PERFORMANCE ISSUES FOR HIGH STRENGTH CONCRETE IN BRIDGES

By

Tatiana Moussalli

Bachelor of Science in Civil Engineering
University of Southern California, 2000

Submitted to the Department of Civil and Environmental Engineering
In Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Civil and Environmental Engineering

at the

MASSACHUSETTS INSTITUE OF TECHNOLOGY
June 2001

Signature of Author________
Tatiana Moussalli
Department of Civil and Environmental Engineering
May 11th, 2001

Certified by________
Jerome J. Connor
Thesis Supervisor
Professor, Civil and Environmental Engineering

Certified by________
Oral Buyukozturk
Thesis Co-Supervisor
Professor, Civil and Environmental Engineering

Accepted by________
Professor Oral Buyukozturk
Chairman, Department Committee on Graduate Studies

PERFORMANCE ISSUES FOR HIGH STRENGTH CONCRETE IN BRIDGES

By

Tatiana Moussalli

Submitted to the Department of Civil and Environmental Engineering
On May 11, 2001 in partial fulfillment of the
Requirements for the Degree of Master of Engineering in
Civil and Environmental Engineering

ABSTRACT

This thesis examines the use of high strength concrete in bridge structures. A literature review on the subject matter is given. Mix design and behavioral aspects are described. The environmental advantages of using high strength concrete are noted. The advantages and benefits of using high strength concrete in various structures such as buildings and offshore platforms are identified. The main part of this thesis focuses on the benefits and potential of using high strength concrete in bridges, as they relate to the performance issues of high strength concrete. Increases in span lengths, reduction of size members, reduction of cross sectional areas of compression, wider girder spacing, thinner plates for segmental construction are a result of the application of high strength concrete. In addition, the economical aspect of the use of high strength concrete is identified.

Thesis Supervisor: Jerome J. Connor
Professor, Civil and Environmental Engineering

Thesis Co-Supervisor: Oral Buyukozturk
Professor, Civil and Environmental Engineering

ACKNOWLEDGEMENTS

I would like to thank Professor Connor for his help, support and kind patience during this year at M.I.T.

I would also like to thank Professor Buyukozturk for his guidance and collaboration on this thesis.

I would like to thank my parents, Amine and Saada and my sister, Evita for their continuous support, patience, encouragements and love, although it sometimes wasn't deserved.

And finally, I would like to thank God for giving me everything I am.

TABLE OF CONTENTS

TABLE OF FIGURES

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

Long-standing structures have become essential to national economies. Concrete is a very old material that was used by the Egyptians in 3000 B.C. The Greek and Roman civilizations also made use of concrete as the major component in infrastructures. However, the concrete that we know today was developed 150 years ago when Portland cement was discovered. Concrete is considered to be the main construction material for many civil applications. It is strong, produced to be durable, can take many shapes and is the least expensive available material on the market. Concrete is used for its compressive strength since it is much stronger in compression then in tension. Since then, research has always tried to improve the quality of the concrete in order to better serve and protect the welfare of people. The compressive strength of concrete was around 2,000 psi (13.8 MPa) and 6,000 psi (41.4 MPa) in the 1900's and 1960's, respectively. In 1932, Thomas Towles discussed on the possible benefits of producing a concrete with a compressive strength of 7,000 psi (48

MPa) as opposed to 5,000 psi (34.5 MPa), which was the maximum compressive strength of concrete at that time. Before the 1970s', designers were satisfied with the use of 6,000 psi (41.4 MPa) concrete for all structural members. Then, in the early 1980s', research proved that the utilization of a 9,000 to 11,000 psi concrete presented not only high performance issues but also was economically feasible. However, with the increase of wear and tear in structures and the need to build for a higher life cycle, new technologies increased the amount of research, leading to better cements and concretes, thus the development of new materials and composites. During the last two decades, the development of new chemicals and admixtures have made it possible to obtain a concrete with a much higher strength than was actually thought possible. Nowadays, concrete with a compressive strength of 14,000 psi to 20,000 psi (98 to 138 MPa) can be found in structures in the United States and Europe.

"Imagine for example, concrete with an available strength of 10,000 pounds per square inch. Smaller columns, thinner and lighter beams and slabs would at once result. Precast units, easy to handle would be available. The present limiting heights of buildings, of spans of bridges would at least be double. A new basis of design, new codes and specifications would be required". Those were the words of Professor S. C. Hollister in 1934, who was ahead of his time in thinking about innovations of concrete applications by giving a good definition of what is known today as High Strength Concrete.

Initially, high strength concrete was used for heavy loaded columns in tall buildings. Now, the application of high strength concrete in the construction of special structures, such as offshore platforms and long-span bridges has become more frequent. Only three decades ago, the use of high strength concrete in bridge construction was only a theory. Two decade ago, engineers started experimenting high strength concrete. Nowadays, the use of high strength concrete in bridges is spreading all over the world.

CHAPTER 2

LITTERATURE REVIEW

2 LITTERATURE REVIEW

2.1 What is High Strength Concrete?

High Strength Concrete is a type of high performance concrete. To this date, there is no exact definition of high strength concrete. A general definition would be a type of concrete that meets special requirements that are not present in standard concrete. Those special requirements are obtained when the four strength parameters (compressive strength, modulus of elasticity, creep and shrinkage) and the four durability parameters (freeze thaw durability, scaling resistance, chloride permeability and abrasion resistance) are optimized in order to achieve high performance. According to the American Concrete Institute (ACI), high performance concrete is “concrete meeting special combinations of performance and uniformity requirements that cannot always be achieving routinely using conventional constituents and normal mixing, placing and curing practices”.

What does high strength concrete really mean? Many definitions have been given on the subject matter, however, a definition for concrete according to its design strength is needed. Generally, high strength concrete is a concrete that has a compressive strength ranging from 9,000 psi (61 MPa) to 19,000 psi (130 MPa) and that is readily available for construction purposes. In Finland, concrete is defined according to strength by three categories:

- Normal structural concrete, nominal strength 2,900 to 8,700 psi (20 to 60 MPa)
- High strength concrete, up to about 14,500 psi (100 MPa)
- Very high strength concrete, usually as much as 21,750 to 36,250 psi (150 to 250 MPa)

The purpose for this categorization has two advantages. Firstly normal strength concrete is currently in common use, high strength concrete is coming more into use and very high strength is still undergoing experiments. Secondly, the making of these three types of concrete is different. The production of high strength concrete is very similar to that of normal strength concrete as will be discussed in chapter 2.

There exist also another definition of concrete categorization on the same basis of strength done by the Strategic Highway Research Program (SHRP):

- Very Early Strength (VES) concrete with a maximum strength of 3,000 psi (21MPa) within four hours of placement
- High Early Strength (HES) concrete with a compressive strength of at least 5,000 psi (34.5 MPa) within 24 hours after placement

- Very High Strength (VHS) concrete with a compressive strength of 10,000 psi (69 MPa) at 28 days

Although there exists many ways of categorizing high strength concrete, it is understood from most studies that a high strength concrete is a concrete that has particular characteristics that are developed for specific applications. Some of theses particular characteristics are:

- Ease of placement
- Compaction without segregation
- Early-age strength
- Permeability
- Density
- Heat of hydration
- Toughness
- Workability
- Durability
- Volume Stability
- Long life in severe environmental conditions

These characteristics will be further discussed in more depth in chapter 3.

2.2 How is High Strength Concrete made?

Dr. Kenneth Hover, a professor and research director at Cornell University, studied in great depth the "concrete matrix" at various curing stages, and illustrated the function and effect of admixtures in the "concrete matrix." "I want to go deep inside the concrete," Hover said. "We want to go all the way inside… get familiar and comfortable there." We will then observe that the concrete is primarily a composite material made out of coarse, intermediate and fine aggregates glued together by an "industrial-strength adhesive which we refer to as hardened Portland cement paste." Hover added that, from a mechanical stands point, the aggregate performance is the critical aspect of the composite; however, from a chemical and durable stands point, the performance still needs to be investigated. The legal definition of cement in the Commonwealth of Pennsylvania now is "cement is to concrete as flour is to fruit cake." When Hover magnified a sample to 500,000 times, he noted that hydrated cement appears as fuzzy "dust bunnies" which began as smooth, hard particles, but expanded on reaction with water to connect with each other to form a stronger matrix. "This interaction is the source of the fundamental strength and mechanical properties of concrete," he said, adding that like Velcro, it's the interlocking action of crystals that gives the connectional capability of holding the aggregate together. As opposed to normal concrete, HSC has a denser microstructure, which is the result of a lower w/c, less void space and less permeability. Hover used a microphotograph of normal concrete to show that "there is more pore volume than there is solid volume present, and the pore volume essentially is the origin of our durability problems. If the connection is the origin of our strength benefits, the void space there is the origin of our durability difficulty, where water can enter, where sulfates, deicing salts, the chlorides and alkalis can move. Most of our deterioration mechanisms will be associated with our ability to get aggressive agents into the concrete, and they get in through that pore space. Concrete in fundamentally a very porous material." In a regular concrete mix, cement paste is about 50 to 60 percent void space, and with aggregates added, about 50:50 porous/solid. The main issue here id to recognize the porosity and "make it more resistant to penetration so it takes longer for these aggressive substances to make their way into the concrete."

High strength concrete is an engineered concrete composed of classic elements of cement, water and fine and coarse aggregates, but with admixtures. To obtain the finest proportioned mix, materials and admixtures are thoroughly chosen in order to achieve the qualities of high strength concrete, such as high early strengths, high ultimate strengths, high workability, high durability, high toughness and long-term mechanical properties. The distinction between normal strength concrete from high strength concrete is based on the proportions of the fundamental components and the types of admixtures used. There exist different types of admixtures, such as fly ash, fibers, silica fume and superplasticizer, which are responsible for the long term properties of high strength concrete as well as contributing to an environmental friendly product. Additionally, these admixtures provoke micro structural changes in the concrete. The strength of the cement matrix depends on the hydration structures and the porosity of the matrix. Therefore, there exists two ways of making high strength concrete: on the one hand decreasing porosity and on the other hand improving the strength of hydration structures. When porosity decreases, the strength of the cement matrix increases. The decrease in porosity can be achieved by reducing the w/c ratio, which will result in a high strength matrix. The addition of admixtures or using optimum curing conditions can improve the strength of hydration structures. In general practice, both strength improvement techniques are performed simultaneously such that the most efficient mix is obtained. For example, the use of admixtures fills up the pore spaces, reducing the matrix porosity and therefore attaining high strength. Material selection, mix proportioning, interaction and strength improvement will be discussed below.

2.2.1 Classic Components

2.2.1.1 Cement

Adequate selection of cement is a key step to the achievement of high strength concrete. For high strength concrete containing no admixtures, a high cement content of 8.0 to 10.0 sacks/cu.yd must be used. Also, the selection of both the type and brand of cement is important. For example, cement fineness of 4,000 cm^2/g was suggested as a maximum (Blaine). It was also proven that type III cement produces a higher strength concrete for high cement contents up to 90 days after casting. (Burgess)

2.2.1.2 Water and Water/Cement Ratio

According to a U.S. Air Force Investigation, the most important variable in obtaining high strength concrete is the lowest water/cement ratio. Studies have proved that in this case, the water/cement ratio should be as low as 0.35. Figure 1 shows the effect of water/cement ratio on concrete mixes with constant cement content.

