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HIGH-STRENGTH CONCRETE, PAST, PRESENT, FUTURE.(U)

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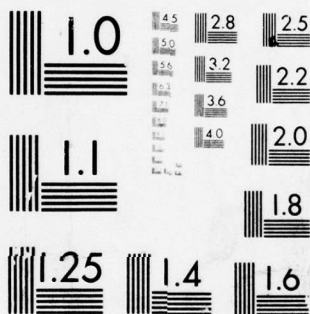
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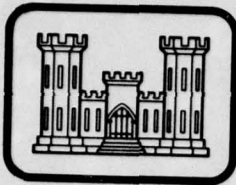


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HIGH-STRENGTH CONCRETE PAST, PRESENT, FUTURE

by

Kenneth L. Saucier

Structures Laboratory

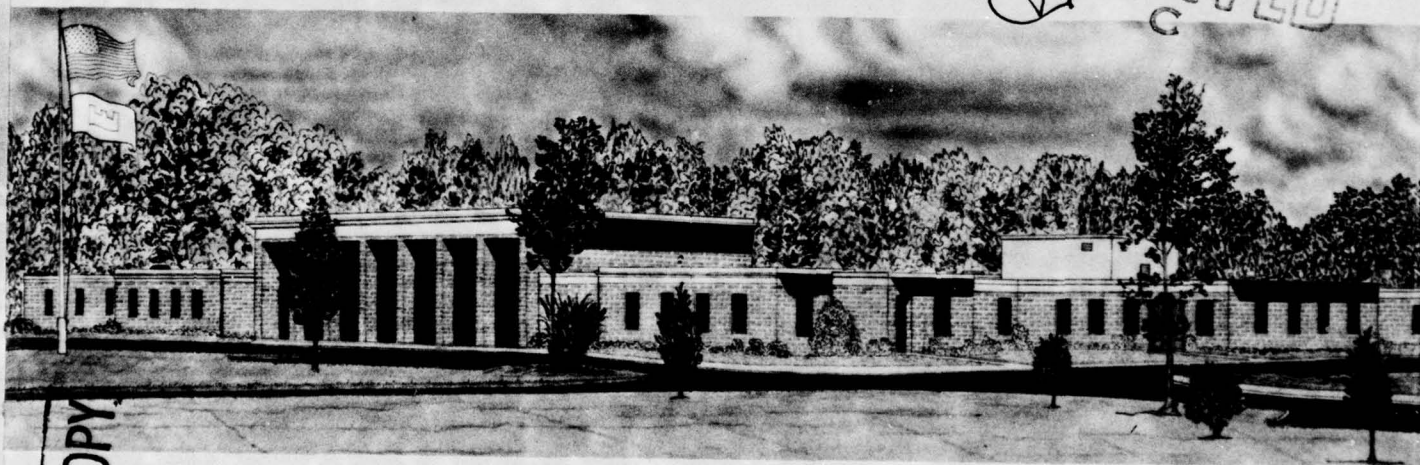
U. S. Army Engineer Waterways Experiment Station
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19. KEY WORDS (Continue on reverse side if necessary and identify by block number) High-strength concretes		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This paper summarizes the current status of high-strength concrete, the research needed, and the information and experience required for high-strength concrete to become universally accepted. Discussion involves examination of three levels of high-strength concrete: (1) the present range of 5,000 to 10,000 psi (34.4 to 68.9 MPa), (2) the available range of 10,000 to 15,000 psi (68.9 to 103.4 MPa), and (3) the exotic area of 15,000 psi (103.4 MPa). Present practices include use of low W/C, high cement factor, mixtures with (Continued)		

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20. ABSTRACT (Continued).

Cont → fly ash, high-quality crushed aggregates, high-range water-reducing admixtures, and more coordination and quality control efforts.

The second range is attainable with available materials and equipment such as slurry mixing, no-slump concrete, closer control, compaction by pressure, new admixtures, longer curing, and polymer material. Research in the areas of vibration and compaction, use of artificial aggregates, polymers, discontinuous reinforcement, interaction with the energy situation, and design considerations will be needed before the 15,000-psi (103.4-MPa) range can be successfully entered. The exotic area may include heretofore impractical techniques such as combining pressure and vibration and development of the silica-lime bond. A prediction is offered of the technique to be used for the manufacture, placement, and consolidation of high-strength concrete in the year 2000.

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PREFACE

This paper was prepared for presentation at the 1979 Annual Convention, American Concrete Institute, Milwaukee, Wisconsin, March 18-23, 1979.

Funds for the publication of this paper were provided from those made available for operation of the Concrete Technology Information Analysis Center (CTIAC). This is CTIAC Report No. 37. The paper was prepared by Kenneth L. Saucier, Research Civil Engineer, Engineering Mechanics Division (EMD), Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES). The paper was prepared under the general supervision of Messrs. John M. Scanlon, Chief, EMD, and Bryant Mather, Acting Chief, SL.

The Commander and Director of WES during the preparation and publication of this paper was COL J. L. Cannon, CE. Mr. F. R. Brown was Technical Director.

