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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 undoubtly 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 to be used in general construction, In 1968, applying the method of manufacturing autoclaved lightweight concrete, by actoclaving 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.

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 rario 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 significatly 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. Superplasticixer 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 naphtalene 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 μm. 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 repidly 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 workabilibty 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 substite 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 be published by the Japan Society of Civil Engineers in October 1995.

Blast furnace slag powder-- Partial replacement of cement with blast 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 fhe 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 producuts 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 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 avallable 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 in 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 m^2. 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