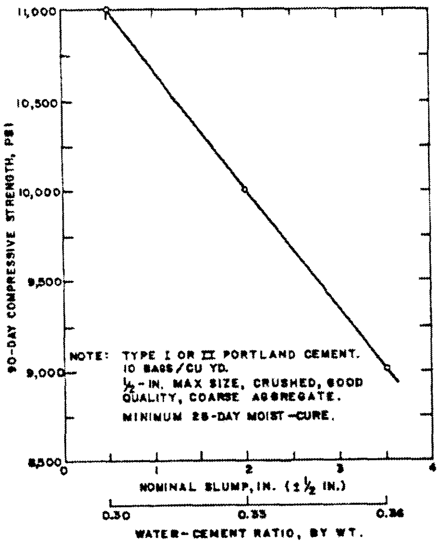


Figure 1:Effect of water/cement ratio and slump on the 90-day compressive strength of concrete (Peterman, Carrasquillo, 1986)

It has also been shown that quality and temperature of water used have no effect on strength.

2.2.1.3 Coarse Aggregates

To achieve high strength concrete, the aggregates have to be tested for strength. The difference in strength and stiffness between the aggregates and the mortar are considerable variables. The optimum size for coarse aggregates in concrete depends on the relative strength of the mortar, the mortar aggregate bond and the aggregate particles. For each strength level, there exists a corresponding aggregate size that will yield the greatest compressive strength. Figure 2 shows the results of the effect of maximum size aggregate on concrete strength efficiency.

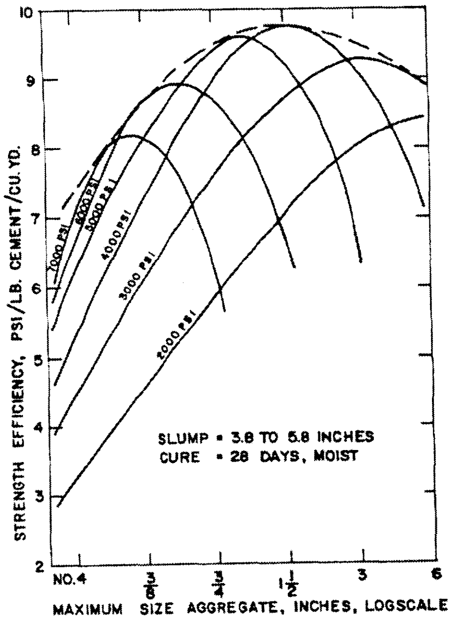


Figure 2: Optimum coarse aggregate size for efficient production of concrete at various compressive strengths (Peterman, Carrasquillo, 1986)

Generally, smaller size aggregates and higher cement contents produce the highest strengths in concrete mixes with and without admixtures. It is also relevant to note that the difference between surface texture and particle shape affects the strength capacities.

2.2.1.4 Fine Aggregates

Although studies have shown that fine aggregates do not have a considerable effect on the strength of concrete, their properties, especially sand particle shape and texture, affect the mixing water requirement of concrete.

2.2.2 Admixtures

2.2.2.1 Superplasticizer

A superplasticizer is a chemical admixture, which helps the concrete mix to reach high strength. It also decreases the water/cement ratio by dispersing the cement particles. Moreover, the superplasticizer will contribute to a reduction in the void ratio because of less air entrainment. A large amount of superplasticizers have been developed. It has been proven that the water to cement ratio having a slump of 100 to 200 mm can be decreased by 30% with the use of superplasticizer, thus increasing the concrete's strength. Figure 3 shows the relationship between the compressive strength and the cement/water ratio. As the cement/water ratio increases, the compressive strength increases as well, up to 100 MPa, with autoclave curing.

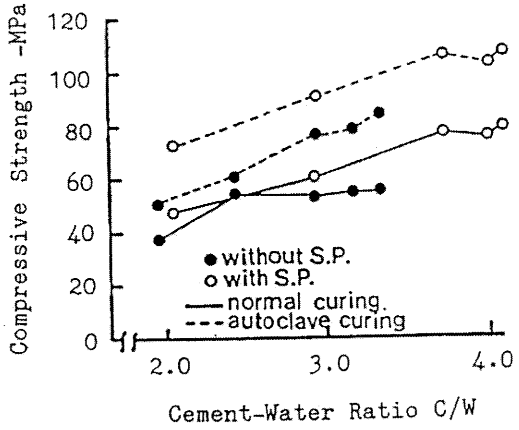


Figure 3: Water/cement ratio and compressive strength relationship (Swamy, 1985)

2.2.2.2 Silica Fume

Silica Fume results from the combination of silicon metal and ferro silicon. It is a very fine powder with an average particle size of 0.1 μm, and it contains 70 to 90% of SiO_2. Norway produces and utilizes the most silica fume (about 50% of the world's production). It is very important to assure that silica fume is used together with a superplasticizer in order to ameliorate the workability of concrete and the dispersion of silica fume. In Figure 4, we observe the effect of curing condition on the pore volume of cement paste containing silica fume. The higher the curing temperature or the longer the curing time, the smaller the pore volume. This results in an increase in strength and durability.

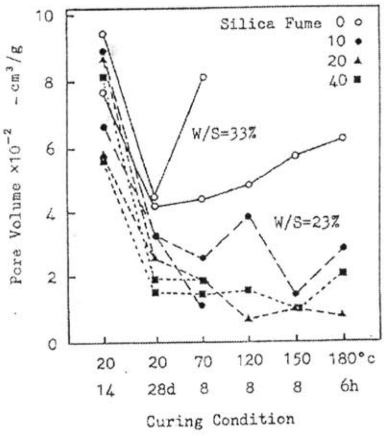


Figure 4: Replacement ratio of silica fume and compressive strength mortar relationship (Swamy, 1985)

2.2.2.3 Blast Furnace Slag Powder

When part of the cement is replaced with blast furnace slag powder, fluidity can be improved as well as the resistance to seawater and chemical attack. This result has been proven in many projects such as marine/offshore structures. Figure 5 shows the relationship between the replacement ratio of blast furnace slag powder with cement and the compressive strength.

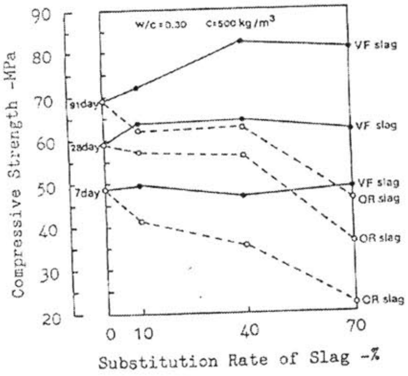


Figure 5: Replacement ratio of slag powder on the compressive strength relationship (Swamy, 1985)

It has also been proven that the use of blast furnace slag powder along with superplasticisers can result in higher strength of concrete.

2.2.2.4 Fly Ash

According to Berry and Malhotra, pozzolan, a type of fly ash, is a siliceous or siliceous and aluminous material which itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Like silica fume and blast furnace slag powder, fly ash along with superplasticizer contribute to an increase in concrete strength, an increase in modulus of elasticity, improve workability and finish ability, decrease permeability and heat of hydration. Additionally, corrosion and reinforcement may be reduced.

2.3 Compacting and Curing

Various compacting methods such as pressing and centrifugal compaction can be used to decrease the porosity and the water to cement ratio by draining out the excess water, thus increasing the strength of concrete. The compaction method is well developed by Yoshida, where a pressure of 10 MPa is applied to a sample during the first curing day. The results of this method are a 70 MPa compressive strength on the first day and a 100 MPa compressive strength on the 28th day. The centrifugal compaction enables the concrete to be compacted into cylindrical shapes (pole, pipes, pipes etc), by removing excess water as a result of the centrifugal force and its vibration.

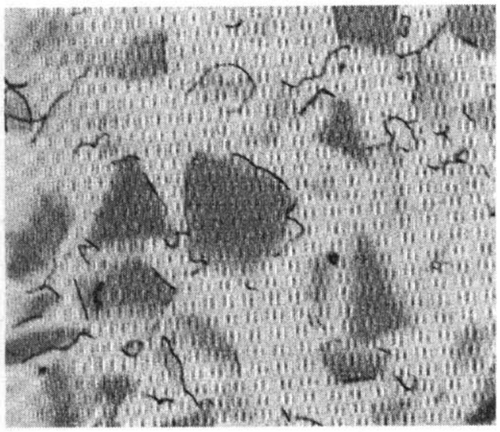
Pressing curing, steam curing and autoclave curing are methods used to achieve high strength. Pressure curing is simply a curing process in normal or high temperature. Steam and autoclave curing are performed under high temperature so that the cement hydration is accelerated and high strength is obtained rapidly.

2.4 Mechanical Behavior of High Strength Concrete

There are many mechanical behaviors of high strength concrete that one can investigate. However, for the purpose of this paper, response of the material under compression tests will be looked into more carefully.

2.4.1 Short-term Compression Tests

Increasing the applied load will result in internal cracking of the specimen, which will determine the shape of the stress-strain curve. The cracks will begin between the aggregates and the mortar. As the load is progressively increased, the bond between the aggregates and the mortar will generate more cracks. As a result, the material properties start experiencing discontinuity and eventually produce failure of the concrete. Figure 6 and 7 below show the difference in behavior of micro cracking for normal strength concrete and high strength concrete.



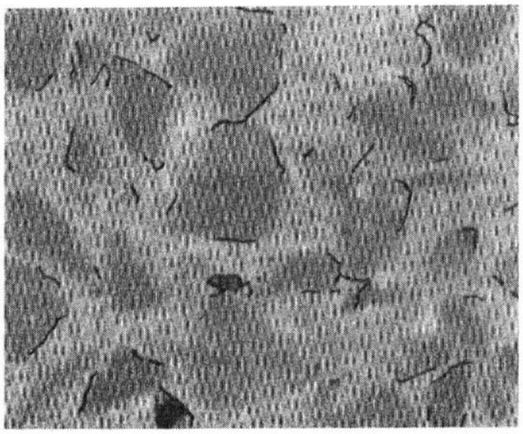


Figure 6:High Strength Concrete

Figure 7: Normal Strength Concrete

Micro-cracking at 90% of ultimate load (Nilson, 1987)

It is understood that usually, micro cracking starts at about 30 percent of ultimate strength and about 65 percent of ultimate strength for normal strength concrete and high strength concrete, respectively. The closer match of strength and stiffness of stone and mortar explain the differences, and the higher interface bond strength associated with cement-rich mixes. (Carraquillo, R. L., ACI)

In addition, it is of interest to compare the fracture surface of a normal strength concrete to a high strength concrete. As seen in pictures 8 and 9 below, the fracture surface for a normal strength concrete appears to be much rougher and rocky, resulting in a large amount of energy dissipation. (This phenomenon is observed in the stress strain curve with the large inelastic deformation). The fracture surface for a high strength concrete is much smoother and its cracks do not cut through the mortar and aggregates as severely.

