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High-Strength Concrete in Chicago High-Rise Buildings

Béton à haute résistance pour les gratte-ciel de Chicago

Hochfester Beton für Chicagos Hochhäuser

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SUMMARY
Commercial ready-mix high-strength concrete is being delivered in the Chicago area for high-rise construction. High-strength concrete is a product of present urban market requirements. It has been the result of the commitment of the construction industry to an optimum economic return in high-rise construction. Historical, technical and marketing steps to incorporate the different levels of high-strength concrete in Chicago high-rise buildings are presented as are the physical properties of various levels of this concrete.

RÉSUMÉ
Un béton préfabriqué, ayant une haute résistance à la compression, est utilisé pour les gratte-ciel de Chicago. Le béton à haute résistance est un produit requis par les conditions actuelles du marché urbain. Il résulte de l'engagement de l'industrie de la construction pour réduire le prix de revient de construction des bâtiments élevés. Les étapes historiques, techniques et économiques de ce développement à Chicago sont décrites, ainsi que les propriétés mécaniques de ces bétons.

ZUSAMMENFASSUNG
In Chicago und Umgebung wird Transportbeton geliefert, welcher hohe Druckfestigkeiten erreicht. Die Verwendung solch hochfester Betone wurde ein Marktbedürfnis infolge wirtschaftlicher Optimierung bei der Erstellung von Hochhäusern. Die historischen, technischen und marktorientierten Schritte, welche zur Verwendung verschiedener Beton-Güteklassen in Hochhäusern führten, werden aufgezeigt. Auch auf die physikalische Zusammensetzung der Betone wird eingegangen.

1. INTRODUCTION

Chicago has been the city of the high-rise buildings and the year, 1986, commemorated one hundred years of high-rise construction. The Home Insurance Building was only twelve stories high, however, it has been considered the first high-rise because of the innovative steel skeleton within its masonry construction in 1886.

Commercial high-strength normal weight concrete has been one of the factors contributing to the development of high-rise buildings in Chicago. The development of this innovative material was by Material Service Corporation, the midwest's largest producer and supplier of concrete building materials and Flood Testing Laboratories. Latest development of this product has been by the quality control department of Material Service Corporation. It has fulfilled the needs of the various members of the construction team.

The developers' requirements for higher structures and larger rentable floor areas in expensive downtown real estate properties have been satisfied by this product. The architects' and engineers' needs to satisfy those demands has been accomplished with smaller and larger capacity columns. Commitment, technology and communication among the construction team members have accomplished the task of increasing the compressive strength of normal weight ready-mix concrete from 5,000 to 14,000 psi (34.5 to 96.6 MPa). This process has taken twenty years.

The complex technical and marketing process to bring each new concrete strength to the construction market has been a lengthy but rewarding process since it has made it possible to divert structures to concrete solutions.

2. ECONOMIC CONSIDERATIONS

Attached to products in the developmental stage is a premium that has to be paid for the additional benefits they provide. The engineer must evaluate the cost of these benefits at the job site, and the ready-mix producer must evaluate the production cost and the price the market can afford for the product.

Figure 1 shows the engineers' perception of the economic considerations in the use of High Strength Concrete. The most economical column has one percent reinforcing using the lowest possible strength of concrete. The information shown in the graphs has been obtained using 1986 Material Service Corporation book prices for concrete and average Chicago steel prices.

For the ready-mix supplier, the development of concretes above 6,000 psi (41.4 MPa) may not show direct economical benefits. The trial and error research program is a long and costly proposition, especially for a product which accounts for no more than a fraction of one percent of total concrete deliveries. The strict quality control for consistent production requires experienced and knowledgeable technicians and reliable equipment. The promotion and sale require professionals capable of answering questions on properties and design. Special equipment and knowledge is needed to test cylinders above 10,000 psi (68.9 MPa) concrete. Few ready-mix suppliers have the company infrastructure, resources, and attitude for such a project.

We feel that all of the previous negative reasons are counterbalanced by some indirect benefits to the ready-mix supplier. Through experience with high-strength concrete, the ready-mix producer is able to improve quality of the lower strength concretes. A better understanding of concrete allows the ready-mix supplier to develop special concretes. High-strength is a product differentiation which facilitates the sale of lower strength concretes. It improves the technical image of the company. These benefits have to be evaluated by the ready-mix company before the decision of moving from a comfortable and known low-strength market into an unknown market with a highly vulnerable position.

