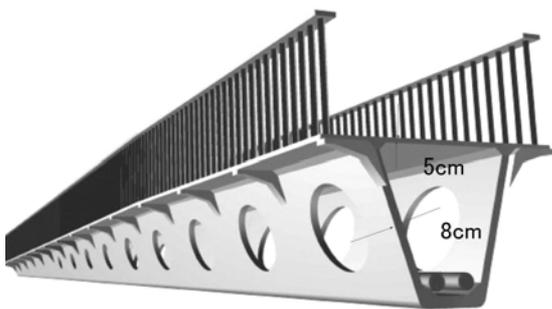

Fig. 38　Chloride profiles

Fig. 39　Measurement of flow value

Fig. 40　Precast block

Fig. 41　Installation of block

107