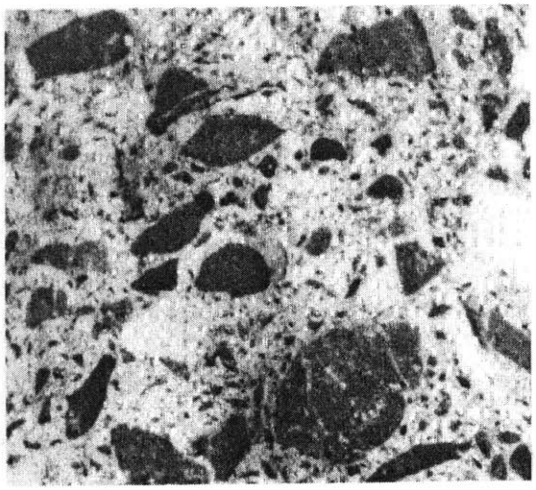


Figure 8 High Strength Concrete

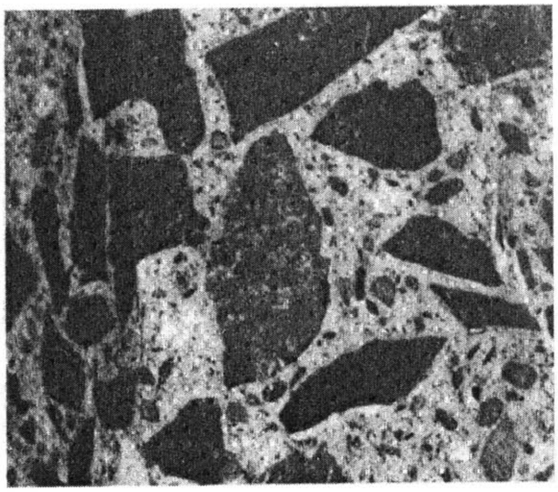


Figure 9. Normal Strength Concrete

Fracture Surface of Cylinder (Nilson, 1987)

This proves that high strength concrete has a linear behavior to loads of 80 percent of ultimate strength; however, the drawback on this aspect is that high strength behaves in a more brittle manner.

2.4.2 Compressive Stress-Strain Curve

Figure 10 shows a typical stress-strain curve obtained from compressive tests using 100 x 200 mm cylinders.

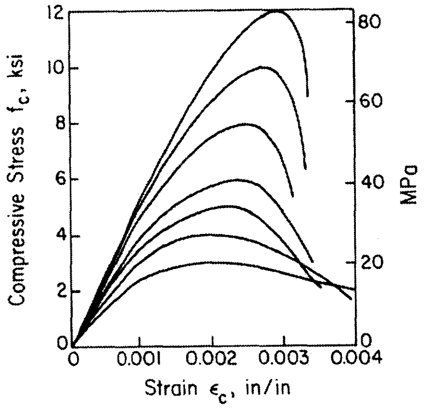


Figure 10: Typical Stress-Strain Curve (Nilson, 1987)

As noted from the figure, high strength concretes have a much steeper and linear ascending parts of the curve. The range of linearity is extended to 80 to 90 percent of ultimate strength. The value of the strain at the peak also increases from low strength concrete to high strength concrete. Yet, the maximum value of the strain is higher for lower strength concretes. Also the descending part of the curve which steeper, which is equivalent to the rapid decrease of stress in the concrete. The failure of high strength concrete is said to be brittle. In order to overcome the brittle aspect of high strength concrete, the addition of materials in the mix, such as fibers, can help improve ductility.

2.4.3 Creep and Shrinkage Coefficients

In order to predict creep and shrinkage, column shortening and prestress losses, it is important to consider the modulus of elasticity. It is understood from most studies that creep decreases with an increase in strength as shown in figure 11.

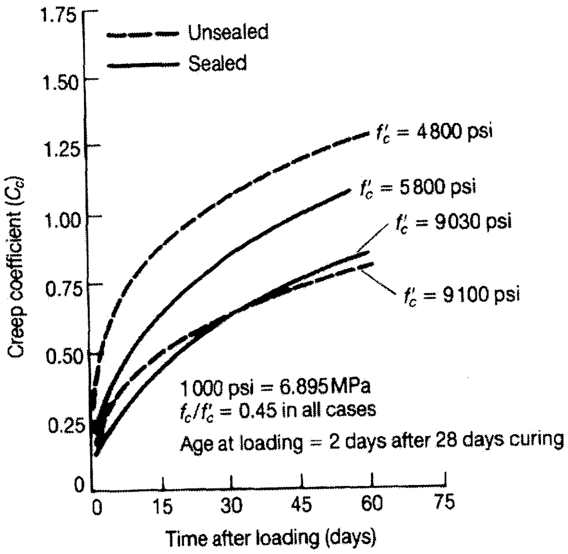


Figure 11: Relation between compressive strength and specific creep (Nawy, 1996)

In addition, creep decreases in high strength concrete as opposed to normal strength concrete as showed in the table below. (Figure 12)

Type of concrete	$f'_{c,28}$ psi (MPa)	C_u	$C_{u,HSC}/C_{u,NSC}$
(1)	(2)	(3)	(4)
Low strength	3 000 (20.7)	3.1	1.0
Medium strength	4 000 (27.6)	2.9	0.94
Medium strength	6 000 (41.4)	2.4	0.77
High strength	8 000 (55.2)	2.0	0.65
High strength	10 000 (69.0)	1.6	0.52

Figure 12: Creep comparison for normal and high strength concrete (Nawy, 1996)

Furthermore, it was found that shrinkage of high strength concrete was slightly lower than normal strength concrete. (Figure 13)

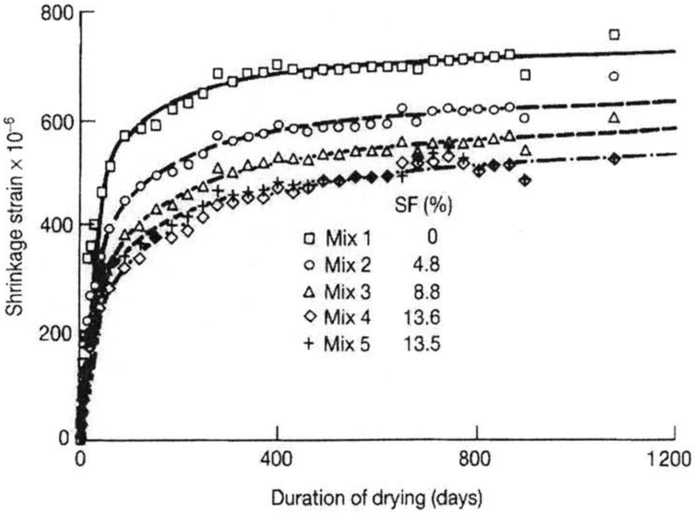


Figure 13: Shrinkage strain for various Compressive Strengths (Nawy, 1996)

2.4.4 Failure Modes

Failure under uniaxial and biaxial compression occurs in a different manner. Under uniaxial compression, cracks form parallel to the applied load and perpendicular to the specimen, as shown in figure 14. In most cases, the cracks propagate along through the mortar and along the aggregate – mortar interface without breaking the aggregate discs. However, under biaxial compression, the cracks described above are prevented due to a minor principal stress application. Consequently, the cracks will form parallel to the unloaded surface of the specimen, as demonstrated in figure 15. It was concluded from Chen, Carrasquillo and Fowler that "theses modes of failure indicate that failure of concrete occurs whenever a certain limiting tensile strain is reached in the unloaded direction."

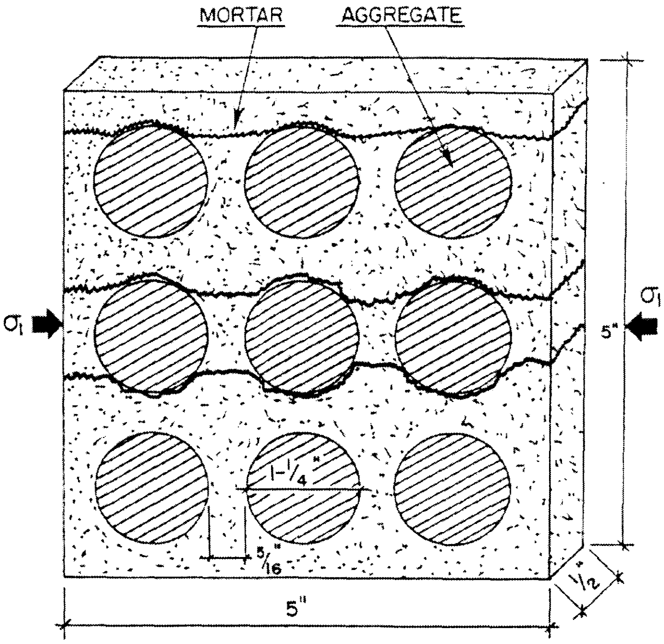


Figure 14: Failure mode in uniaxial compression (Chen, 1985)

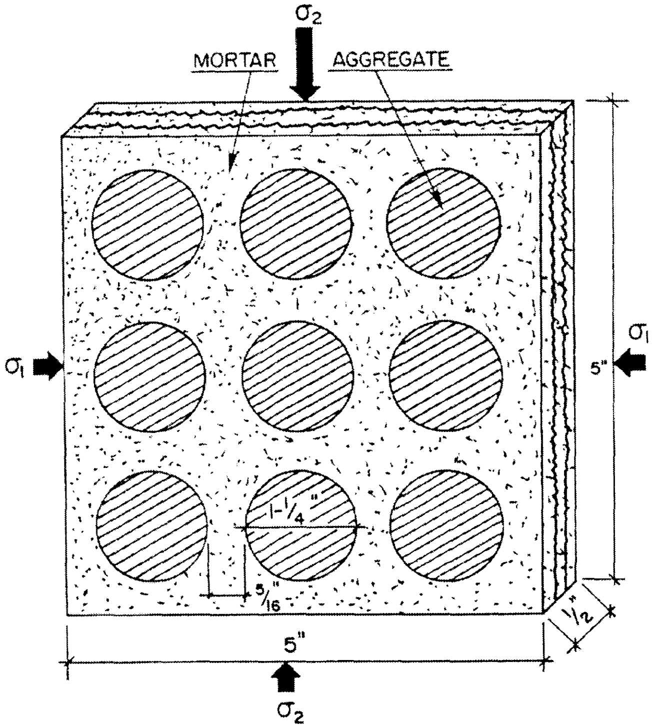


Figure 15: Failure mode in biaxial compression (Chen, 1985)

CHAPTER 3

HIGH PERFORMANCES CHARACTERISTICS OF HIGH STRENGTH CONCRETE

3 HIGH PERFORMANCE CHARACTERISTICS OF HSC

3.1 Properties

It is understood that a structure has to withstand significant construction loads since the first few days of concrete placement. Cement/cementitious paste is the binding matrix in concrete responsible for the strength, impermeability and volume stability of concrete. As described in the previous chapter, a good mix proportion, the use of chemicals and mineral admixtures, the curing, the degree of compaction, temperature and humidity control are factors that contribute to high strength concrete's early properties.

Temperature control is a major factor in the early ages of concrete. Since high strength concretes achieve high strength at early stages and generates less heat because of the replacement of part of the cement content in the mix, temperature rise at early ages can be controlled.

Studies have been made on high strength concrete monitoring at early stages. Electrical conductivity, thermal flow, ultrasonic-wave dissipation and speed of sound are all mean of recording the chemical processes as they relate to the mechanical properties of the final product.