3. HIGH-RISE APPLICATIONS

Since 1965, 7,500 psi (51.7 MPa) concrete has been the high-strength concrete most widely used and accepted by the construction industry in the Chicago area. More than 50 projects have received the benefit of this strength. It fulfills the architectural and structural requirements for the lower columns of 20 to 25 story residential buildings with maximum column spacing up to 24 feet (7.2 Mt). This strength is also used for intermediate columns in buildings with higher strength in lower columns.

Starting in 1972, 9,000 psi (62.1 MPa) concrete became more frequently specified and it has been used in more than 40 buildings in the Chicago area. This strength was used in the Water Tower Place and its instrumentation has provided basic information shown later in this paper. Also, this concrete strength has been used for caisson construction.

The use of 11,000 psi (75.9 MPa) concrete was limited to two experimental columns in the River Plaza project in 1976. However presently, in 1986, its use has become more common for columns in different types of high-rise buildings.

Strengths above 14,000 psi (96.6 MPa) concrete were obtained for two columns in the Chicago Mercantile Exchange project and other projects. Instrumentation to measure concrete temperatures and actual shortening was placed on those two columns. A mock column was built at Material Service's yard 1 to obtain cores and their strength to be compared with the strength of standard 6x12 in. cylinders. Cylinders were made to measure creep and shrinkage and they have been tested by the Portland Cement Association.

Because only a small number of buildings are designed for over 50 stories, concretes over 14,000 psi (96.6 MPa) have limited application. Consequently, high-strength concrete technology for high-rises in the Chicago area presently has exceeded market requirements. The knowledge obtained from the development of high-strength concrete has led Material Service Corporation to several new products, including chemically resistant concrete, flowing, impermeable, corrosion resistant, fast track and other special concretes being sold as performance concretes.

4. PHYSICAL PROPERTIES

Sufficient information is now available for the safe use of this material by the construction industry. However,various research organizations are conducting additional research for better understanding of the physical properties of high-strength concrete.

4.1 Creep and Shrinkage

Creep and shrinkage have been part of the development of this product and measurements for these properties have been done in the laboratories of the Portland Cement Association. The specific creep (creep strain by unit of applied stress) decreases with the increase of strength, see Figure 2.

4.2 Measured Shortening in Columns

Actual shortening in columns has been measured in the same buildings mentioned previously for creep and shrinkage measurements. The results for the Chicago Merchantile project for the 14,000 psi (96.6 MPa) concrete columns are shown in figure 3. These measured shortenings are lower than the calculated shortenings.

4.3 Heat of Hydration

The increase of temperature within the concrete depends upon the cement content, water cement ratio, and size of the member. The historical records of the heat of hydration are presented in Figure 4 for the 11,000 psi (75.9 MPa) and the 14,000 psi (96.6 MPa) concrete. In both cases the peak of the heat of hydration occurs at about two days after the concrete is placed. No special curing is used for the columns where high-strength concrete is used. The removal of the forms is usually done the following working day after placing of the concrete.

4.4 Ductility

Recent investigations at the University of Illinois at Chicago on member ductility tested in flexure were found to be higher for the beams made of high-strength concrete compared to the beams made of low-strength concrete. The ratio of tension steel area to balance steel area was found to be the most important parameter governing the ductility of the members tested. For the same concrete strength, ductility decreased drastically as the above ratio increased. These results are available in the form of a Ph.D thesis and are being summarized for publication. Consequently, the concern about the lack of ductility caused by the use of high-strength concrete appears to be unfounded.

4.5 Modulus of Elasticity

Research conducted at Cornell University suggests Ec = 40,000 · f'c + 1,000,000 (Wc/145)E1.5 psi instead of the traditional ACI formula.

5. MIXTURES DESIGN

The mixture designs for the 9,000 psi(62.1 MPa) and 11,000 psi (75.9 MPa) columns of concretes used in the Water Tower Place and the River Plaza projects are as follows:

Material	9,000 psi(62.1Mp.)	11,000 psi(75.9Mp.)
Cement	846 lbs.	850 lbs.
Sand	1025 lbs.	1040 lbs.
5/8 in. Stone	1800 lbs.	--
1/2 in. Stone	--	1730 lbs.
Water	300 lbs.	330 lbs.
Water Reducer	25.4 fl.oz.	43.0 fl.oz.
Fly Ash	100 lbs.	100 lbs.
Slump	4-1/2 in.	4-1/2 in.

