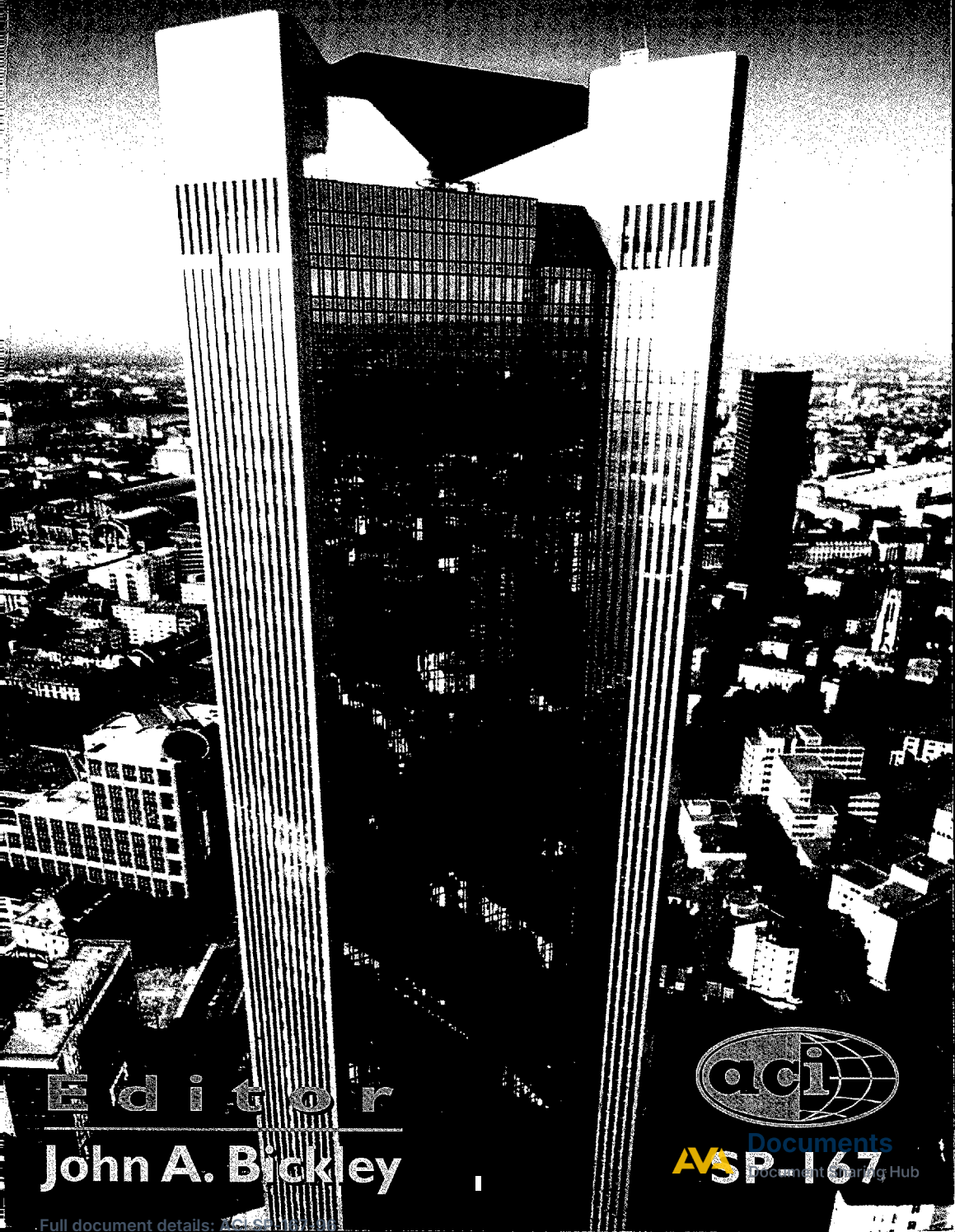


High-Strength Concrete: An International Perspective



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High-Strength Concrete: An International Perspective

Papers presented at three half-day
sessions at the ACI Convention in
Montreal, November 1995

The sessions were cosponsored by ACI
Committee 363, High-Strength Concrete,
and by Concrete Canada, the Network
of Centres of Excellence on
High-Performance Concrete

Editor
John A. Bickley



DISCUSSION of individual papers in this symposium may be submitted in accordance with general requirements of the ACI Publication Policy to ACI headquarters at the address given below. Closing date for submission of discussion is August 1, 1997. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the November-December 1997 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

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Printed in the United States of America

Editorial production Anne Sharp

Library of Congress catalog card number 96-79562

PREFACE

The 15 papers in this special publication were presented at three sessions at the ACI Fall Convention in Montreal in November 1995.

The 15 papers were submitted from nine countries. Five papers were by invited speakers from Japan, France, Norway, Holland, and Germany. These authors were asked to present a view of activities in this field in their countries. Five papers were presented by researchers from Concrete Canada and provide a view of some of the work done by this group. The remaining five papers were chosen from those submitted in response to a call for papers published in *Concrete International*.

Thanks are due to those who reviewed the papers for publication: Pierre-Claude Aitcin, Scott Alexander, Michael Collins, John Fowler, Doug Hooton, Brian Hope, Yvette Hughes, Bob Loov, Jim McGregor, Denis Mitchell, Rusty Morgan, P. K. Mukerjee, Dave Rogowsky, John Ryell, Phil Seabrook, Michael Shirlaw, Michael Thomas, and Paul Zia.

It is hoped that these papers make a small but valuable addition to the literature on high-strength concrete.

John A. Bickley

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High-Strength Concrete in Japan: History and Progress

by Shigeyoshi Nagataki

Synopsis: In Japan high strength concrete was first achieved as early as the 1930s. Yoshida reported in 1930 that high strength concrete with 28-day compressive strength of 102 MPa was obtained. This result was obtained by a combination of pressing and vibrating processes without the use of any chemical and mineral admixtures. This method has been applied for production of high strength segments.

In the 1960s, superplasticizers were developed in Japan and West Germany which were very effective chemical admixtures to decrease the water content in concrete. With the use of superplasticizers, it became possible to decrease the water to cement ratio while maintaining the workability of the concrete. This technique was applied very widely and many bridges, high-rise buildings, precast concrete members have been produced.

In the 1970s, the combined use of superplasticizers and ultra-fine materials such as silica fume, finely ground blast furnace slag or anhydrous gypsum based additives were studied and has been applied to concrete structures until today.

Finally, super high strength concrete greater than 120 MPa in compressive strength was achieved with selected materials and special techniques and this kind of concrete has been applied in other industries instead of in the construction industry. This paper summarizes the history and progress of the development of high strength concrete in Japan.

Keywords: Blast furnace slag; bridges (structures); buildings; concretes; gypsum; high-strength concretes; precast concrete; silica fume; superplasticizers.

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INTRODUCTION

For structural construction, if the material strength can be increased, not only can the cross-sectional dimension be reduced, the dead load can also be lightened. As a result, the use of high strength materials is significantly important to the rational design of a structure, especially a concrete structure. Therefore research on improving concrete strength has been carried out for many years in Japan.

At present, by using a superplasticizer (it is also called a high range water reducing agent), the water to cement ratio can easily be reduced by about 30%. As a result, concrete of 80 to 100 MPa compressive strength not only can be manufactured in a factory but also can be produced on site.

However, during the period when water reducing agents were not available, reports showed that concrete strengths greater than 100 MPa had been successfully achieved by expressing excessive water out of concrete (1). This is attributed to the reduction in final water to cement ratio. From this example, it can be seen that the reduction of water to cement ratio is undoubtedly an effective measure to obtain high strength concrete. At present, research has been carried out to establish methods of obtaining high strength concrete by controlling the microstructure and composition of the hydration products in concrete, with improved curing methods or with the use of various mineral admixtures, in addition to the reduction of water to cement ratio. Some of these methods have been put into practical use.

As a state of the art report for high strength concrete, this report summarizes the history and progress of the development of high strength concrete in Japan.

DEFINITION AND HISTORY OF HIGH STRENGTH CONCRETE

The definition of high strength concrete is varied among different countries and kinds of structures. There is no standard criterion of strength required for high strength concrete. For example, at present, the specified design strengths of concrete for reinforced concrete buildings in Japan are 36 MPa for 25 stories, 42 MPa for 30 stories and 48 MPa for 40 stories in height respectively. Higher strength concrete shall be used in the construction of higher multistory buildings (2). On the other hand, in the recommendations published by the Japan Society of Civil Engineers (3), high strength concrete is defined as concrete having a compressive strength of 60 to 80 MPa.

However, as an overall interpretation, it can be considered that high strength concrete is defined as having compressive strength of 50 to 120 MPa, and beyond this range it is defined as super high strength concrete. Currently 100 to 120 MPa is considered as the upper limit for concrete strength used in the construction industry. Beyond this limit, there is at the moment no merit recognized for the design as well as the financial aspect of construction, and it is used as a material for other industries.

As mentioned previously, high strength concrete with compressive strength greater than 100 MPa has been obtained since the 1930's. Figure 1 shows the results obtained by Yoshida (1) in 1930. It shows that compressive strength at the age of 28 days up to 100 MPa can be obtained as a result of compaction by high pressure. In 1934, Menzel (4) also reported that cement paste of compressive strength greater than 130 MPa was obtained by autoclave curing. Almost at the same time, Freyssinet also reported the achievement of obtaining compressive strengths greater than 100 MPa.