3.2 Elastic Strength Expressions

The elastic strength expressions define the performance of the material and the structure at initial loading. It is recognized that the following expressions take into account long term effects such as creep, shrinkage and temperature effects.

Elastic Modulus E_c

E_c (psi) = (40,000 $*f'_c$ + 1.0 x 10^6)(w_c/145)^1.5

Where w_c = unit weight of concrete, lbs/ft^3

f'_c = compressive strength of concrete

E_c (MPa) = (3.32 $\sqrt{f'_c}$ + 6895)(w_c/2320)^1.5

Where w_c = unit weight of concrete, kg/m^3

f'_c = compressive strength of concrete

This expression is valid for a concrete with compressive strength of 12,000 psi (83 MPa). For a compressive strength of around 20,000 psi (140 MPa), a stress strain diagram based on fiels tests should be used to determine Ec at this time. (Nawy) Long-term effect on Ec gives:

$$E_{ct} = E_c \sqrt{(f'_c)_t / f'_c}$$

Where E_c, f'_c are 28 day values, $(f'_c)_t$ = compressive strength at later ages

Modulus of rupture f_r

f_r (psi) = 11.7 $\sqrt{f'_c}$

f_r (MPa) = 0.94 $\sqrt{f'_c}$

Tensile Splitting Strength f'_t

f'_t (psi) = 7.4 $\sqrt{f'_c}$

f'_t (MPa) = 0.59 $\sqrt{f'_c}$

3.3 Workability and Cohesiveness

High strength concrete performance necessitates a dense, void-free mass with full contact with steel reinforcement. Slumps have been well suited with these fundamental needs to achieve high strength and high performance. The advantage of high strength concrete is that the mix proportioning provides a workable mixture, easy to vibrate and fluid enough to be able to pass through closely placed reinforcing bars. The average adequate slump is around 5 in for good workability. However, higher strength concrete with higher slumps has been used.

The workable property of high strength concrete depends on its cohesiveness. As discussed previously aggregate selection and proper grading is essential in reducing the need of much higher water content. In additions, since there exists a high volume of fine particles in the matrix, high strength concretes have natural cohesiveness. Furthermore, high strength concretes are produced with the addition of superplasticizers, which contributes to the workable aspect of the concrete, because of the elimination of most voids.

3.4 Permeability and Environmental Issues

Because concrete is subjected to various external effects such as chemical, physical and mechanical factors, any penetration into the concrete can result in the reduction of its long-term properties. Therefore, permeability, which is defined as the degree of penetration of solutions through the concrete, is most of the times the major cause of deterioration. By trying to reduce the permeability rate, the concrete's resistance to the outside environment is increased. The use of admixtures such as silica fume can reduce the permeability of concrete.

A high strength concrete contains admixtures and superplasticizers, which are crucial in the fight against penetration and degradation of the concrete.

3.4.1 Carbonation and Corrosion

Carbonation is defined as the chemical reaction caused by the diffusion of carbon dioxide in the air into a permeable concrete and its reaction with $Ca(OH)_2$ compound of the hydrated cement such that it carbonates to $CaCO_3$. The carbonation process contributes to an increase in shrinkage with progressive scaling of the protective cover of the reinforcement. Corrosion of the steel accelerates with the oxidation reaction, which would eventually lead to a deterioration of the concrete. By reducing the permeability of concrete or by protecting the reinforcing steel, corrosion can be prevented.

3.4.2 Alkali-Silica Reaction

The alkali in the concrete can react with silica, which will result in deterioration of the concrete. This is observed in abutments and pavements. The remediation to this phenomenon would be to decrease the cement ratio and replace it with fly ash, slag or silica fume.

3.4.3 Freeze-Thaw Cycles

The freezable water content in a concrete matrix determines the freeze-thaw damage level in a concrete element. (Nawy) Long term performance which is affected by freeze-thaw and wetting-drying cycles depends on the coefficient of permeability of the concrete matrix. High strength concretes possess the lowest permeability because of the presence of high cementitious pozzolan. When concrete is critically saturated and not air-entrained or protected, it can collapse. A proper air void system is required and this is achieved by using a good selection of aggregates. Therefore, high strength concretes are more resistant to freeze-thaw cycles than normal strength concrete as shown in the figure below.

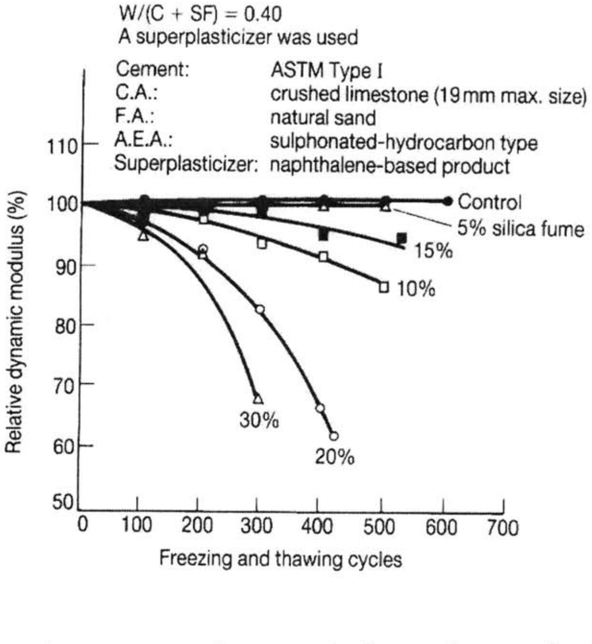


Figure 16: High strength concrete performance in freeze-thaw cycles (Nawy, 1996)

3.4.4 Sulfate Attack

Calcium aluminate reacts with sulfates and causes distress in the concrete. In order to avoid a sulfate attack, cement with a lower level of calcium aluminates (type II or V) can be used.

3.5 Volumetric Stability

Volumetric changes, which are caused by shrinkage and creep, can affect the long-term durability properties of the concrete.

3.5.1 Shrinkage

3.5.1.1 Plastic Shrinkage

Plastic shrinkage occurs during the first few hours after placing fresh concrete in the forms. It is a result of the loss of water though evaporation or downward suction of the water by a sub-base or a formwork material. When water is no longer dispersed within the paste, plastic shrinkage stops. A high strength concrete with its high performance characteristics protects fresh concrete from loosing its moisture content and therefore decreasing the rate of plastic shrinkage.

3.5.1.2 Drying Shrinkage

Drying shrinkage occurs in the hardened concrete. Studies have limited information on the drying shrinkage of high strength concrete. A higher rate of shrinkage was noticed, however, it had little effect on the concrete.

On of the advantages of high strength concrete is that in general it develops less drying shrinkage than normal strength concrete and thus less cracking shrinkage. Studies have showed that the incorporation of silica fume or fly ash reduces the pores in size and number and increases the surface tension in the concrete.

3.5.2 Creep

Creep, which is the flow of material under sustained load, is a very important factor for the performance of concrete. High strength concrete definitely has high performance qualities since research has proved that the value of creep is much lower than in normal strength concrete. Using cemetitious replacement additives, creep strain values were found to decrease. The amelioration of the creep effect contributes to the high performance aspect of high strength concrete.

3.6 Toughness

Toughness is measured by the degree of energy absorption. Toughness is the energy absorbed in breaking a specimen into flexure due to fatigue or dynamic loading. The fatigue resistance of concrete is also related to the total energy absorbed at failure. Energy absorption strength can improve in high strength concrete because of the presence of silica fume, which is responsible for the toughness and endurance properties of the concrete.

3.7 Constructibility

Constructibility is the action of placing the already mixed and proportioned concrete efficiently and economically into a form such that it meets short-term and long-term performance properties. This definition includes batching, mixing, transporting, placing, pumping curing and quality control procedures. The first quality control after the mixing and transporting is the flow properties and the cohesiveness. Then follows the remaining steps. The slump test is then executed, which is a measure of workability.

The use of high strength concrete in bridge construction requires a more precise, meticulous and higher degree of control in all the areas of the construction site. Ideally, the use of advanced techniques and modern equipment would be favorable, such as electronic batching plants for batching and mixing of the concrete.

Also, specific machines for placement of the concrete will be needed. For instance, if a high strength concrete is made with superplasticizers, the time between the mixing and placement should be minimized as much as possible, since concretes with superplasticizers have a tendency to loose their workability property. Moreover, if condensed silica fume is used, operations while feeding concrete into the batching machine must be carefully monitored, since the silica fume may fly off.

In order to obtain good compaction, high frequency vibrators should be used. The fresh cement must also be protected from the wind and sun since its water content is relatively low.

3.8 Abrasion Resistance

Abrasion resistance is important in highway pavements and concrete bridge decks. The maintenance costs of such a major structure is very high and has great impact on the national economy. It was estimated in 1996 that about $400 billion would be spent on the maintenance and rehabilitation of the highway pavements by the year 2000. As will be seen in chapter 6, the utilization of high strength concrete is economically sound particularly for highway bridge decks. Previous work done on high strength concrete has shown that an increase in strength contributes to an increase in service life.

3.9 Fire Resistance

The available existing information on fire resistance of high strength concrete is limited. Various tests have been performed some of which had contradictory results. So far, it seems that the endurance performance of high strength concrete to fire is very similar to that of normal strength concrete.

CHAPTER 4

GENERAL APPLICATIONS OF HIGH STRENGTH CONCRETE

4 GENERAL APPLICATION OF HIGH STRENGTH CONCRETE

4.1 Products

The appropriate use of curing methods, such as steam curing and autoclave curing, can contribute to an increase in strength for precast concrete. To obtain a high strength finish product, a combination of the above techniques must be used. For example, when silica fume is used and reduction of water/cement ratio is taken into account with the use of superplasticizer, high strength prestressed concrete piles are manufactured by centrifugal casting followed by steam and autoclave curing. In 1994, Japan produced 5,901,014 tons of piles, 90% of which were high strength concrete.

4.2 High-rise buildings

Regarding high rise reinforced buildings, superplasticizers are used in order to attain a strength ranging from 36 to 48 MPa. On going research is still aiming to increase the strength for buildings. High strength concrete is used for the columns of high-rise buildings, designed to carry the loads more economically, provide more floor space by having smaller cross sections.

Since most tall building designs are controlled by stiffness requirements, the use of high strength concrete will provide this additional stiffness. Its high modulus of elasticity results in a lower inter-story drift.

In addition to a stiffness advantage, on-going studies in wind tunnel analysis have showed high strength concrete in tall buildings result in lower peak acceleration. A study for the Texas Commerce Plaza was done in the mid-seventies showing that a higher damping ratio was used for concrete. Since the fundamental wind resisting elements are concrete members, the damping ratio was 2%, whereas for an all-steel building, a 1% ratio is commonly used. Hence, a much lower peak acceleration.

Furthermore, the use of high strength concrete for building frames decreases the risks of axial shortening. In a composite frame for example, most interior columns of structural steel have only elastic axial shortening, while the exterior composite columns experience axial shortening due to stress, shrinkage and creep. It is understood that using high strength concrete in this case would reduce axial shortening of a concrete column.

Also, the use of high strength concrete in building construction offers many advantages. In term of concrete forming, it is understood that it is possible to strip high strength concrete columns and beams forms at a much earlier stage than normal strength concrete. This is due to the low stress level and the relatively high strengths at early stages. This results in acceleration in the construction schedule.