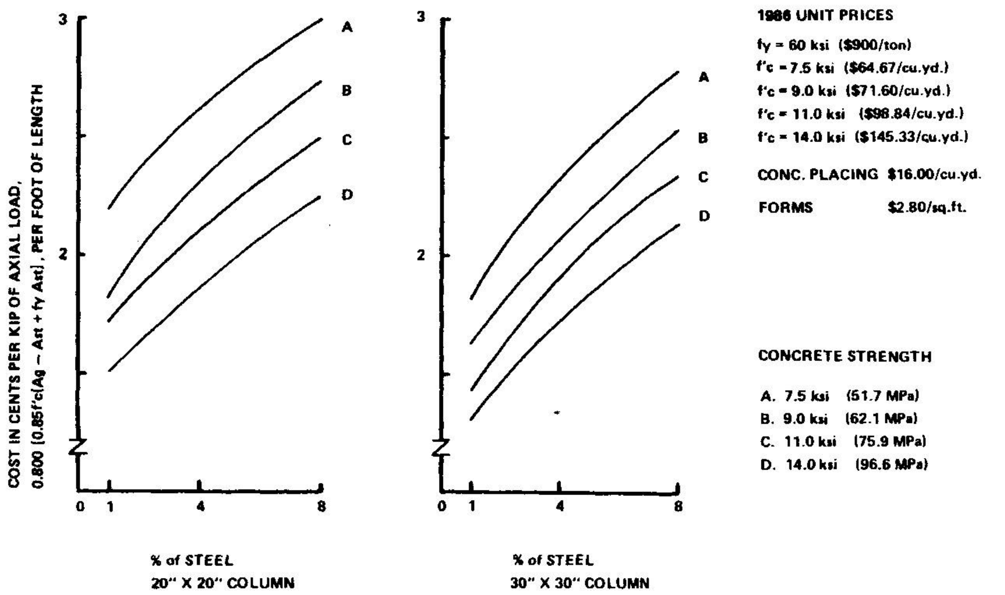
Recent developments in concrete technology have allowed the ready-mix industry to improve and optimize the mixtures shown in this table. The new mixtures for high-strength concrete are proprietary and this type of concrete is being sold as perfomance concrete.

6. CONSTRUCTION CONSIDERATIONS

For the contractor, the use of high-strength concrete implies some special considerations to comply with (10.13) ACI Code requirements regarding transmission of column loads through the floor slabs. When the specified concrete strength of the column is greater than 1.4 times that specified for the floor system, the transmission of load through the floor system is accomplished by placing concrete of strength specified for the column in the floor system for an area four times the column area. For the contractor, it implies special coordination since two different concretes are placed at the same time in the slab.

7. CONCLUSIONS

1. The production of high-strength concrete in excess of 6,000 psi places the primary responsibility for performance on the ready-mix supplier. 2. To produce high-strength concrete, a ready mix supplier must possess a complete infrastructure consisting of research and development, quality control, promotion, sales, and equipment. 3. Using Chicago prices, the cost per unit load carried by concrete decreases when the concrete strength increases. 4. High-strength concrete is a minimum percentage of the ready-mix supply, which may not make it commercially appealing for the ready-mix supplier. 5. The production of high-strength concrete improves the quality of lower strength concretes. 6. High-strength concrete helps the marketing and sales of lower strength concretes. 7. The technology of high strength concrete has exceeded the present market requirements for high-rise buildings in Chicago. 8. There is sufficient information on concretes up to 14,000 psi (96.6 MPa) for the safe design of structures. 9. High-strength concrete research has led to the development of new products like highly fluid concrete and other specialty concretes.