As the attainment of concrete strength of 100 MPa became certain, prestressed concrete structures with high strength concrete became lighter as well as more economic than steel structures under certain circumstances. In view of this, a high strength concrete committee was set up in FIP. A report was submitted by the committee at the 5th FIP Congress in 1966 (5). In this report, a number of methods of obtaining high strength concrete were introduced. Among these methods, most of them were at the laboratory level, but practical methods liked resin concrete and polymer impregnated concrete, etc., were also included. However, all these latter methods are very costly as special facilities are required. Therefore, they are not suitable

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to be used in general construction. In 1968, applying the method of manufacturing autoclaved lightweight concrete, by autoclaving mortar containing silicate powder, a technique of obtaining a compressive strength of 80 MPa was reported. In 1970, a technique of obtaining a compressive strength of 90 MPa was reported (6) by using a large quantity of superplasticizer under autoclave curing instead of using silicate powder. This technology is the first practical example in the history of high strength concrete of the use of a superplasticizer. Since then, the development of the high strength concrete has become impossible without the use of superplasticizer. In view of this significant role, many international conferences and workshops on the use of superplasticizer have been held one after another (7,8,9).

Figure 2 shows a very interesting phenomenon. It shows the relationship between the train speed in the Tookaido Line and the corresponding allowable concrete stress in the history of Japan National Railway (10). It can be seen that the correlation is fantastically high. However, in Japan, prestressed concrete has been used in railway structures only since 1955. If the railway structures are made with prestressed concrete, then the allowable concrete stress will become even larger. In such a way, high strength concrete can be effectively used.

CLASSIFICATION OF STRENGTH IMPROVING METHODS

By considering concrete as a two phase composite material with cement paste and aggregate, methods of strength improvement of concrete can be classified into four categories as shown in Figure 3. These are:

1. Strength improvement of cement matrix
2. Strength improvement of aggregate
3. Improvement of bond strength between the cement matrix and aggregate
4. Strength improvement by confinement

Category 1 may further be classified into two sub-categories. These are reduction of porosity and strength improvement of hydration structures. This report mainly focuses on category 1 to discuss the high strength improvement of concrete.

STRENGTH IMPROVEMENT OF CEMENT MATRIX

The strength of the cement matrix is dependent on the strength of the hydration structures and the porosity of the matrix due to its porous character. The strength of the cement matrix increases with a decrease in porosity. The porosity can be reduced by decreasing the water to cement ratio. Therefore, reducing the water to cement ratio is a method of attaining high strength matrix.

The strength of hydration structures can be improved by the addition of various mineral admixtures or using optimum curing conditions.

However, in actual practice, reduction of water to cement ratio and strength improvement of hydration structures are not carried out separately to improve cement matrix strength. These two measures are usually carried out together at the same time. For example, in the case of using various mineral admixtures to attain high strength, the matrix porosity decreases together with an increase in the strength of hydration structures. The decrease in porosity is due to the hydration products filling up the pores. Similar to this example, most of the cases of attaining high strength are as a result of the combination of these two measures. From here onwards, the measures of strength improvement will be discussed in detail.

Methods of compaction and curing

Pressing compaction and centrifugal compaction can be used to reduce porosity and to reduce the water to cement ratio by pressing out the excessive water as a measure to attain high strength. Yoshida is well known for his research (1) on the pressing compaction method. Pressure of 10 MPa is applied to specimen during its first day of curing followed by standard curing. It is reported that this method will result in 70 MPa compressive strength at the age of one day and result in 100 MPa at the age of 28 days. To date, this method is still being used to manufacture concrete segments as pressed concrete. Centrifugal compaction is used to manufacture cylindrical products such as poles, piles and pipes, etc., at factories. The use of the centrifugal force, not only enables the concrete to be homogeneously compacted into cylindrical shapes, but the water to cement ratio is also reduced by a decrease in porosity and expression of excessive water from the matrix as a result of compaction by the centrifugal force and its induced vibration.

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Among the curing methods available, pressure curing, steam curing and autoclave curing are all used to obtain high strength. Pressure curing can be further classified into normal temperature or high temperature curing. Steam curing and autoclave curing are carried out under high temperature so as to accelerate cement hydration and thus achieve high strength within a short period. Especially, for autoclave curing, hydration products are different due to hydrothermal reaction. Depending on the molar ratio of CaO/SiO_2 of the material used and the curing conditions different compressive strengths are obtained. Therefore, with an optimum mixture and curing condition, high strength can be attained (4,11). In practice, superplasticizer and mineral admixture usually are also used in addition to these curing methods to produce high strength concrete.

Superplasticizer

Superplasticizer is a chemical admixture which aids in attaining high strength concrete. It can significantly improve the dispersibility of cement particles and thus enable a decrease in the water to cement ratio. In addition, it will result in decrease in void ratio due to smaller air entrainment. Superplasticizer was first introduced by Hattori in 1962 with sulphonated naphthalene-formaldehyde condensates as its basic chemical component. A few years later, superplasticizer with sulphonated melamine-formaldehyde condensates as its basic chemical component was introduced by Aignesberger in West Germany. Since then, a number of the same kind of superplasticizer have been developed. At present, the superplasticizers used in Japan can be divided into four categories, i.e. naphthalene type, melamine type, polycarboxylic acid type, and aminosulfonic acid type. The majority of them are of the naphthalene type. Many studies have been carried out on the properties of concrete containing superplasticizer. It has also been used on many construction sites. With the use of superplasticizer, the water to cement ratio of concrete having a 100 to 200 mm slump can be reduced by about 30% thus resulting in high strength of concrete. Figure 4 shows the relationship between the cement to water ratio of concrete and compressive strength. It can be seen that compressive strength increases with an increase in the cement to water ratio and that compressive strength of 100 MPa can be obtained by autoclave curing (6,12). Superplasticizer (High range water reducing and air entraining agent) was put into the Japan Industrial standard A 6204 (Chemical admixtures for concrete) in March, 1995.

Ultra fine powder

Silica fume-- Silica Fume is the by-product of manufacturing silicon metal and ferro silicon. It contains 70 to 90 % of SiO_2 and is in the form of an ultra fine powder with average particle size of $0.1 \mu\text{m}$. Norway is the country producing and utilizing most silica fume (13). Research on the utilization of silica fume in concrete started at the Norway Technological Research Institute in 1950. However, the use of silica fume in concrete increases rapidly only after its significant effect on concrete was reported at the First International Conference on Fly Ash, Silica Fume, Slag and Other Mineral By-products in Concrete (14) in 1983. Many reports on silica fume was presented at the following International Conferences (15) as well as the workshops (16) on silica fume.

Silica fume is in the form of ultra fine powder. It is necessary to use it together with superplasticizer to improve the workability of the concrete and to ensure the dispersion of the silica fume. Figure 5 shows the effect of curing condition on the pore volume of cement paste containing silica fume (17). The longer the water curing period or the higher the curing temperature, the smaller the pore volume. Therefore, with proper mixture design and curing, concrete containing silica fume can be obtained with high strength and excellent durability. In view of this, silica fume is considered as a suitable admixture for making high strength concrete. However, in Japan, it is 4 to 5 times more expensive than cement. Therefore, it can not be considered as a substitute for cement, in the same way as fly ash and slag powder. Figure 6 shows the relationship between the replacement ratio of silica fume with cement and corresponding compressive strength of mortar with a water to cement ratio of 0.30 (18). The replacement ratio for obtaining the maximum strength is varied for different curing methods. For the case of water curing, a 15% replacement ratio results in maximum strength. For the case of high temperature curing, maximum strength is obtained at a replacement ratio of 30%. This is attributed to the effects of hydration. The maximum strength for water curing at the age of 28 days is 100 MPa and for autoclave curing, it is 140 MPa at the age of 3 days.

A recommended practice for the use of silica fume in concrete was published by the Japan Society of Civil Engineers in October 1995.

Blast furnace slag powder-- Partial replacement of cement with blast

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furnace slag powder can improve fluidity and enhance the resistance to sea water and chemical attack, and also reduce the heat of hydration etc. These performances have been proved in many actual projects. In recent years, research on utilizing blast furnace slag powder with Blaine fineness values ranging from 8000 to 10000 cm^2/g as a high strength mineral admixture have been carried out in Japan. Figure 7 shows the relation ship between the compressive strength of concrete and the replacement ratio of blast furnace slag powder with cement (19). Together with superplasticizer, the use of ultra fine blast furnace slag powder (VFslag) can result in higher strength at early ages as compared to the use of the blast furnace slag powder of ordinary fineness (ORslag) with superplasticizer. The strength is almost as high as that with only superplasticizer alone. In addition, the long term compressive strength of the former is also significantly increased.

Table 1 shows that together with VFslag and superplasticizer, the use of water granulated iron-blastfurnace slag sand can be used to obtain compressive strengths greater than 100 MPa at the age of 28 days (20). The Japan Industrial standard A 6206 (Ground granulated blast-furnace Slag for use in Concrete) was authorized in March 1995. In this standard, blast furnace slag powders are divided into three classes, 4000, 6000, and 8000. These number indicate fineness of the powder by Blaine method. The 8000 class is mainly used for high strength concrete.

Anhydrous gypsum admixture

Table 2 shows the chemical composition of a high strength admixture with anhydrous gypsum as its main composition. Figure 8 shows that with the use of this admixture together with superplasticizer, even without autoclave curing, high strengths of 100 MPa can also be obtained. The water to cement ratio was 0.29 when the cement content 470 kg/m^3 and fine aggregate ratio 42%. This is one of the mix proportions that is being currently used in Japan for the production of high strength concrete piles. For this mix, the strength is about 80 MPa just after steam curing, and the 28-day strength is over 100 MPa. Figure 9 shows the hydration process of hydraulic material at each curing stage. It clearly shows that the formation of ettringite increases with a decrease in anhydrous gypsum followed by the active reaction of alite. The increase in compressive strength is attributed to the formation of ettringite together with a decrease in pore volume as shown in Figure 10 (21,22).