4.3 Offshore/Marine Structures

The use of high strength concrete for offshore/marine structure is becoming more popular since it has proven its performance such as effectiveness, durability, high strength and low density. For example, during the last two decades, 27 major structures have been built for the North Sea, using high strength concrete. Some of these structures are placed at 80 to 350 meters under water and are resistant to the harsh marine environment.

Besides the mechanical and durability necessary properties, the issue of workability presents a much more challenging and crucial aspect for under-water structures. This is due to the fact that designs for these types of structures require reinforcement and cast-in items. To ensure proper compaction, the concrete should have a slump of 200 mm and more, which is achieved by using superplasticizers or any other type of admixtures. Slip forming is related to the concrete's setting time, early high strength and moderate heat of hydration. Hence, the use of high strength concrete facilitates construction methods, since it offers more workability than normal strength concrete. Also, high strength concrete offers a much more durable aspect than normal strength concrete since there often is little or no maintenance required. Moreover, it is recognized that high strength concrete offers considerable technical and economical advantages in the design of gravity based structures due to an improvement in buoyancy and floating stability during floating phases. High strength concrete is therefore a highly durable, workable and reliable material for marine structures. It corresponds to a tremendous cost saving potential for offshore and deep-water platform construction.

CHAPTER 5

IMPLEMENTATION OF HIGH STRENGTH CONCRETE IN BRIDGES

5 IMPLEMENTATION OF HIGH STRENGTH CONCRETE IN BRIDGES

5.1 Introduction

Bridges are a vital link in a country's transportation system. High strength concrete has become a major material in the development of a city's infrastructure. The use of high strength concrete in bridge construction has been very successful worldwide. High strength concrete is receiving more attention theses days since it has proven its efficiency and economical benefits as will be discussed later in this thesis. With its strength and durability parameters, high strength concrete contributes to the long-term performance of structures such as bridges. The performance issues related to high strength concrete are proven to be successfully implemented, as it will be discussed in the following projects.

5.2 Background

The table below lists a few of the major high strength concrete bridges.

Bridge	Location	Year	Max. Span (m)	Max. Design Conc. Strength (MPa)
Nitta Highway Bridge	Japan	1968	30	59
Kaminoshima Highway Bridge	Japan	1970	86	59
2nd Ayaragigawa Bridge	Japan	1973	50	60
Iwahana Bridge	Japan	1973	45	89
Ootanable Railway Bridge	Japan	1973	24	79
Fukamitsu Highway Bridge	Japan	1974	26	69
Akkagawa Railway Bridge	Japan	1976	46	79
Kylesku Bridge	Scotland	N/A	79	53
Deutzer Bridge	Germany	1978	185	69
Tower Road Bridge	Washington	1981	49	62
East Huntington Bridge	W. Virginia	1984	274	55
Annacis Bridge	Vancouver	N/A	N/A	55
Sylans Viaduct	France	1986	N/A	60
Re Island Bridge	France	1987	N/A	60
Braker Lane Bridge	Texas	1987	26	66
Pont du Joigny	France	1988	46	60
Pont du Pertuiset	France	1988	110	65
Arc sur la Rance	France	1989	N/A	60
Giske	Norway	1989	52	55
Sandhornoya	Norway	1989	154	55
Boknasundet	Norway	1990	190	60
Helgelandsbrua	Norway	1990	425	65
Kwung Tong By Pass	Hong Kong	1900	N/A	65

Figure 17: High Strength Concrete Bridges

According to Lane and Podolny, one of the first major application of high strength concrete in a cable-stayed bridge was in the East Huntington Bridge crossing the Ohio River in West Virginia as seen in the picture below.

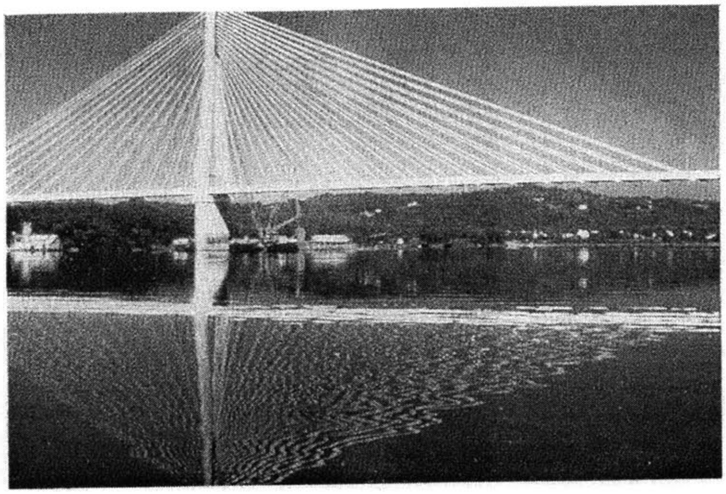


Figure 18: East Huntington Bridge, West Virginia

This bridge was not originally designed for high strength concrete. The original design included structural steel and orthotropic box-girder design. However, the design was later changed since the already completed pier was designed for lighter steel. The concrete needed to be lighter, hence the use of high strength concrete.

Another relevant bridge is the Annacis cable-stayed bridge near Vancouver, British Columbia, Canada, (figure 19) which used 8,000 psi (55 MPa) concrete for both the composite pre-cast deck and the cast-in-place concrete overlay in order to reduce the dead load.

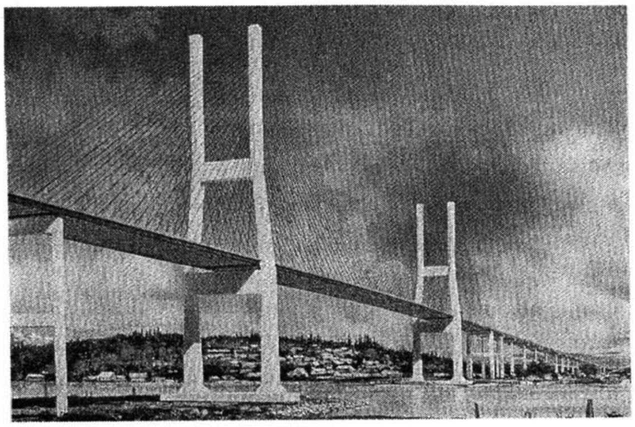


Figure 19: Annacis Bridge, British Columbia, Canada (Lane, Podolny, 1993)

5.3 Smaller Member Dimensions

The Bretonne cable stay bridge, with its one plane of stay in the middle, greatly benefited from the use of high strength concrete, because the dimensions of the pylon were reduced, hence a decrease in the deck's excessive width. Higher strength to obtain smaller dimensions is achieved with the use of superplasticizers.

A more recent application is the use of high strength concrete ion the design of the 2808 ft (856 m) center span, cable-stayed, Normandie Bridge in France. (Figure 20)

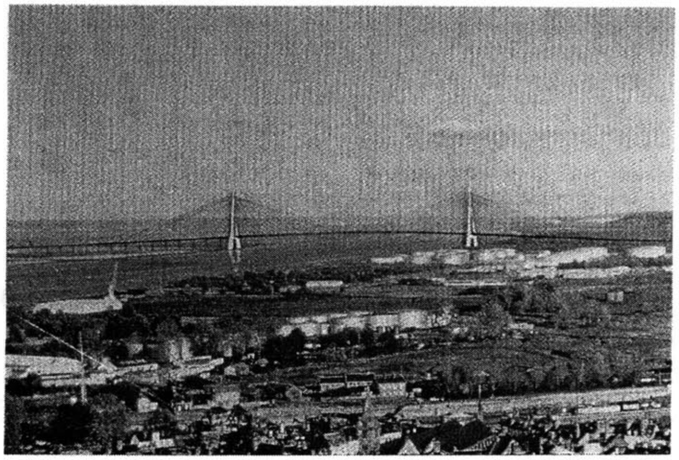


Figure 20: Normandie Bridge, France (Lane, Podolny, 1993)

The design of the bridge, which originally included 5,800 psi (40 MPa) concrete, was revised to 8,700 psi (60 MPa) concrete. This change in concrete strength for the pylon enabled a reduction in thickness of the pylon from 24 to 16 in (600 to 400 mm). Also, the thickness of the bottom flange of the box girder in the side spans was reduced from 8 to 7 in (200 to 180 mm).

5.4 Longer Spans

In addition, the use of high strength concrete in bridge construction allows for longer spans with fewer supports or fewer beams for a specific span. Studies have shown that using high strength concrete in pre-tensioned bridge girders can result in significant increases in span length of 10 to 40 percent increase. This was the case for the Gateway Bridge Brisbane with a span of 260 m. (Figure 21)

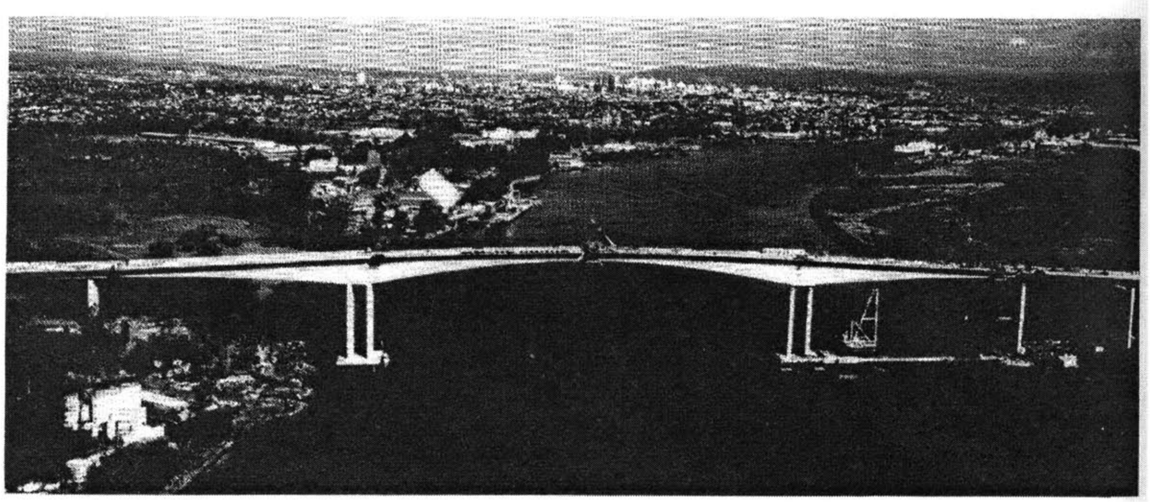


Figure 21: Gateway Bridge Brisbane (Walther, 1987)

Although a normal strength concrete cable stay would have been cheaper, the location of the bridge did not allow for high pylons. In Addition, this strategy will contribute to a decrease in production, transportation and construction cost and foundation cost also since the superstructure will be much lighter.

Construction Technology Laboratories, Inc. (CTL) performed a study to evaluate the benefits of high strength concrete on span capabilities. The study found that an increase in concrete compressive strength form 5,000 to 8,000 psi, increases the span capacity to about 15 percent. The figure below is taken from a study that found a relation between the increase in strength, the decrease in beam depth and the increase in span length for continuous, cast-in-place, post tensioned box girders of different girder depth in the span range of 150 to 250 ft (46 to 76 m).