COLUMN COST

FIGURE 1

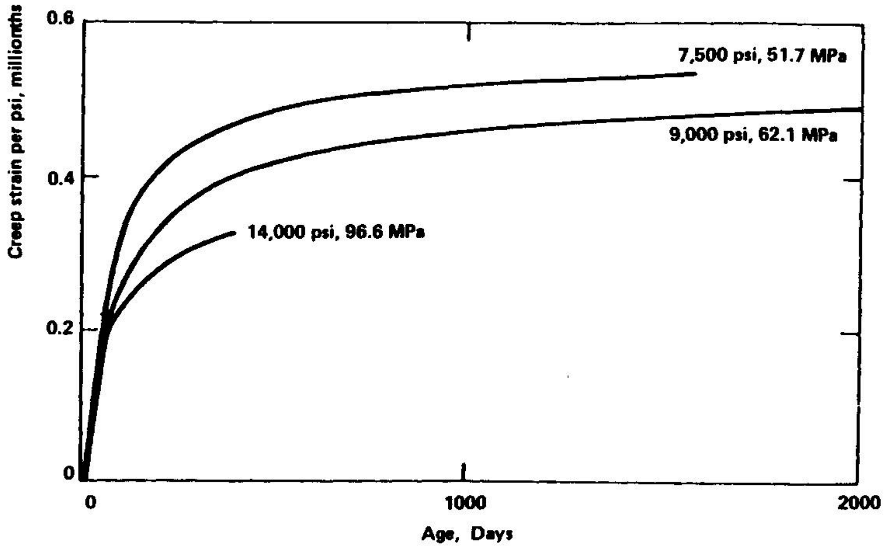


FIGURE 2

MEASURED CREEP IN 6 X 12 INCH CYLINDERS

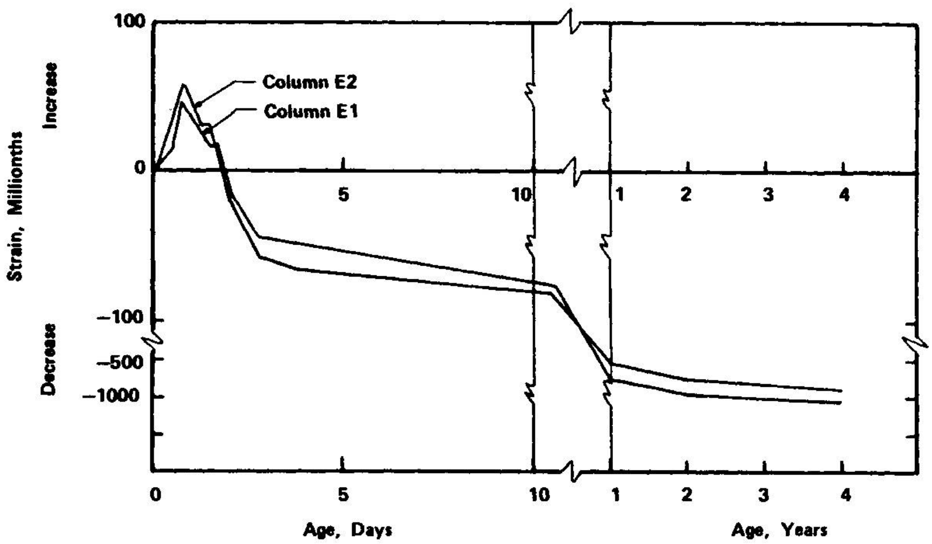


FIGURE 3

STRAINS AT THE CHICAGO MERCANTILE EXCHANGE
14,000 psi (96.6 MPa) COLUMNS

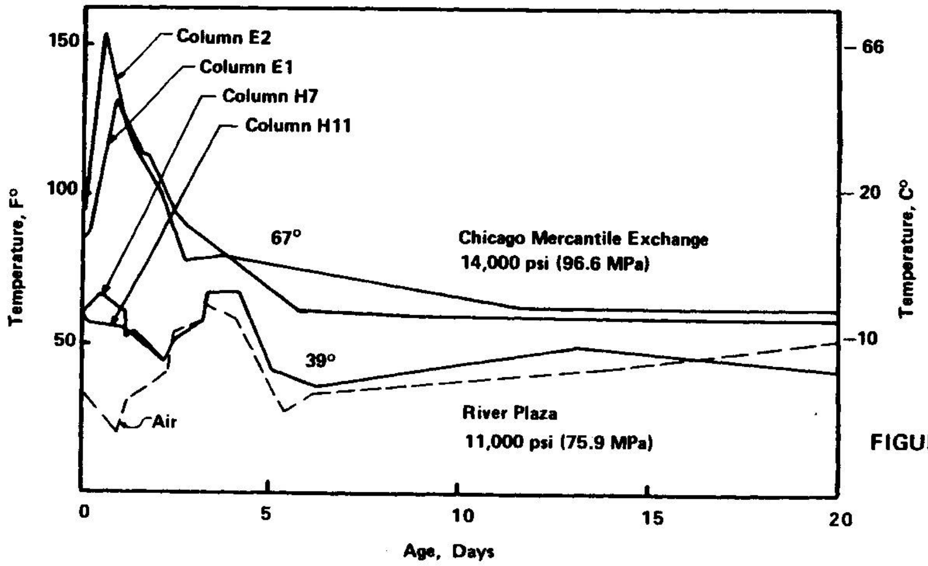


FIGURE 4

MEASURED TEMPERATURES