In comparison with autoclave curing, the use of this admixture has an advantage of producing a concrete with a lesser loss of induced prestress. Therefore, it has been used to manufacture high strength prestressed concrete piles and poles, and high strength driving pipes, etc..

STRENGTH IMPROVEMENT BY OTHER MEASURES

Higher strength can also be achieved by improving the interfacial bond strength between the aggregate and cement matrix. Using cement clinkers as aggregates is one of the ideas to enhance bonding strength.

Also the use of stronger aggregates with superior surface characteristics improves the strength. Figure 11 shows the relationship between the water to binder ratio and the compressive strength of DSP mortars with various kinds of aggregates (23).

APPLICATIONS OF HIGH STRENGTH CONCRETE

Factory products

Factory products (precast concrete) can be placed in special curing such as steam curing and autoclave curing etc. Therefore, by positively and effectively making use of these curing methods, high strength concrete can be produced. To attain high strength factory products, a combinations of the above mentioned high strength approaches are usually carried out. For example, by using ultra fine powder as a mineral admixture, together with a reduction in the water to cement ratio by the use of superplasticizers, high strength prestressed concrete piles can be produced by centrifugal casting and then steam curing followed by autoclave curing. High strength piles or other products can also be made by using high strength admixtures together with steam curing. All these products have already proved to have excellent performance such as a decrease in the number of piles required for construction and lower losses upon placing of piles. The production of piles in Japan in 1994 was 5,901,014 tons and about 90% of them were high strength concrete piles. In addition, centrifugally cast reinforced concrete pipes (especially, driving types), prestressed concrete beams and members of prestressed concrete truss bridge members etc. are also among these factory

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products. Examples of prestressed concrete bridges using high strength concrete with superplasticizers are summarized in Figure (12).

High-rise buildings

For the construction of high-rise reinforced concrete buildings the strength of concrete utilized generally ranges between 36 to 48 MPa and chemical additives such as superplasticizers are usually used. In 1988, the Building Research Institute in the Ministry of Construction (MOC) started a 5 year research and development project called "Development of High-strength and High-quality Reinforced Concrete Construction System (New RC Project)", which aims to develop advanced reinforced concrete buildings with high strength and high quality materials. According to this report, 60 MPa as design strength of concrete is a target at present. As shown in Table 3, it is possible to manufacture concrete with 60 MPa design strength utilizing materials available on the market, but high strength concrete of over 60 MPa has less possibility of actual usage at the moment (2).

High strength concrete is used in the columns of high rise reinforced concrete buildings to carry the loads economically and to provide relatively more floor space by having smaller cross-sections. All the high rise buildings in Japan are designed for earthquake excitations. For these special design conditions, the arrangements of the reinforcement in the joints is rather congested. Consequently the flowability and the filling capacity of fresh concrete is very desirable. Slump loss in fresh concrete is a serious problem in relation to flowability and filling capacity.

As shown in Photo 1, Shinagawa Prince Hotel was built by using high strength concrete. Total floor area is 108,536 m². Height is 137.98 m, 39 stories and 2 stories underground. In the construction of this building, 60 MPa high strength concrete with silica fume and superplasticizer was filled into steel tubes up to 61 m long at a time using the technique of bottom-up concreting. Concreting was conducted under extremely simple and clean conditions (24).

Bridges

In the 1970s, many railway bridges and highway bridges were

constructed of high strength concrete as shown in Figure 12. The purpose of using high strength concrete was to reduce the dead load. In the Second Ayaragigawa railway bridge, the weight of the main girder with normal strength concrete (40 MPa) would have been 170 tons. This was reduced to 150 tons by the use of 60 MPa high strength concrete. The production of girders was done in a yard near the construction site, and concrete was supplied by a ready mixed concrete plant about 2 km from the yard. The strength of the concrete with job-site curing resulted in 62 to 72 MPa, with an average strength of 65 MPa.

In the construction of Iwahana railway bridge, precast concrete members were primarily used but cast-in-place concrete was used for the joints. The water to cement ratio for the cast-in-place concrete was about 0.29 and the average strength attained was 74 MPa.

The main towers of Aomori Oohashi highway bridge were constructed in 1989 and 59 MPa high strength concrete was used (25). In this prestressed concrete cable-stayed highway bridge, high strength concrete was employed to achieve a slender structure with reduced dead load and attractive aesthetic appearance.

Very recently, CNT-super bridge was constructed as shown Photo 2.

This bridge is very small, 41.2 m in length, 1.7 m in width, 1.02 m in height (26). This is a pedestrian bridge between two main buildings. The designer of these buildings and bridge emphasized that the height to span ratio of this bridge had to be smaller than 1/40, from the point of visual balance of buildings. Finally, a post-tensioned box section bridge was constructed. A mass damper type vibration controller was installed in order to prevent vibration of bridge due to the small height to span ratio. The mix proportion of the high strength concrete was as follows: the water to binder ratio 0.20, water content 135 kg/m³, cement content 574 kg/m³, and silica fume content 101 kg/m³. Slump and slump flow of the fresh concrete were controlled at 250 ± 20 mm, 600 ± 50 mm respectively. The design strength of concrete was 102 MPa and 122 MPa was the target concrete strength.

Unique applications

One of the unique applications of high strength concrete in Japan is the beds of a machine in which 108 MPa strength concrete with DSP materials was used (27). High strength concrete is very advantageous for

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this application because of high rigidity and vibration damping properties.

The next unique application is a press die for vehicle manufacture. Photo 3 and 4 show the die made of high strength concrete and a part of a vehicle produced by the concrete die. High strength concrete used in this system is called NF ceramic (Non-Firing ceramics). Table 4 (28) shows the NF ceramic characteristics.

In addition, an oil drilling rig to be used in the Arctic Ocean was made in Japan, using high strength lightweight concrete. In the construction of diaphragm walls, it is desirable to use high strength concrete for deep underground large scale walls, which are subjected to higher water and earth pressures. In some cases 60 MPa strength has been attained even though concrete was cast into bentonite slurry through a tremie pipe.

SUMMARY AND CONCLUSIONS

There are widespread applications of high strength concretes in Japan. In this paper, precast concrete products, high-rise buildings, bridges are introduced.

Generally speaking, the strength of concrete has a close relation to durability of concrete. Therefore high strength concrete will be used more and more from the viewpoint of not only the need for strength but also for enhanced durability.

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Concrete (in Japanese), Concrete Journal of JCI, Vol.25, No.8, pp.15-23, 1987.

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TABLE 1 — MIX PROPORTIONS AND COMPRESSIVE STRENGTH OF CONCRETE WITH ULTRAFINE SLAG POWDER

Type of Cement	Type of Sand	W/(C+S _g)	Slump (mm)	Air (%)	Compressive Strength(MPa)		
					3d	7d	28d
OPC+UGS 1:1	SS+RS 1:2	0.30	110	1.5	56.0	78.1	105.6
OPC	RS	0.29	105	1.8	55.4	67.7	83.4
OPC	RS	0.50	95	4.6	15.3	23.0	34.9

USG = ultra-highly pulverized granulated blast furnace slag;

SS = granulated blast furnace slag; RS = river sand.

TABLE 2 — CHEMICAL COMPOSITION OF ANHYDROUS GYPSUM

Blaine Fineness (cm ² /g)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	SO ₃
7850	11.1	1.7	0.5	40.6	48.1

TABLE 3 — DEVELOPMENT OF HIGH-STRENGTH CONCRETE FOR HIGH-RISE REINFORCED CONCRETE BUILDING IN JAPAN

Design strength (MPa)	Proportioning strength (MPa)	Selection of materials				Mix proportion		Remarks
		Cement	Aggregate	Chemical Admixture	Mineral Admixture	Water binder ratio	Unit dosage of binder (max)	
42 - 48	60	Possibly manufactured by cement on the market. Present JIS standard is applicable.	(*) JASS 5 quality standard is applicable.	Use water reducing agent Present JIS A 6204 quality standard is applicable.	(*) JASS 5 quality standard is applicable.	0.35 ~ 0.30 (construction site)	500 kg/m ³	Execution of construction works are increasing.
60	80	Possibly manufactured by cement on the market, but the present JIS standard may not be appropriate.	(*) JASS 5 quality standard is applicable.	Use water reducing agent. Need to provide the quality and application standard.	Favourable if super fine powder such as Silica fume, blast furnace slag are mixed. Need to provide the quality and application standard.	0.30 ~ 0.25 (construction site) 0.35 ~ 0.30 (laboratory)	600 kg/m ³	Experiments have been done with ready-mixed concrete.
100	120	Possibly manufactured by cement on the market. But, the present JIS standard is not appropriate.	(*) JASS 5 quality standard is insufficient. Quality standard for aggregate is required.	Use water reducing agent. Need to provide the quality and application standard.	The use of super fine powder of Silica fume and Slag is indispensable. Need to provide the quality and application standard.	0.25 ~ 0.20 (construction site) 0.25 (laboratory)	700 kg/m ³	Possible to produce in the laboratory. Recently practical manufacturing was reported.
120	140 - 150	Dubious whether manufactured by using cement on the market or not. Development of new cement might be necessary.	(*) JASS 5 quality standard is inadequate. Might be necessary to consider special aggregate.	Development of super high range water reducing agent is needed.	Development of certain new appropriate mineral is required.	0.20		Possible to produce in the laboratory by the use of special material and methods of producing and curing.