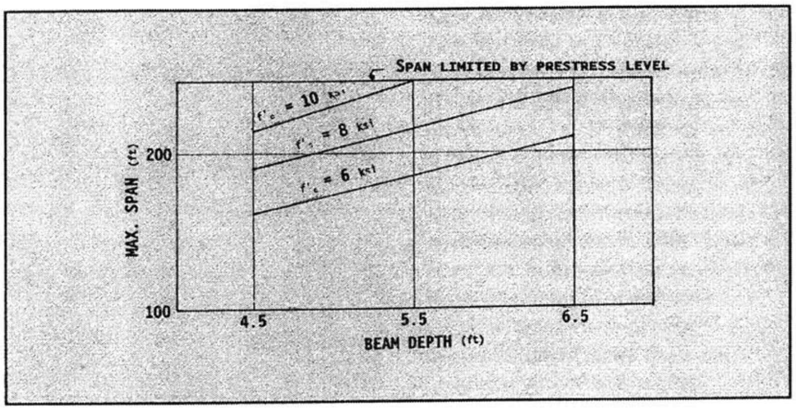


Figure 22: Span capabilities from the two span continuous box girder bridge (Lane, Podolny, 1993)

5.5 Number of Girders and Girder Spacing

Another advantage of using high strength concrete is the reduction in the number of girders and therefore an increase in their spacing. To demonstrate this aspect, two designs for a 150 ft (46 m) simple span bridge were made by researchers.

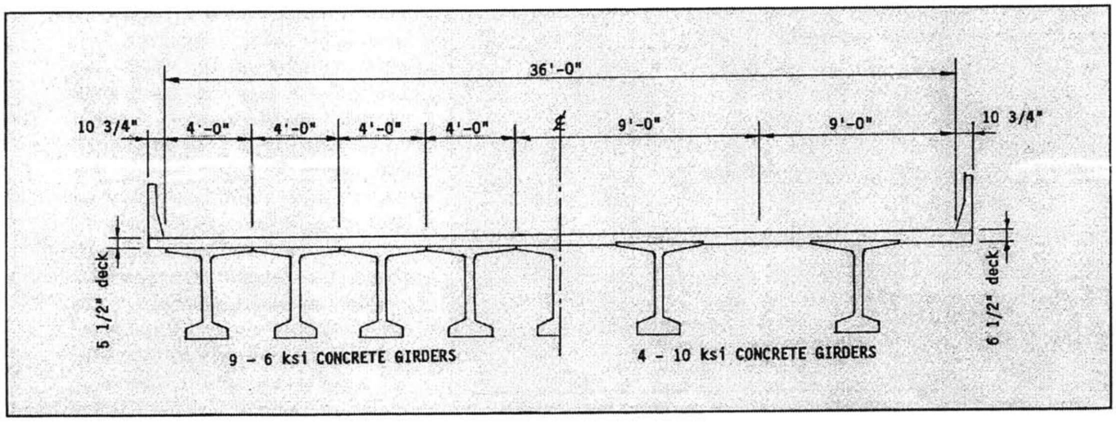


Figure 23: Two 150 ft (46 m) simple span bridge with different concrete strengths (Lane, Podolny, 1993)

The result from the first design was nine girders of 6,000 psi (41 MPa) concrete, spaced at 4 ft (1.22 m). The result from the second design was four girders of 10,000 psi (69 MPa) concrete, spaced at 9 ft (2.74 m). Although there was an increase of 1 in. in the deck thickness in the second alternative, the overall dead load of the second design was decreased as opposed to the first design, thus lowering the total prestressing requirements.

5.6 Segmentally Post-Tensioned Box Girders: Reduction of Flange Thickness

The Shubenacadie Bridge in South Mainland, Nova Scotia is a good example of the benefits of using high strength concrete in a post-tensioned box girder bridge.

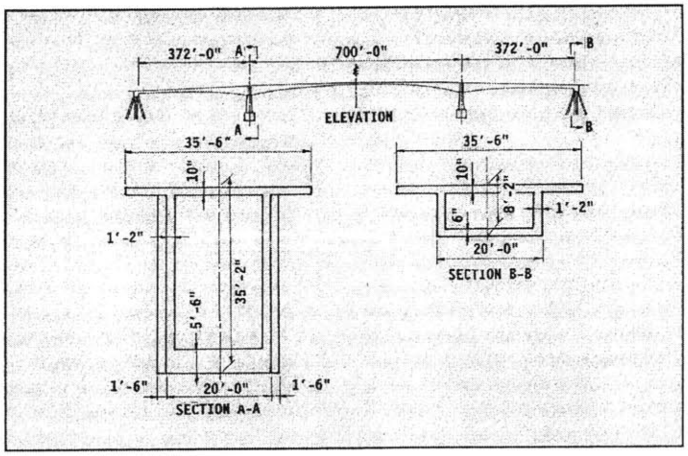


Figure 24: Shubencacadie Bridge, Nova Scotia, Canada (Lane, Podolny, 1993)

This 700 ft (213 m) main span and 372 ft (113 m) side span, was constructed using 5,000 psi (35 MPa) concrete and used 1.25 in. (31.75 mm) diameter thread bars for post-tensioning. The bridge was reanalyzed using 10,000 psi (70 MPa) concrete to find out the amount of reduction of the thickness of the lower flange and the overall effects of the moments. Figure 25 shows that the use of high strength concrete reduced the total flexural prestress force by more than 10 percent as a result of the reduced dead load. Also, the optimum thickness of the lower flange was 1.6 ft (0.5 m) for a compressive strength of 8,000 psi (56 MPa).

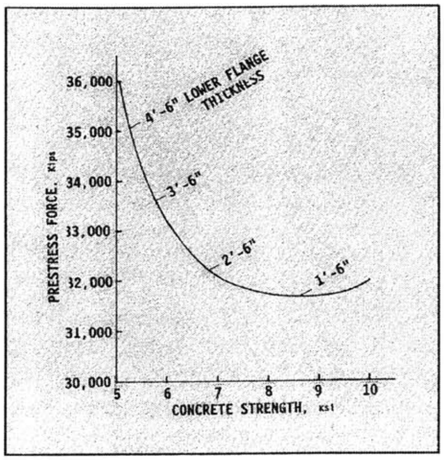


Figure 25: Variation of prestress force and flange thickness with concrete strength (Lane, Podolny, 1993)

5.7 Lighter overall Structure

Nowadays, more bridges are being constructed using high strength concrete because it primarily reduced the dead load. The higher the concrete strength, the more the weight of the concrete structure can be reduced. For example, the weight of the main girder of the Ayaragigawa railway bridge in Japan using normal strength concrete (40 MPa) would have been 170 tons. However, the use of high strength concrete (60 MPa) reduced the weight to 150 tons. Anything that decreases the weight of the bridge is very advantageous in producing a more economical bridge. Additionally, the use of high strength concrete for bridges reduces the maintenance cost because of its long-term properties.

5.8 Thin Wall Sections for Bridge Piers

A study by Jose and Moustafa involved a circular and a square pier with 6 in (152 mm) wall thickness. The circular pier had a hollow outside diameter of 15 ft (4.6 m) with a pre-stress steel area of 20.2 sq. in (130 cm^2). The square pier had a 10 ft (3 m) hollow and a pre-stress steel area of 18.4 sq. in (118 cm^2). For both piers, concrete strength was studied at 6,000 and 10,000 psi (42 and 70 MPa). The 1977 AASHTO specifications were used to design the piers. Interaction diagrams were built using the assumption of a concrete stress equal to *0.85f'$_c$* and distributed as a rectangular stress block. The interaction diagrams obtained in figure 26 and 27 show the increase capacity of the piers when the concrete strength in increased from 6,000 to 10,000 psi (42 to 70 MPa).

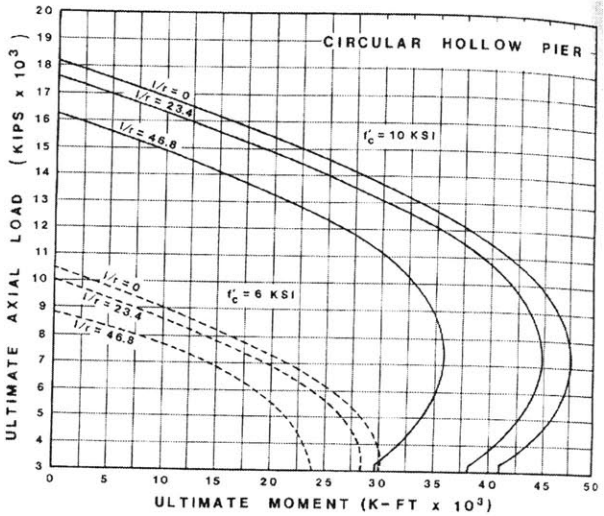


Figure 26: Interaction Diagram – 15ft diameter circular pier (Jobse, Moustafa, 1983)

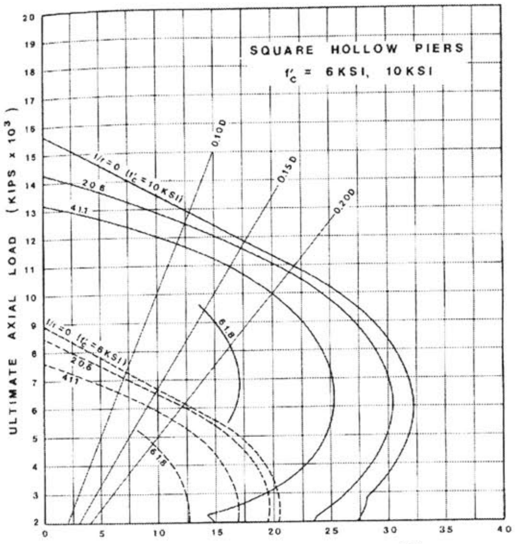


Figure 27: Interaction Diagram – 10 ft square hollow pier (Jobse, Moustafa, 1983)

This study proved that high strength concrete enables the use of thinner wall sections to pier construction for a major bridge span. This also leads to fewer piers, hence longer spans

5.9 Architectural Purposes

Studies have shown that the increase in high strength concrete bridge is closely related to the aesthetics of the bridge. Smaller dimensions, sections and decks are architecturally pleasing. Also, one of the main qualities of HSC is the high workability. This result in more manipulation options in the design stage.

5.10 Aerodynamic Stability

Everyone remembers the disastrous failure of the Tacoma Narrows Bridge, which had a deck that did not provide any torsional stiffness. Nowadays, it is very important to accommodate bridge decks with torsionally stiff decks. This could be achieved be achieved by using box-girders of high strength concrete, as demonstrated in the Barrios de Luna Bridge in Spain.

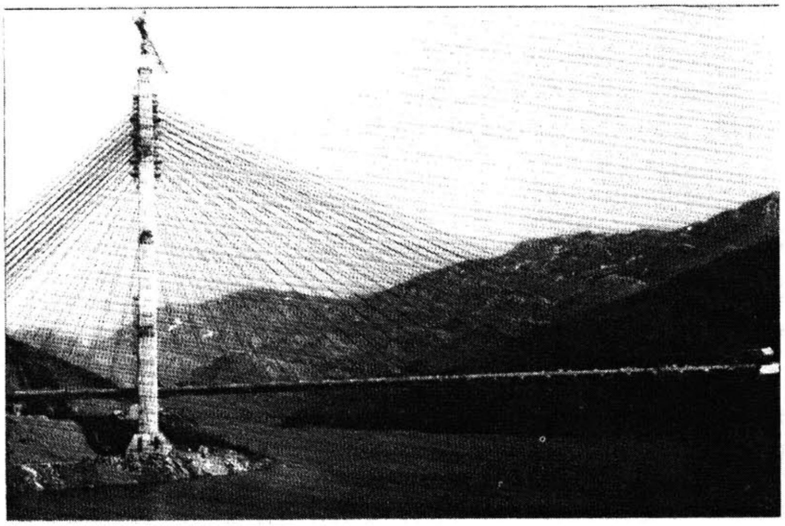


Figure 28: Barrios de Luna Bridge in Spain (Walther, 1987)

CHAPTER 6

ECONOMICS OF HIGH STRENGTH CONCRETE

6 ECONOMICS OF HIGH STRENGTH CONCRETE

6.1 Introduction

The on-going accelerated research in the development of high strength concrete has favored new and more applications of high strength concrete in structures, especially in bridges. The high performance issues of high strength concrete (as were discussed in chapter 4) justify the increase in utilization and the economical benefits of building stronger structures, with smaller component dimensions and larger member spacing.

6.2 Major Factors affecting Cost

6.2.1 Research and Development

Studies on concrete have been going on for more than a century. Particularly, the previous chapters have demonstrated that research and development on high strength concrete has been extensive for the past 3 decades. Since high strength concrete has specific characteristics that are different from those of normal strength concrete, the research is at a much higher cost. Although high strength concretes possess numerous advantages, they also come with various disadvantages. The brittleness and ductility properties need to be dealt accounted for. Studies have showed that more research and development are needed for design parameters that are affected by concrete strength such as shear, torsion, development length and repeated loading.

6.2.2 Design, Codes, Engineering Specifications

In terms of design, the usual assumptions that have been made about the concrete and steel have to slightly be modified. Design rules must be incorporated into current design specifications. For example, the stress-strain curve for a high strength concrete in uniaxial compression is almost linear up to failure as opposed to normal strength concrete, which is mainly parabolic. Studies have suggested that the rectangular stress block assumption may not be accurate enough for design especially if the members are prestressed (over reinforced beams). If modifications are not made, owners will be reluctant to use high strength concrete, since general acceptance obtained by standardization and codification is not available. High strength concretes are made from different material characteristic than normal strength concretes, and therefore, those differences need to be taken into account for construction in the codes and specifications. It is also up to the engineer to determine the specifications for high strength concrete as it applied to a particular structural system and its construction.

6.2.3 Quality Control and Assurance

A numerous amount of control test have to be performed in order to make sure that high strength concrete has been achieved and has meet its special requirements. The American Concrete Institute (ACI) and the American Society for Testing and Materials (ASTM) have established standard tests such as the ASTM C9.03.01 and the ACI 363, both testing for high strength.

6.3 Studies and Comparisons with Normal Strength Concrete

6.3.1 High Strength concrete in Prestressed Bridge Girders

Although the basic cost per cubic yard increases with the increase in compressive strength, this initial cost increase is offset by the reduction in the total volume amount. Studies have showed that the major savings in the use of high strength concrete comes form the reduction in nonmaterial costs associated with the girders. This reduction in the number of girders has positive impacts on other costs such as the labor production cost of the girders, the transportation costs, the erection costs and the overhead expenses associated with each cost. Although the number of strands per girder increases, from 30 strands to 58 strands per girder, for the normal strength and the high strength concrete case, respectively, the overall total number of strands for the high strength concrete case is still lower than the normal strength concrete case. Thus, it is the reduction in the number of girders in a specific project that influence the overall costs. The table below gives a comparison between normal strength concrete of 6,000 psi (42 MPa) and high strength concrete of 10,000 psi (69 MPa).

Bridge item	Cost ($/ft)			
	6 000 psi fly ash		10 000 psi microsilica	
Bridge deck[a]	$5.90 per ft^2 × 36 ft width	= 212.40	$7.46 per ft^2 × 36 ft width	= 268.56
Strands[b]	270 × $0.40 per strand	= 108.00	232 × $0.40 per strand	= 92.80
Girder concrete	9 girders × 0.203 yd^3 × $40	= 73.08	4 girders × 0.203 yd^3 × $85	= 69.02
Girder nonmaterial[c]	9 girders × $46.68	= 420.12	4 girders × $46.68	= 186.72
	Total	= 813.60	Total	= 617.10

Figure 29: Cost Comparison for prestressed girders (Nawy, 1993)

The calculations apply to the Louisiana Bridge, based on a 7 in. thick slab with a design span of 4 ft for the 6,000 psi girders, and 8 in. thick slab with a design span of 9ft for the 10,000 psi girders. All labor, placement and overhead costs are included. A saving of $196.5 /ft ($645/m) was obtained by using the higher strength concrete. Additionally, the table below shows a comparison of costs using various mixes for high strength concretes.

Mix proportions	6 000 psi[a]	6 000 psi fly ash	High f'_c	High f'_c fly ash	High f'_c microsilica
Cement, type III (lb/yd^3)	658	480	846	559	559
Fly ash (lb/yd^3)	0	178	0	205	209
Microsilica (lb/yd^3)	0	0	0	0	80
Coarse aggregate (lb/yd^3)	1 800	1 800	1 835	1 835	1 792
Fine aggregate (lb/yd^3)	1 200	1 200	1 174	1 213	1 051
Retarder (oz/yd^3)	20	20	25	15	26
HRWR (oz/yd^3)	72	72	270	220	112
Water (lb/yd^3)	263	363	291	200	234
W/C ratio	0.40	0.40	0.34	0.26	0.30
Total cost ($)	45.36	40.13	60.46	49.13	84.97

Figure 30: Costs of various mixes of different compressive strengths (Nawy, 1993)

From both tables, it is clear that the use of high strength concrete is much more cost-effective than normal strength concrete.

6.3.2 Case Study: Norddalsford bridge and Holandsfjord bridge in Norway

The use of high strength concrete in bridge construction has many beneficial aspects. The first aspect that will be covered is the extension of the span length for cantilevered bridges in an economical way. For this specific example, an economic analysis has been carried out and the result proved the cost-benefit aspect of high strength concrete. The Norddalsford Bridge was built in 1987 in Western Norway. The bridge is composed of prestressed concrete deck panels C45 and is built following the free cantilever method. (Figure 31)

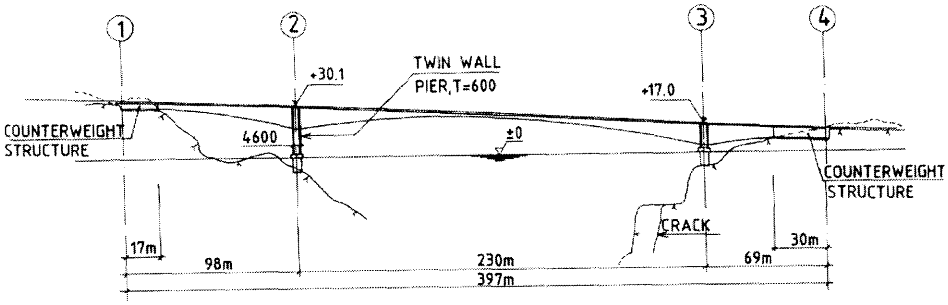


Figure 31: Nordalsfjord Bridge, elevation (Giaever, 1987)

At the time of construction, the main span of the bridge was 230 m, making it the longest for this type of bridge in Europe. The dead load of the super structure accounted for about 85% of the total moment at the supports. The introduction of high strength concrete enabled a tremendous reduction in the overall weight of the structure thus, decreasing the overall cost of the bridge. Three alternatives were considered in order to obtain the optimal cost-efficient solution. The first alternative substituted concrete C45 with C85 in part of the bottom slab. The dimensions remained the same and the total savings added up to 1.5% of the total tender price. The second alternative considered using high strength concrete LC55 for the main span. The rest of the bridge would be built using concrete C45. The total savings added up to 4.5% of the total tender price. The third alternative involved the use of high strength concrete LC55 for the entire main span and C45 and C55 for part of the bottom and top slabs. The total savings added up to approximately 5% of the total tender price. It is relevant to note that the above savings are only material cost savings. A decrease in cost due to a reduction in construction time has not been taken into account. Since the bridge utilized high strength concrete, it was cast in longer, and therefore, fewer segments.

The construction of the Holandsford Bridge investigated in different bridge structures associated with different concrete qualities. Figure 32 shows the breakdown of the concrete composition for the bridge for the first alternative.

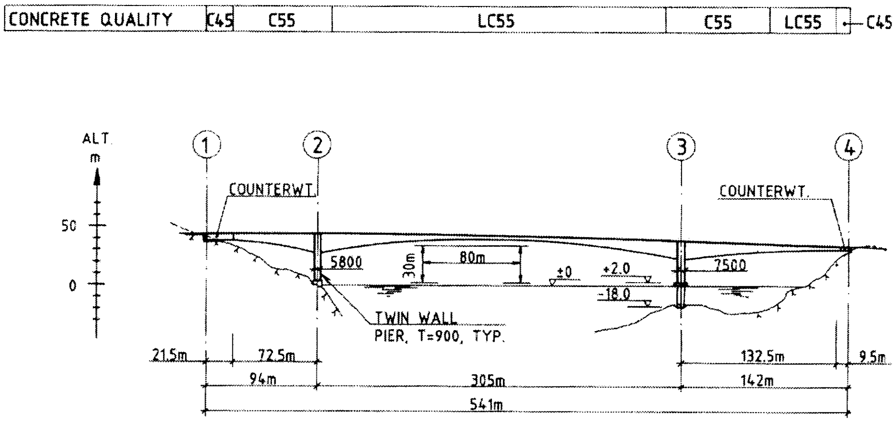
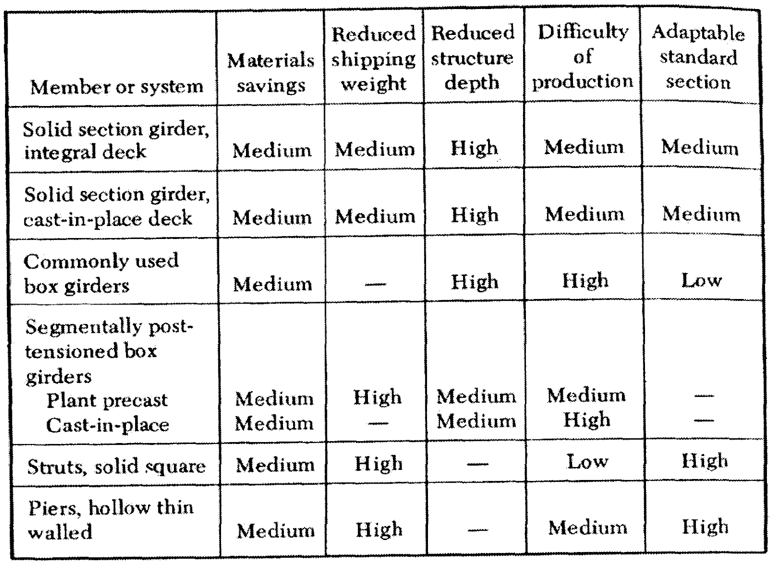


Figure 32: Holandsfjord Bridge, elevation (Giaever, 1987)

The prestressed concrete free cantilever bridge utilized LC55 and different concrete qualities for the main span and the rest of the bridge, respectively. The bridge geometry for the second alternative is about the same as the first one, and the LC55 in the main span is replaced by C55. The estimated construction cost for the second alternative was about 9.4% higher than for the first alternative. This is due to the fact that the first alternative employs high strength concrete as opposed to normal strength concrete.