(*) JASS 5: Japanese Architectural Standard Specification, Chapter 5: "Reinforced Concrete Work".

TABLE 4 — CHARACTERISTICS OF NF CERAMIC

Item	Materials	NF ceramic	Cast iron
	Compressive	118~160	588~1280
Strength (MPa)	Tensile	5.9~8.8	196~412
	Bending	9.8~11.8	—
Modulus of elasticity(GPa)		40~50	70~110
Hardness(Hs)		(61)	38~41
Specific gravity(g/cm ³)		2.5	7.1~7.3
Water absorption rate(%)		0.9~1.0	0.0016
Thermal expansion coefficient ($\times 10^{-6}/^{\circ}\text{C}$)		10.8	10~11
Thermal conductivity (w/m $\cdot$ $^{\circ}\text{C}$)		1.74	29~58

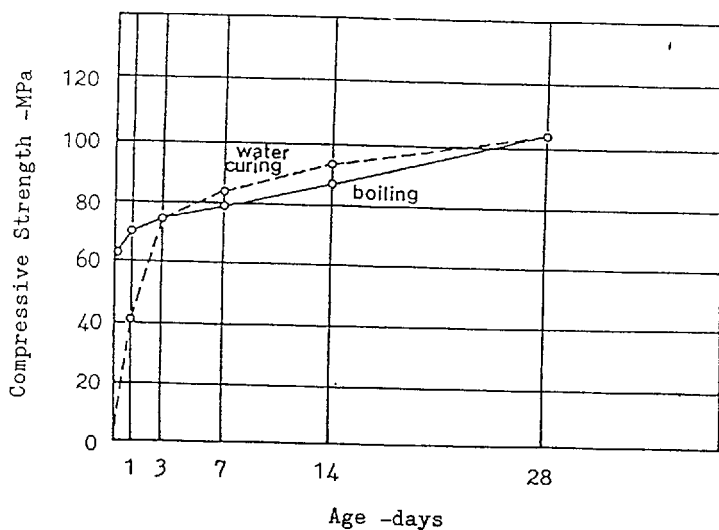


Fig. 1—Compressive strength of concrete cured under pressing compaction

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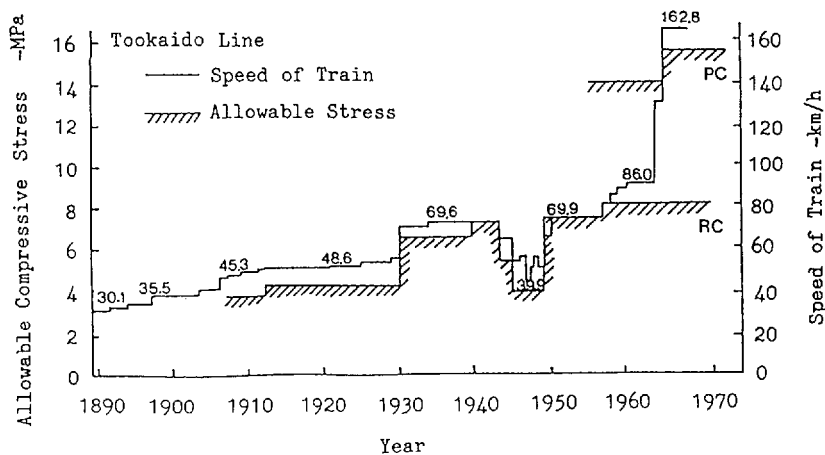


Fig. 2—Relationship between allowable compressive strength and speed of train in Tookaido Line

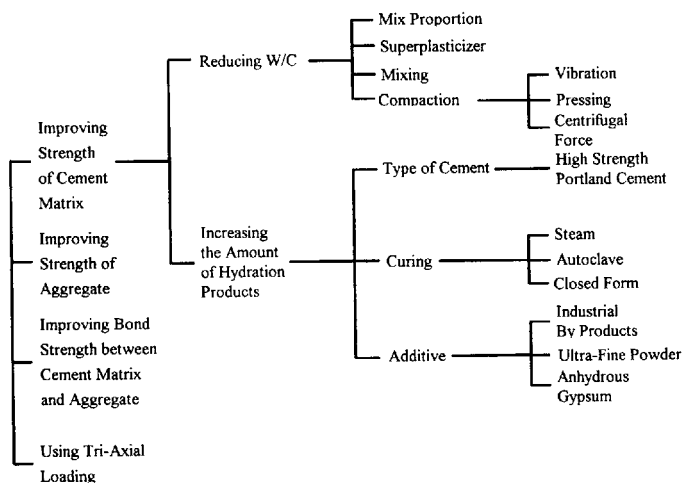


Fig. 3—Techniques for attaining high strength

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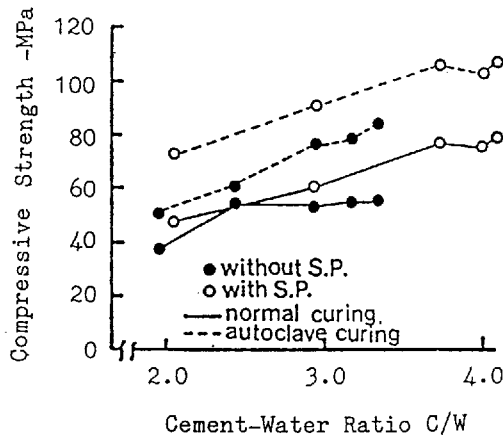


Fig. 4—Relationship between water-cement ratio and compressive strength of concrete

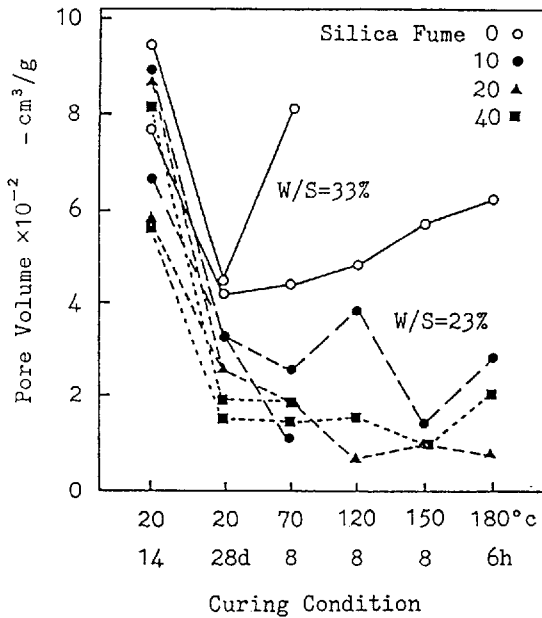


Fig. 5—Relationship between replacement ratio of silica fume and compressive strength of mortar

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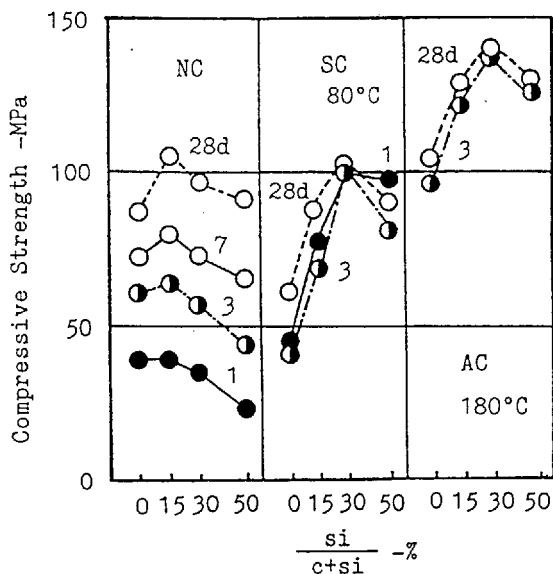


Fig. 6—Effect of curing condition on porosity of cement past with/without silica fume

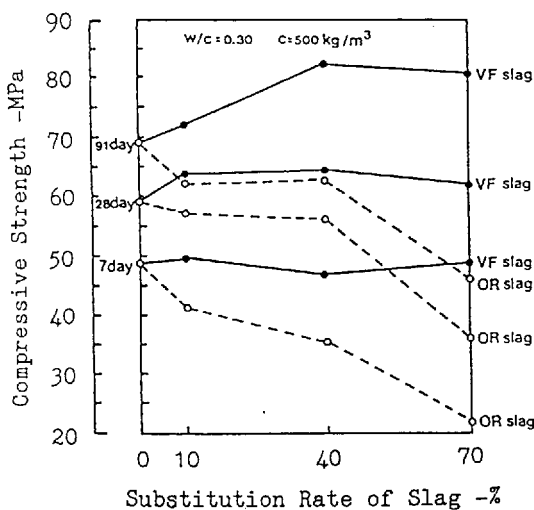


Fig. 7—Effect of replacement ratio of slag powder on compressive strength of concrete

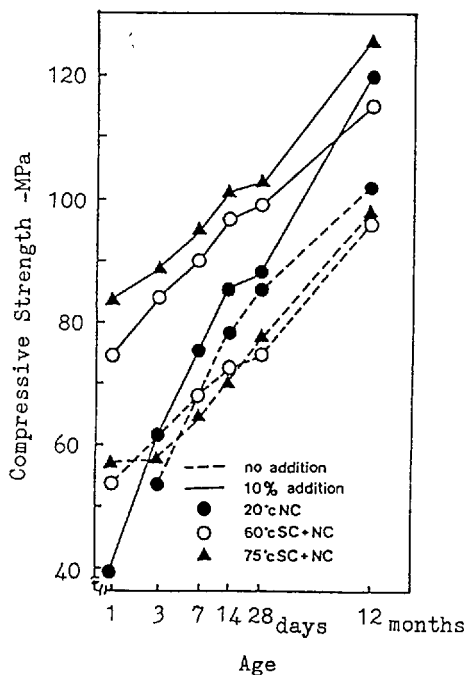


Fig. 8—Effect of addition of anhydrous gypsum on compressive strength of concrete

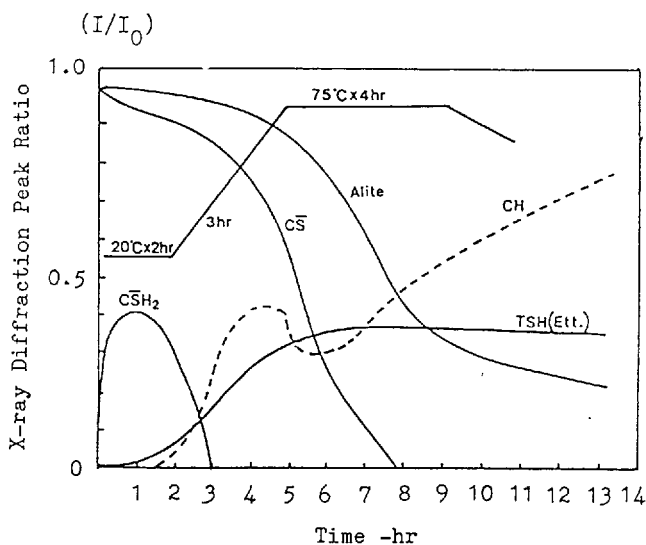


Fig. 9—Hydration process of hydraulic materials

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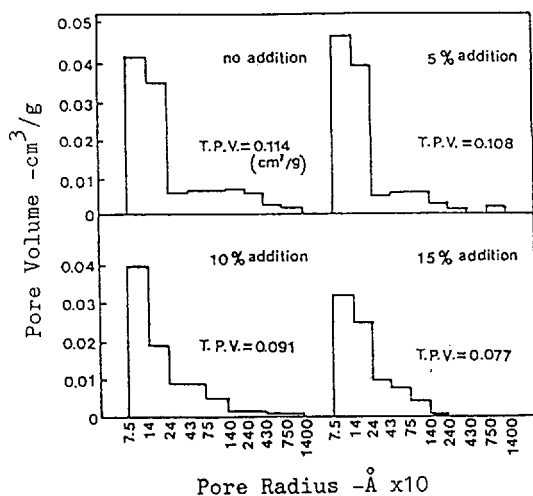


Fig. 10—Pore size distribution of hardened cement paste

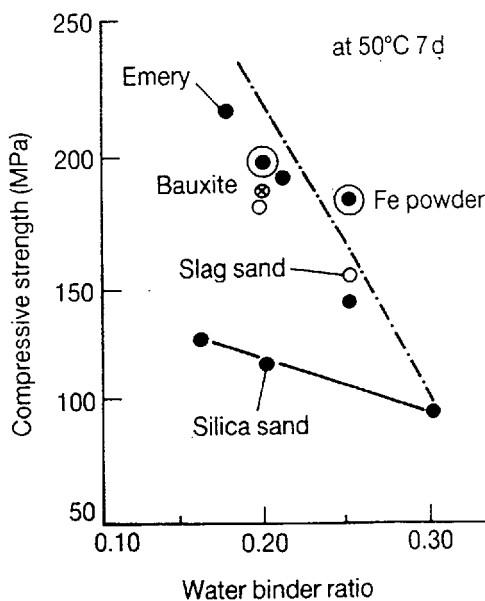


Fig. 11—Relation between water-binder ratio and compressive strength of DSP mortars with various types of aggregate

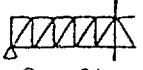
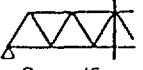
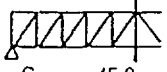
Name of Bridges	Construction Year	Type of Structures	Design Strength (MPa)	W/C (%)	Slump (mm)
Second Ayaragigawa Railway Bridge	1973	I Girder Bridge Span : 49m	58.8	30.0	120±25
Ootanabe Railway Bridge	1973	 Span:24m	78.5	31.9	210±20
Iwahana Railway Bridge	1974	 Span:45m	78.5 58.8	23.8 29.0	120±25
Kazuki Railway Bridge	1974	I Girder Bridge Span : 47.8m	58.8	27.2	130±20
Akagawa Railway Bridge	1976	 Span : 45.9m	78.5	30.0	120±25
Nitta Highway Bridge	1968	Simple Girder Bridge Span : 30m	58.8	35.0	60
Kaminoshima Highway Bridge	1970	Box Girder Bridge Span:86m	58.8	39.3	40
Fukamitsu Highway Bridge	1974	Simple Girder Bridge(Pre-Beam Type)Span:25.8m	68.6	31.4	180±20
Kamihasu Highway Bridge	1977	Simple Girder Bridge(Pre-Beam Type)Span:27.6m	53.9	31.0	180±20
Jodoji Highway Bridge	1977	Simple Girder Bridge Span:53m	58.8	35.6	100~160
Seto Highway Bridge	1977	Simple Girder Bridge Span:53m	58.8	37.3	100~160

Fig. 12—Example of prestressed concrete bridges with superplasticizer in Japan

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Photo 1—Overview of Shinagawa Prince Hotel

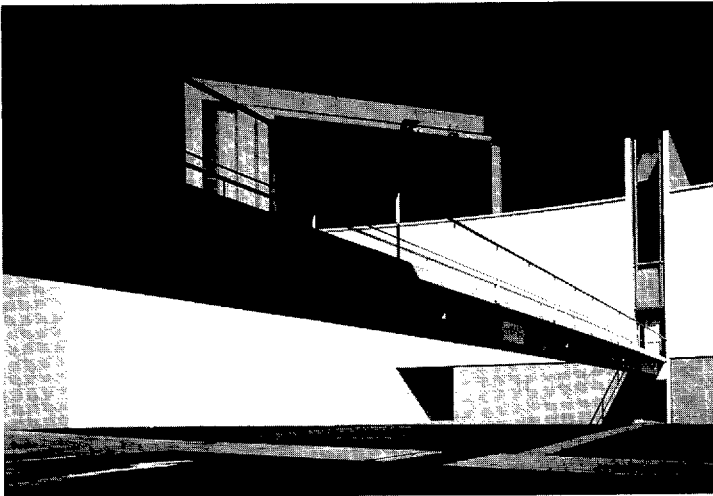


Photo 2—Overview of CNT-Super Bridge

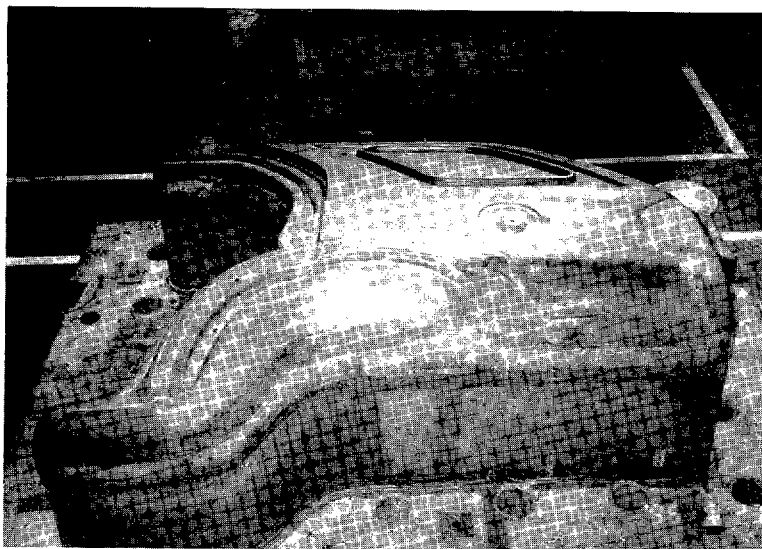


Photo 3—Super-high-strength concrete die



Photo 4—Part of vehicle

SP 167-2

Application of High-Strength Concrete in Norway

by Steinar Helland

Synopsis: High strength concrete (HSC) is defined by FIP/CEB as *"concrete with a cylinder strength above 60 MPa (~8700 psi) and up to 130 MPa (~18900 psi), the practical upper limit for concretes with ordinary aggregates. It also includes lightweight aggregate concrete with a cement paste of similar properties "*. FIP/CEB similarly regards high performance concrete as material with water-binder ratio (w/b) less than 0.40

According to these definitions all concrete installations built in Norway in the 1990s for the oil and gas-fields in the North Sea and most highway structures are built with HSC/HPC. This amounts to about 20 - 25 % of our total domestic concrete production.

Norway was the first nation in the world to have HSC with characteristic cube strengths up to 105 MPa (~15300 psi) incorporated in its code of design, NS 3473, in 1989.

This paper describes the main Norwegian experience by using these qualities in full scale. The presentation is supplemented by some case studies illustrating some typical applications.

The main lesson from some 15 years experience is that the introduction of these "hi-tech" concrete grades should be accompanied by a proper upgrading of the workforce's competence on all levels to ensure the intended quality.

Keywords: Abrasion resistance; diffusion; high-strength concretes; silica fume; water-reducing agents.

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INTRODUCTION

High strength concrete (HSC) is defined by FIP/CEB (1) as *"concrete with a cylinder strength above 60 MPa (~8700 psi) and up to 130 MPa (~18900 psi), the practical upper limit for concretes with ordinary aggregates. It also includes lightweight aggregate concrete with a cement paste of similar properties"*. FIP/CEB similarly regards high performance concrete as material with water-binder ratio (w/b) less than 0.40

(FIP - Fédération Internationale de la Précontrainte and CEB - Comité Euro-International du Béton are two international bodies presently in the process of merger. They act as the umbrella organisation for some 50 national concrete associations worldwide)

According to these definitions all concrete installations built in Norway in the 1990s for the oil and gas-fields in the North Sea and most highway structures are built with HSC/HPC. This amounts to about 20 - 25 % of our total domestic concrete production.