6.3.3 Evaluation of Benefits

A study on the application of high strength concrete to bridges members, conducted by H. Jobse and S. Moustafa, listed numerous qualitative advantages as can be seen in the table below.



Member or system	Materials savings	Reduced shipping weight	Reduced structure depth	Difficulty of production	Adaptable standard section
Solid section girder, integral deck	Medium	Medium	High	Medium	Medium
Solid section girder, cast-in-place deck	Medium	Medium	High	Medium	Medium
Commonly used box girders	Medium	—	High	High	Low
Segmentally post-tensioned box girders					
Plant precast	Medium	High	Medium	Medium	—
Cast-in-place	Medium	—	Medium	High	—
Struts, solid square	Medium	High	—	Low	High
Piers, hollow thin walled	Medium	High	—	Medium	High

Figure 33: Evaluation of benefits of high strength concrete applications

Struts and hollow piers relatively as opposed to member sizes did the most material savings. A possibility of reducing the shipping weight for hollow pier prismatic members or plates suggests new techniques in construction.

6.4 Cost/Effectiveness

Ready-mix suppliers have provided studies with cost/benefit charts in order to have an early evaluation of the cost if the project required high strength concrete. The figure below is an example of an optimization chart based on the 1992 cost data due to the Material Service Corporation in Chicago.

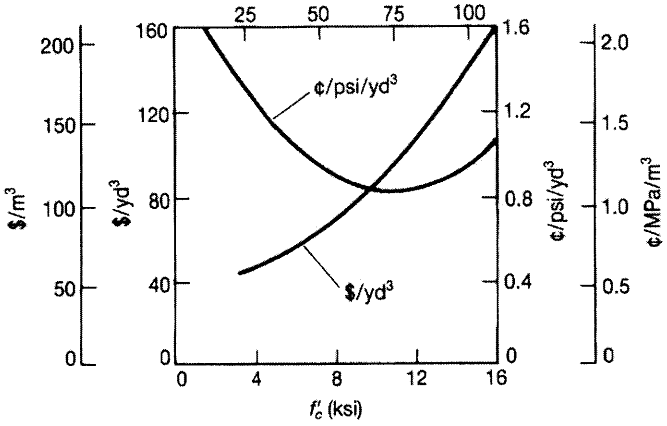


Figure 34: Cost optimization of high strength concrete (Nawy, 1996)

Furthermore, it is important to consider teamwork coordination since the cost/benefit ratio is dependent on the planning and management phases' ion a project. The figure below shows the different tasks involved in the production of a cost-effective structure.

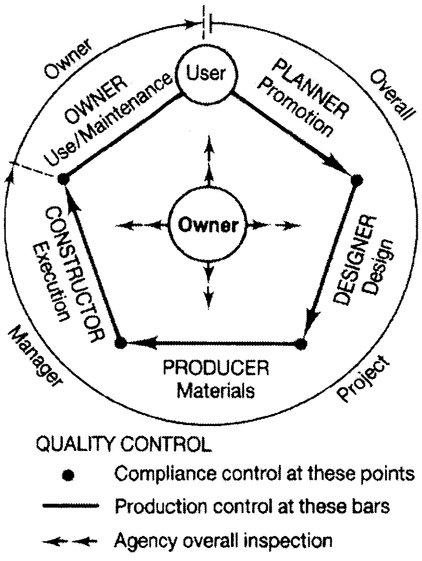


Figure 35: Coordination for Quality Control for cost-effectiveness (Nawy, 1996)

CHAPTER 7

FUTURE OF HIGH STRENGTH CONCRETE

7 FUTURE OF HIGH STRENGTH CONCRETE

As soon as engineers realize that high strength concrete has remarkable long-term properties, the use of high strength concrete in bridge construction will definitely increase. Not only will high strength concrete enhance the performance of the bridge, but it will also contribute to a lower overall cost. Additionally, the widespread use of high strength concrete will play a role in the innovation of new construction methods, since high strength concrete has unique properties that normal strength concrete does not have. High strength concrete is not as widely used because the people are still reluctant to its design codes. Although some of the design parameters in the ACI building codes might not be affected, some areas need to be further investigated such as shear, torsion, stability, cracking and deflection, since the increase in strength leads to slenderer members and less ductility. In the next years, the use of a higher strength concrete of 30,000-40,000 psi (206-275 MPa) for every day application is predicable. High strength concrete already faces competition. The development of a concrete called Reactive Powder Concrete (RCP), with a much higher compressive strength ranging from 30,000 to 100,0000 psi (200 to 700 MPa). As a mean of comparison, it is worth noting that the compressive strength of steel is about 350 MPa. In addition, RCP has a lower chloride ion permeability. Also, a combination use of RCP and steel tubes offer technological advantages. This combination can contribute to a higher compressive strength and a high ductility.

CHAPTER 8

CONCLUSION

8 CONCLUSION

Although high strength concrete seems to be more expensive at first, its application to bridges offers a numerous amount of advantages that balance the initial increase in material costs. Below is a summary of the major advantages that can be obtained:

- Reduction in member size, resulting in a decrease in volume of concrete used and therefore saving in construction time
- Reduction in total self-weight as well as dead load, and smaller foundations
- Reduction in form work area and cost, with a reduction in shoring and stripping due to early high performance properties
- Longer span and fewer beams for the same load
- Reduction of number of supports and supporting foundations

- Long-term service performance under various loadings such as static dynamic and fatigue
- Decrease in creep
- Higher stiffness as a result of higher modulus E_c
- Better resistance to external factors such freeze-thaw cycles, scaling, chemical attack and considerable long-term durability and workability and less crack propagation
- Increase in overall life cycle of the structure and reduction in maintenance and repair costs
- Lower depreciation as benefit

Research and studies have demonstrated that the application of high strength concrete to bridges offers not only structural benefits but also considerable savings of the construction cost, particularly on a long-term basis. Modern technology and state-of-the-art development has enabled concrete producers to manufacture the optimal mix for a specific application. Revolutionary evolutions of new materials and improvement of certain aspects of high strength concrete's behavior are taking place. These developments have been facilitated by the studies of long lasting materials, creation of more powerful instruments, new monitoring techniques, and the urgent need for higher performance materials. Urban cities are growing rapidly and the need to build a suitable infrastructure is a priority. From world population statistics, it is evident that the use of concrete would double or triple, as to overcome the population demand. In addition, rehabilitation purposes will greatly benefit from a better performing concrete, such as the retrofit of offshore platforms. Furthermore, high strength concrete is being used for the construction and retrofit of structural elements subject to earthquake loads. After the Northridge, California earthquake in 1994, research is testing on implementing safer advanced design of precast elements using high strength concrete. Research is focusing on the use of HSC for seismic resistant structure. However, additional research still needs to be done. Professionals are not coming to an agreement on the use of HSC in seismic regions. Many views differ from each other. One could argue that using HSC in seismic regions in beams could reduce the demand for stirrups and permits large stirrups spacing. On the other hand, one could argue that more confinement reinforcing is needed with HSC. Similar arguments could be made about beam column joints and various shear issue in structural walls. Engineers need to understand performance issues such as ductility, and behaviors of members under dynamic loads such as earthquakes. The codes need to be adjusted and ensure safety.

High strength concrete will dominate future construction processes, although other materials that can accomplish similar performances are challenging it. Studies in high strength concrete have proven its economical advantages.

REFERENCES

Anonymous, "High-performance concrete for bridge decks," Concrete International, v. 21 n 2, February 1999.

Berry, E. E., and Malhotra, V. M., "Fly Ash for use in concrete _ A Critical Review," Journal of the American Concrete Institute, Vol. 77, No. 2, March-April 1980.

Burgess, A. J., Ryell, J., and Bunting, J., "High Strength Concrete for the Willow Bridge," Journal of the American Concrete Institute, Vol. 67, No. 8, August 1970.

Chen, R., Carrasquillo, R., Fowler, D., "Behavior of High Strength Concrete Under Uniaxial and Biaxial Compression," American Concrete Institute, Detroit, Michigan, 1985.

Colaca, J., "75-Story Texas Commerce Plaza Huston – the Use of High Strength Concrete," High Strength Concrete, SP-87, American Concrete Institute, Detroit, Michigan, 1985.

Dolan, C.W., "Report of the PCI High Strength," PCI Journal, v. 38 n 3, May-June 1993.

Giaever, N.A. et al, "High Strength Concrete – Applications in Bridge Construction," Utilization of High Strength Concrete, Proceedings, Symposium in Stavanger, Norway, June 15-18, 1987, Tapir Publishers, 1987.

Goodspeed, C.H., Vanikar, S., Cook, R.A., "High-performance concrete defined for highway structures", Concrete International, v. 18 n 2, February 1996.

Jobse, H., Moustafa, S., "Applications of High Strength Concrete for Highway Bridges," PCI Journal, v. 29 n 3, 1984.

Lane, S.N., Podolyn, W., "The Federal Outlook for High Strength Concrete Bridges," PCI Journal, v 38 n 3, May-June 1993.

Moreno, J., "High-performance concrete: Economic considerations," Concrete International, v 20 n 3 March 1998.

Nawy, E.G., "Fundamentals of High Strength High Performance Concrete," Longman Group Limited, 1996.

Nilson, A.H., "High Strength Concrete – An Overview of Cornell Research," Utilization of High Strength Concrete, Proceedings, Symposium in Stavanger, Norway, June 15-18, 1987, Tapir Publishers, 1987.

Peterman, M. B., Carrasquillo, R. L., "Production of High Strength Concrete," Noyes Publications, Park Ridge, NJ, 1986.

Russell, H.G., “High Strength Concrete in North America,” Utilization of High Strength Concrete, Proceedings, Symposium in Stavanger, Norway, June 15-18, 1987, Tapir Publishers, 1987.

Swamy, R.N., “High Strength Concrete – Material Properties and Structural Behavior,” High Strength Concrete, SP-87, American Concrete Institute, Detroit, Michigan, 1985.

Taly, N., “Design of Modern Highway Bridges,” McGraw-Hill Companies, Inc, 1998.
Thorenfelt, E. et al, “Mechanical Properties of High Strength Concrete and Application in Design,” Utilization of High Strength Concrete, Proceedings, Symposium in Stavanger, Norway, June 15-18, 1987, Tapir Publishers, 1987.

Walther, R., “Potentiality of Utilizing High Strength Concrete in Structures,” Utilization of High Strength Concrete, Proceedings, Symposium in Stavanger, Norway, June 15-18, 1987, Tapir Publishers, 1987.

Webb, J., “High-Strength Concrete: Economics, Design and Ductility,” Concrete International: Design & Construction, v. 15 n 1, January 1993.

“High Strength Concrete: An International Perspective,” American Concrete Institute, Farmington Hills, Michigan, 1996.

“High Performance Concrete: Research to Practice,” American Concrete Institute, Farmington Hills, Michigan, 1999.

“High Strength Concrete,” American Concrete Institute, Detroit, Michigan, 1985.