Norway was the first nation in the world to have HSC with characteristic cube strengths up to 105 MPa (~15300 psi) incorporated in its code of design, NS 3473, in 1989 (2).

In the same year, the Ministry of Transportation revised its general specification for highway constructions and put an upper limit on the w/b-ratio of 0.40 combined with a demand for silica fume (3). This was to build up the defence lines against the alarming observations of chloride ingress in previously constructed bridges.

During the last few years a maximum w/b ratio of 0.38 combined with > 5% silica fume has also appeared as a typical specification for the off-shore petroleum installations in the North Sea (4).

There are in particular three historical reasons why Norway has developed into a frontrunner in the field of HSC/HPC.

- * Long tradition in using plasticizers
- * Availability of silica fume
- * The impact of offshore/marine structures acting as "locomotives" for the whole concrete industry

Plasticizers

Due to its wood and paper industry, Norway is the world's largest supplier of lignosulphonates and thus plasticizers. The utilization of such additives started early, and during the last 3 decades close to 100% of all concrete batched contains on average 2 - 3 litres per m^3 . For more demanding structures such as offshore and highway construction, the average dosage is normally between 6 and 10 litres, in a combination of ordinary plasticizers and superplasticizers. These figures are extremely high in an international context. When the demand for higher strengths and a more durable material arose in the 1970s, this technology was already accepted by the industry and the public.

As a result, almost every ready-mix plant today produces concrete with w/b below 0.40 on a regular basis.

The most used consistency both for ordinary and high quality concrete is in the range of 20 cm (8") slump.

Silica fume

Silica fume is a by-product of the smelting process used to produce silicon metal and ferrosilicon alloys. About 50% of the world's production takes place in Norway.

The first research on the use of this waste started in Norway just after WWII (5). In the late 1970s environmental requirements forced the smelting plants to collect the dust by filtering the smoke. Thus, this super active pozzolan became readily available to our building industry at a fair price. Today 1/3 of all our concrete contains on average about 3 - 5% silica fume. At first this pozzolan was used as a cement replacer, today the trend has shifted to give a good concrete enhanced qualities.

This large scale use has given us unique experience and the ability to produce high performance concrete. Particularly for structures exposed to chloride ingress this enhanced quality has been appreciated, or where high strength is wanted.

Offshore / Marine structures

During the last two decades 27 major concrete structures for the North Sea have been built or are under construction. 20 of these, representing some 1 850 000 m^3 (~ 2 400 000 cy) of high quality concrete, have been built in Norway (6). These are placed at water depths of 80 to 350 metres (260 - 1150 ft).

Typical for the last generation of off-shore platforms is the application of high strength normal density concrete of grade C-75 MPa (~ 10900 psi) and lightweight concrete of grade LC-60 MPa / 1950 kg/m^3 (~ 8700 psi / 122 pcf) (Fig. 1).

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The evolution of these giants designed for a harsh marine environment has certainly advanced the frontiers of concrete technology with general profit for the whole Norwegian building industry. The demand for optimal use of HSC concrete in tough competition with steel, has resulted in a series of major national research programmes funded by the international oil companies, contractors and the Research Council of Norway. The centre of these activities has been located in the laboratories at SINTEF in Trondheim.

Major Norwegian Research programmes on HSC		
Design and Structural Utilization of HSC	1983 - 1986	350 000 US\$
Materials Development / HSC	1987 - 1991	4 000 000 US\$
High Strength Concrete	1986 - 1993	6 000 000 US\$
Lightweight Aggregate Concrete for Floaters	1989 - 1991	1 500 000 US\$
Lightcon	1993 - 1995	2 300 000 US\$
Economic Design and Construction with HSC (Together with other European partners)	1992 - 1995	5 000 000 US\$

Norwegian Code of design

As a result of these efforts, we gradually felt that we mastered the HSC-technology. In 1989, combined with a major revision of our Code of Design, NS 3473, we included detailed guidelines for the use of concrete with characteristic strength up to 105 MPa (~15300 psi) and lightweight aggregate concrete (LWAC) up to about 85 MPa (~12300 psi).

This code was also used for the design of the Canadian offshore structure to be installed at the Hibernian field off Newfoundland.

In agreement with CEN, the European Standardisation Organisation, the newly formed ISO/TC-67 Committee for the design of fixed offshore concrete structures, has also decided to refer to this Norwegian Code.

During the last 6 years, Finland, Germany and The Netherlands have, or are in the final phase of, incorporating HSC into their standards. In North America, the codes have no upper limit on the use of HSC (Table 1).

Last winter, a joint FIP/CEB working group lead by the newly elected ACI honorary member, Professor Ivar Holand from Norway, completed their

addendum to Model Code 1990 on HSC (7). (MC-90 is acting as the model for code writers in major parts of the world including Europe). This prenormative document forms the basis of the HSC clauses in the revised Eurocode 2 (design of concrete structures) to be published in 1998. In this edition, characteristic strengths up to C-100/115 will be covered.

Present status

Norway was a world pioneer when we adopted modern concrete technology in full-scale use. The main milestones were in the late 1980s when we published the revised design rules, NS 3473, incorporating high strength concrete.

I was myself involved in this process and still consider this document to be satisfactory, but we missed one very important aspect. We did not make a sufficiently strict definition of the required level of competence for those allowed to work with this material.

For steel structures it is well accepted that personnel involved in welding different qualities of steel must possess certificates proving their proficiency. The concrete industry has very little tradition of certification for workers, engineers or designers. Thus, when Norwegian clients, design offices and contractors observed that the new generation of "hi-tech" concrete qualities were standardized, they considered them to be free to use by everybody. The result has been that Norway has acted as a full-scale laboratory and training field for the industry and major clients for a number of years. Initially in this period, we experienced an unacceptable number of problems in handling these delicate qualities for the inexperienced participants in the market. In particular cracking in the plastic phase was a phenomenon all new participants in this field had to face and learn to control the hard and expensive way.

What other industry would ever open its doors to new technology without anchoring it to a competence requirement ?

Today in our complex world, most professions have a system of certification based on personal practical and theoretical competence to protect society against rascals.

This is hardly the general case in the concrete industry anywhere.

In Norway we have actually had a requirement since 1986 in our standard for material and execution, NS 3420, for leading workers and supervisors that they are to have a 3 year practical and theoretical education with a public diploma as craftsmen.

This is well implemented for ironworkers and carpenters, but due to tradition, it is more or less ignored for concrete-workers.

For engineers the standards require an undefined "special skill in concrete technology".

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General competence is a balanced mixture of practical skill and theoretical understanding. Practical skill can be obtained during daily work by conscientious workers. The observation of honeycombing and other visual macrodefects, will be enough to improve their techniques. The feedback loop is short and I am not too concerned about this part of our workers' competence that takes care of the "outside" qualities of structures. What are more difficult to obtain are the theoretical aspects of the profession and in particular the understanding of deterioration mechanisms and advanced concrete technology representing the "inner" qualities. The only way of learning this is through traditional lecturing on the school-bench.

Our readymix-industry have faced this situation and put in specific requirements for documented competence with emphasis on HSC/HPC. Their plants are by law subject to certification by a public body. Six years ago this industry organized a modular system of courses with examination and diplomas. At the same time the certification agency required documentation of this theoretical competence for all operators as well as supervisors. Merely to be able to obtain the necessary certification of the plant and stay in business, the Norwegian ready-mix industry had to go through a massive process of schooling. This process probably represents the major push in recent years to lift the competence in concrete technology in our country. Generally speaking, this part of the industry now represents a stronghold that is to ensure quality. This is an example where a bureaucratic public body is in charge of following up a requirement.

For the contractors and designers, their competence, or lack of such, in the general understanding of modern "hi-tech" concrete technology like HSC/HPC, results in functional or nonfunctional structures for the client. Even if such shortcomings might result in structural collapse, the normal consequence will be increased maintenance costs in the future. This is however not defined as a field of priority for the public building control. The various clients are therefore considered as those with prime responsibility for checking that the clauses in NS 3473/3420 are fulfilled.

Again, due to tradition, clients very seldom put emphasis on other elements than the lowest bid. Any process of prequalification based on level of competence or checking of the actual proficiency for the design or construction crew during the job would be an exception. Surprisingly, this is also the case for major public clients. Since there is very little outside pressure on this part of the industry to educate their staff in this field, the process of raising the level of competence is too slow as it actually represents quite a heavy investment for employers.

In Norway, the Association of General Contractors (LBA) has organised a course in the theoretical aspects of the profession in a similar way as the

readymix-industry with special emphasis on HSC/HPC and the "inner" qualities of the concrete. The duration is 40 hours on the school-bench and some 15 hours of homework. For those passing the final examination, the reward is a diploma documenting formal competence. This module is further accepted by the Standardisation Board (NBR) as a valid entry concerning the requirements presently formulated in NS 3420. For craftsmen in adjacent professions such as carpenters and ironworkers, this addendum gives them the formal qualifications as concreters as well. Similarly for those with the education of an engineer, this satisfies the requirement in the Standard for "special skill in concrete technology". In 1991, the board of LBA determined that this training programme should be a matter of priority to counteract society's criticism concerning inadequate quality standards in the industry.

The response by employees to this offer has been very positive. Workers are by nature curious and they are proud of their profession. One main consideration in implementing these theoretical courses on grown-up blue-collar workers has been the fear of producing social losers. This has so far not been the case and the Unions have on the contrary put pressure on contracting companies to get their members upgraded.

In our own company with a total workforce of 2800, more than 300 have passed the course. By the end of this year there will be another 150 candidates, so we expect to be in line with our obligations to NS 3420 and our own ambitions.

The weak and critical part of the strategy for contractors and designers in Norway is however that we miss the second and important part of our pair of tongs, the pressure from the clients. Thus many companies still do not regard this offer to upgrade their labourforce as "an offer they cannot refuse".

The road ahead

There is continuous competition between the various building materials. In Norway, concrete is presently losing market shares to steel both for offshore structures and for structural framework in industrial buildings. If we are not able to cope with society's growing scepticism to concrete we will get severe problems. The main challenge is to improve durability and produce cheaper structures. To achieve these goals, we have to supplement the old "low-tech" way of construction with some elements of the new "hi-tech" approach. The main answer to this challenge is a denser low-porosity concrete ending up with enhanced durability performance as well as high strength. In Norway, a major motivation for using this material has no doubt been the need to slow down the deterioration mechanisms. Since the raised strength then has come as a "free" extra benefit, the designers have been forced to take

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advantage of this capacity in the structural design to optimize a cost-effective structure.

There is however a major problem in designing HSC-structures. There are minimum dimensions for a member because of practical reasons. The steel needs a certain cover. Space is needed for the reinforcement and for ducts. We also need space for the concreting process itself. By traditional design, these requirements normally give a sufficient compressive capacity even with ordinary strength concrete.

The designers therefore have to twist their minds to obtain the benefits from HSC.

In many ways, the concrete industry is in the same phase of innovation as the shipbuilding industry was after WWII when they replaced the old techniques with rivets by welding. In this industry, this new method resulted in total different shapes and concepts of design.

These are illustrated later in this presentation by some examples of structures in Norway illustrating how our industry is trying to cope with this challenge.

Another main benefit from the introduction of HSC in the market has been the "locomotive" effect for the rest of the concrete works. The research activities and the implementation of this technology have created a lot of attention. This process has raised the standards on constituents such as cement and additions. It has resulted in a general upgrading of the batching plants and the process of training the personnel to handle these qualities has had a major positive influence on their level of proficiency also for handling normal grade concrete. There is no doubt that concreting has been regarded by the public as a low prestigious profession. The growing acceptance that we are in a process of moving frontiers and involved with the world's top expertise, has improved the image of our profession. This again has both resulted in public funding for R & D activities and has given us a better position while trying to recruit the best qualified youths to our profession.

A few years ago there were only a few countries and research centres that worked in this field. In those days, over ten years ago, it was easy to be in line with the latest developments within technology.

Today this topic has developed and become the most prestigious subject for researchers all over the world. This is reflected in the number of internationally available reports on HSC (Fig 2) (8). Today it is more or less impossible for one country to cover all aspects.

A main challenge for those with an ambition to be among the first to implement new technology is therefore to keep up the funding for R&D even after the HSC has been covered by the standards. We must also become partners in international networks with sufficient resources to possess in-depth competence on all the relevant aspects and specialities within this fast developing technology.

CASE STUDIES

The following case studies present examples of Norwegian structures where HSC/HPC was used in order to illustrate how the Norwegian construction industry has applied this technology in practice.

"SHORE APPROACH" - SUBSEA CONCRETE TUNNEL

A unique underwater structure has been located at the west coast of Norway since 1982. A 560 m long concrete tunnel protects the pipeline transporting gas from the Statfjord oil field in the North Sea from the impact of waves in the landfall zone (Fig 3).

The tunnel consists of prefabricated elements weighing up to 7000 tons. HSC/HPC is a major part of this unusual structure exposed to extreme environmental loads.

After 12 years of service life, the high quality concrete proved remarkably resistant against ingress of chlorides (9).

Reason for the use of HSC

The structure consists of 5 prefabricated box-girders resting on 6 in-situ cast foundations. The cross-sections of the girders vary from 30 to 45 m². The wave loads on the elements are a function of the size. By this reason the projects gained a double bonus by applying HSC. It made it possible to reduce the dimensions, which again reduced the load on the structure.

Reason for the use of HPC

During the last decades, durability problems due to the ingress of chlorides have been a major concern to concrete engineers. To ensure the integrity of this key part of Europe's energy infrastructure, it is of major importance that the service life requirement is fulfilled. This project represents the first generation of major in-field structures where all the main principles of modern technology have been applied, which means a low water-binder ratio combined with silica fume and a fairly high dosage of plasticizers.

Execution and mix design

The construction period from when the contract was awarded on the contractor's conceptual design until the tunnel was installed, stretched from February to October in 1982.

The elements were cast in dry-dock and towed to the site (Fig 4, 5).

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The mix design for the superstructure was:

Portland cement	400 kg/m ³	Max size aggregate	18 mm
Silica fume	32 kg/m ³	Slump	24 - 26 cm
plasticizer	7 kg/m ³	Mean cube strength at 28 days	85 MPa
		Standard deviation	5 MPa
w/c+s	< 0.38	Mean cube strength at 90 days	95 MPa

The total volume of concrete in the project was 10 000 m³

Design considerations

The tunnel has to withstand the load of a design wave of 18.5 m height. NS 3473/1975 was applied in the design. In this version the upper tabulated strength grade was C-65, i.e. a characteristic cube strength of 65 MPa. This did thus limit the utilization of higher strengths. Conceptual studies demonstrated that with a strength grade of below 50 MPa, the project could probably not have been realized.

The average density of reinforcement was 250 kg/m³ plus 80 kg/m³ of prestressing cables (10).

Field performance

The structure has been inspected several times since the completion. The most remarkable results are those connected to the resistance towards chloride ingress. Chloride profiles have been analysed and so-called "effective diffusion coefficients", D , according to Fick's 2nd law have been calculated. These coefficients then take into account all effects from the construction to the time of testing.

After 7 years these coefficients varied from 9 to 13 mm²/year (11).

Investigations after 12 years support these findings. By using these values in a traditional conservative extrapolation with a constant D , this will give a period of 50 - 100 years before a concentration of 0.1% chlorides of the concrete reach the reinforcement with 50 mm cover. However, chemical analyses of the concrete skin have revealed that an ion exchange is taking part between the concrete and the magnesium in the sea water. This is gradually blocking the pores (12) and will result in a further decrease in the D -values.

Taking account for this effect and applying the more realistic models for chloride ingress as described in (13), the period for obtaining the 0.1 % level at 50 mm will more likely be tripled compared to the prediction given above.

After this possible initiation of corrosion, there will still be a considerable period before noticeable damage will occur.

DESIGN AND CONSTRUCTION OF THE STONGASUNDET BRIDGE

Stongasundet is a narrow sound between the mainland and a sparsely populated island on the western coast of Norway.

This particular bridge, built in 1990, presented an opportunity to gain experience with the use of HSC in slender beam structures. The prefabricated beams were made as slim as possible in order to utilize the high stress capacity of the concrete (14).

Choice of bridge design

It was in this case advantageous to perform as much as possible of the construction work at a central site some distance away from the bridge site. The chosen design was therefore a concrete beam bridge with two parallel precast post-tensioned girders. The total bridge length was 173 m, divided into four spans. These consisted of two main spans with lengths of 50 and 70 m and two side spans with lengths of 37 and 16 m respectively. The longest beams became 62.5 m and cantilevered out 12.5 m from the central pier, while the shorter beams in the main span became 57.5 m long. The main beams were designed based on a minimum concrete grade of C-65 with an optional use of concrete grade C-75 if required. The beams were designed with varying depth and curvature in the vertical plane. This solution also contributed to aesthetic appearance of the structure.

Beam design

In order to utilize the capacity of the HSC, the beams were made as slender as possible. The dimensions were dictated only by the minimum required space for the prestressing tendons and the 40 mm cover for the ordinary reinforcement. Much efforts had to be put into detailing of the girders, in particular the in-span joints and the beam ends which were heavily reinforced. They were designed as tapered beams with depths varying from 2.4 m to 3.5 m and with vertical curvature on both the top and bottom flanges. Since the upper flanges were to be used as the road surface, these were designed with a fairly large width which also contributed to lateral stability during the lifting and installation phases (Fig 6).

The main elements were post-tensioned using three 19-6 tendons with a minimum yield capacity of 4.4 MN in each beam. The design was based on concrete grade C-65. The longest members with lengths of 62.5 m weighed about 220 tons and the second longest weighed about 200 tons.

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The construction of the bridge components was carried out at two sites. One was a central site where the beams were constructed, post-tensioned and made completely ready for installation. The other site was at the bridge location itself where the abutments and pillars were constructed.

Stability during construction and installation

Due to the extreme slenderness of the beams, extra care had to be paid to the stability of the beams during all construction and installation phases.

Two major factors contribute to lateral stability during the lifting of long elements:

- * The lifting points should be as far in from the ends as possible
- * The roll axis of the lifting points should be as high as possible above the centre-of-gravity line of the beam

Concrete mix design

The concreting of the deep and extremely thin webs required a mix with the following main criteria:

- * A high slump and a very good flowability, i.e. required slump measures in the order of 24 - 26 cm
- * The mix would need to withstand segregation during difficult concreting, e.g. in particular in the lower portions of the web.
- * A minimum required strength of C-65

This resulted in the following recipe:

Portland Cement	470 kg/m ³	Sand 0 - 8 mm	1080 kg/m ³
Silica fume	40 kg/m ³	Gravel 8 - 16 mm	720 kg/m ³
Plastizicer	6.5 kg/m ³	w/(c+s) =	0.35
Superplastizicer	4.0 kg/m ³	Slump	24 - 26 cm
Water	180 kg/m ³	Achieved characteristic strength at 28 days	75 MPa

Concreting method

Quality control and work procedures were considered in detail due to the recognised difficulties involved in concreting the beam webs with both tendon

ducts and ordinary reinforcement.

The concreting work on each beam was performed using two pumps. The concrete was directed through funnels connected to attached flexible hoses which were lowered into the beam webs. In this manner the free fall of the concrete was limited to less than 1.0 m. The concrete was vibrated using 40 mm poker vibrators. The vibrators were operated from the top of the formwork and lowered into the beam webs within the concrete cover space, i.e. between the ordinary reinforcement and the formwork.

THE HEIDRUN TENSION LEG PLATFORM

The construction of the Heidrun floating oil-production is just completed in Norway and this structure was installed at a water depth of 345 metres in the North Sea during mid-summer of 1995 (Fig 7, 8).

Heidrun is the world's first tension leg platform (TLP) with a concrete hull and represents a break-through for high strength lightweight aggregate (LWA) concrete as a building material in floating offshore platforms. Exposed to a harsh marine environment, the design life requirement for the structure is more than 60 years (9), (15), (16).

Some key data for the project

Water depth	345	metres
Deck weight	65 500	tonnes
Concrete, LWA-C60, hull	58 000	m ³
Concrete, LWA-C60, MSB	5 800	m ³
Reinforcement (ordinary)	27 000	tonnes
Reinforcement (pre-stressed)	4 100	tonnes

Application of high strength LWA concrete for tension leg platforms

A large displacement is necessary to achieve the buoyancy required for a TLP of this size. Buoyancy members of steel have to withstand large hydrostatic pressures. A high strength concrete shell which can take the water pressure in direct compression is ideal for such exposure.

A concrete hull will be heavier than a steel hull. Consequently the necessary buoyancy and displacement need to be increased. The mooring tether forces tend to increase with the displacement.

However, more important is the location of the centre of gravity. For a concrete platform this will be at about the same elevation as the resultant of the first order wave forces. Thus the tether forces from the concrete hull are significantly lower than those from a steel hull which are to carry the same topside weight.

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Experience from the existing offshore concrete structures shows an unequalled durability towards all kinds of deterioration. A concrete structure can be reinforced to achieve a high degree of robustness against all external impacts, e.g. from ships and dropped objects. The anticipated costs for inspection, maintenance and repair of a concrete platform will therefore be small relative to its counterpart made of steel.

Concrete mix design

The mix design for Heidrun TLP has been developed over several years, starting some 10 years ago.

The reduced weight is achieved by replacing the natural coarse aggregate with lightweight materials made of expanded clay. The other constituents are the same as used for normal density (ND) concrete of high strength.

Portland Cement HS- 65	420 kg/m ³	Natural sand 0-3 mm	720 kg/m ³
Silica fume	20 kg/m ³	Liapor "8" 4-8 mm	307 kg/m ³
Superplasticizer	6-9 kg/m ³	Liapor "8" 8-16 mm	254 kg/m ³
Air-entr. admixture	1-3 kg/m ³	w/(c+s) corrected for water absorption	0.37 +/- 0.02

Properties of hardened concrete

The table below shows the requirements and results from the concrete production during the dry dock phase. Both strength and density comply with the requirements.

		required	mean	st. dev.	charact.
Slump	cm	> 20	25		
Wet density	kg/m ³	< 1950	1885		
7 days density	kg/m ³	< 1940	1901		
7 days strength	MPa		70	3.0	64
28 days density	kg/m ³	< 1950	1943		
28 days strength	MPa	> 60	79	3.5	74

Compressive strength in MPa measured on 100 mm cubes. Documented

cylinder/cube strength ratio for this concrete quality is between 0.90-0.93.
Density measured on water stored cubes.

Design criteria for LWA concrete

The design is based on Norwegian codes supplemented by criteria specified by the Norwegian Petroleum Directorate (NPD) (17).

HIGHWAYS E-6 & E-18

During the summer of 1989, 110 000 m² were paved on these two highways. The total volume of concrete was 22 000 m³, and a GROMACO 5000-S slipform paver was used (Fig 9).

In Norway almost every car is equipped with tires having small steel studs to improve the friction between the tire and road for better driver control during the winter season (Fig 10, 11, 12). Although asphalt is the traditional pavement for these highways, the Ministry of Transportation had expressed their desire in gaining experience with modern qualities of concrete. The main motivation was to reduce the maintenance costs, but also safety aspects and concern about the pollution of abraded asphalt were considered (9), (18).

Mix design

The basic mix design for these two projects was:

Portland cement P-30-4A	390 kg/m ³	W/c+s	0.36 - 0.38
Silica fume	20 kg/m ³	slump	2 - 6 cm
Plasticizers	4 - 8 kg/m ³		
Obtained characteristic cube strength at 28 days for the E-18 parcel	85 MPa	Obtained characteristic cube strength at 28 days for the E-6 parcel	90 MPa

To ensure a lowest possible tendency of segregation, the particle distribution was designed as a continuous curve without any gaps.

This created some problems with regard to the surface tolerances.

As all commercially available pavers are designed for the paving of ordinary concrete where priority is put on surface smoothness and not on wear resistance, these machines prefer a minor gap grading of the aggregates to obtain segregation and thus a surplus of mortar for the finishing at the surface.

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The required smoothness was not met 100%, and the pavement had to be partially ground with a CUSHION CUT PC-5000 diamond grinding machine.

Design considerations

In 1989, HSC of grades up to 105 MPa was included in the general Norwegian Standards, ie NS 3420/86 and NS 3473/89. These documents were used for the production and placing of the concrete. However, the structural design of the pavement had to be performed based on a preliminary addendum to the Ministry of Transportation's "Norm 018, Construction of highways".

Based on this, 18 cm thickness was chosen for the E-6 parcel and 22 cm for the E-18.

Later, in 1992, "Norm 018" was revised and specific guidelines for the application of grades up to 105 MPa were included. According to this, the E-6 pavement had been designed a few cm too thin.

Field performance

After 4 years of service life, the wearing resistance of this HSC is according to the expectations. However at the E-6 some longitudinal cracks have appeared close to some of the joints. The probable reason is that the extreme low thickness has resulted in damage due to fatigue.

MAINTENANCE - THE SMESTAD TUNNEL PAVEMENT

The Smestad highway tunnel in Oslo consists of two parallel sections, each 400 m length and with two lanes.

The tunnel was constructed in 1983 and paved with a 55 MPa concrete. In 1989, the traffic had resulted in 35 mm depth grooves in two of the lanes, and the pavement had to be repaired.

The following procedure was chosen:

A track with a width of 800 mm and 35 mm deep, altogether 1600 m, was milled by one passage of grader-mounted equipment normally used for renovation of asphalt pavements.

The concrete was transported to the site with automixers, and slump was adjusted to about 6 cm by an extra addition of 3 - 10 litres of plasticizers. The great variation on the dosages of additives reflected the variation in temperatures during the construction period ranging from 12 to 30 °C. The concrete was placed by the help of a small modified asphalt paver and glued to the old pavement by the help of epoxy.

Finally a CUSHION CUT PC-500 grinding machine was used to obtain the required smoothness.

The repair mix consisted of :

Portland Cement P-30-4A	450 kg/m ³	w/c+s	0.22 - 0.24
Silica fume	75 kg/m ³		
Lignosulph. based water reducer	5 - 14 kg/m ³	Naphthalene based plasticizer	10-17 kg/m ³

The average cylinder compressive strength at 28 days was 130 MPa. Specimens were sawn from the actual pavement, both from the repaired and unrepaired sections, and tested in an accelerated road-wear simulator. The results for the HSC were comparable for those normally obtained on massive granite, and the predicted service life is 4 times that of the old 55 MPa pavement.

By this repair technique, the main cost is to prepare the milled grooves for concreting, while the material cost even for this high quality mix is modest due to the moderate quantity.

After 6 years of service, the pavement performs as expected and no debonding has been observed (19).

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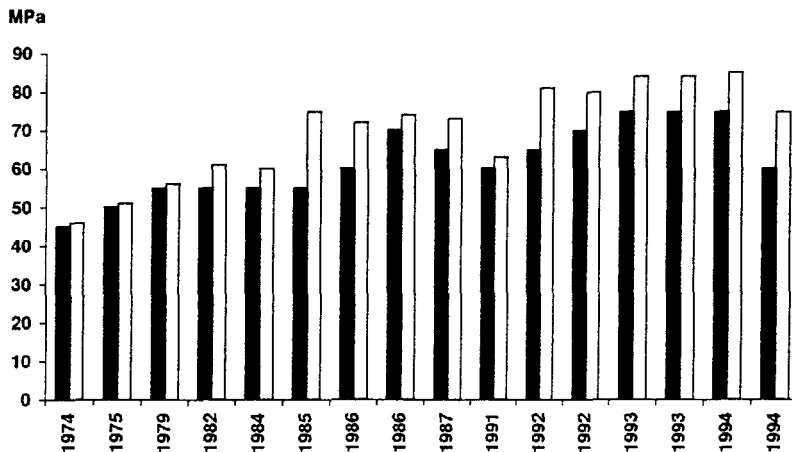


Fig. 1—Specified and obtained characteristic strength, 16 Norwegian-built offshore structures; second 1994 structure is by LWAC with density of $< 1950 \text{ kg/m}^3$