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HIGH-STRENGTH CONCRETE, PAST, PRESENT, FUTURE

The term high-strength concrete is, of course, relative to any assemblage of concrete technologists. Only a few years ago 5000-psi (34.4-Mpa) concrete was considered high strength. Even today in some parts of the country 5000 psi is a barrier, either physically or physiologically. The physiological barrier can be broken by careful selection of materials and construction practices; but in some areas the additional cost will preclude the use of high-strength concrete. A physical barrier or "ceiling" may not exist, rather it may move progressively upward depending on the development of new materials, admixtures, and processes. Also, if the need exists, the technique will likely be developed. At the ACI Seminar on high-strength concrete in Pittsburgh in 1977, skepticism was expressed that designers, producers, and users in New York City would even consider using concrete greater than 6000 psi. Yet 1 yr later, inspired by the need to conserve space, a 50-story office tower, the Palace, is under construction using 8000-psi (55.1-Mpa) concrete.¹ However, most people are reluctant to try to use high-strength concrete, due to the adverse reports they have heard.^{2,3}

The precast and prestress people are by far the largest users of high-strength concrete. They have been using 7500-psi (51.7-Mpa) concrete for 10 to 15 yr and some are using concrete approaching 10,000 psi (68.9 Mpa).⁴ Nuclear power plants require concrete in the 8000-psi range. The WES developed 10,000-psi (68.9-Mpa) concrete for the Air Force 15 yr ago to be used in underground silos.⁵ About 10 yr ago 10,000-psi (68.9-Mpa) concrete was used in the Willows Bridge in Toronto.⁶ The most extensive use of high-strength concrete in building construction has been in the Chicago area where concrete up to 10,000 psi (68.9 Mpa) was used in at least six different buildings.⁷

Most concrete technologists consider the present high-strength area to be in the range of 5000- to 10,000-psi (34.4- to 68.9-Mpa) compressive strength. The next step up encompasses the 10,000- to 15,000-psi (68.9- to 103.4-Mpa) area in which some specialists are now working. This level is achievable with available materials and techniques in a highly controlled

environment. The highest level to be considered for conventional portland cements, 15,000 psi (103.4 Mpa) plus, requires exotic procedures, processes, and materials. These levels or ranges should not be considered permanent; we have every reason to believe that advances in technology will allow us to go higher in all ranges, restricted only by economical considerations and the technology available at any given time.

There are ten different facets of concrete production which have received special consideration in the production of concrete in the range of 5000 to 10,000 psi (34.4 to 68.9 Mpa).^{5,8}

(1) Use of a high cement factor - up to 940 lb/cu yd (550 kg/cu m). In the range of 2- to 3-in. (50.8- to 76.2-mm) slump, a good rule of thumb is 1000 psi (6.89 Mpa) for each 100 lb (45 kg) of cement used. However, above 940 lb/cu yd (550 kg/cu yd) this does not work.

(2) More stringent requirements of cement.^{8,9} The service records of the potential cement(s) should be checked, along with their availability. A high minimum compressive strength for the cement should be specified.

(3) Use of a low W/C ratio - in the range of 0.30. This, of course, interplays with the cement factor and the minimum workability required, presumably about 2 in. (50.8 mm) of slump.

(4) Use of WRA; little or no AEA. Practically all high-strength concrete used to date has employed either a lignosulfonate or hydrocarboxylic water reducer and no air entrainment. The water reducer is almost mandatory while air entrainment reduces strength. The WRA should be checked for compatibility with the cement.

(5) Use of a pozzolan - usually fly ash. This is not necessary, but fly ash usually results in higher later-age strength and always produces less heat rise. A fly ash with an ignition loss of 3 percent or less is desirable.

(6) Later-age strength requirement. There is nothing sacred about the 28-day strength. Structures quite often are not loaded until 3-months to 1-yr age. Why not control on a 60- or 90-day test age?

(7) Careful selection of coarse aggregate. For compressive strengths above 7500 psi (51.6 Mpa), good quality crushed coarse aggregate must be used. The coarse aggregate must also be kept clean and dust free.

(8) Use of a coarse sand. Due to the high cement content, a coarse sand ($FM \leq 3.0$) is helpful. A lower sand/coarse aggregate ratio may also be possible.

(9) Lab program of evaluation.^{8,10} A laboratory program to develop mixtures of the required consistency and check the compatibility of materials is a necessity.

(10) More inspection, coordination of activities.^{11,12} Due to the need to control the concrete closer than normal, and facilitate rapid placement, more and better qualified inspectors are needed. Dead time must be eliminated. Hot weather practices are good to follow.

The next level of concrete strength, 10,000 to 15,000 psi (68.9 to 103.4 Mpa) is achievable with present technology if the producer is willing to invest extra effort and money. Techniques include:

(1) Slurry mixing.¹³ This is a preblending of the cement and water with high speed mixing said to produce more efficient hydration. Strength increases are reportedly in the area of 10 percent.

(2) No Slump Concrete.¹⁴ Very dry concrete with water-cement ratios in the range of 0.25 to 0.30 and sometimes compacted by vibratory rollers. One must have the facilities to handle such material and the placement conditions must fit the product.

(3) New Admixtures.¹⁵ Perhaps the most important development in the high-strength area in recent years is the advent of the high range admixtures or superplasticizers. Water reduction of 20 percent or more with strength increases of 40 percent are possible. To take advantage of these materials for strength increase, the minimum workability is maintained and the water-cement ratio lowered. Additionally, the beneficial effect of the superplasticizers is greatest at high cement factors. Tests at the WES on the high range water reducers when they first appeared indicated problems with their resistance to freezing and thawing. Apparently, these problems have now been overcome.

(4) Cementitious Aggregates. ~~Some of the aggregates used in the production of high strength concrete are made from cement and sand. The use of these aggregates in the production of high strength concrete is reported to be 10 percent.~~¹⁶ Cement

clinker when used as aggregate has been reported to increase compressive strength.¹⁷ Tests at the WES did not confirm this, however.

(5) Tighter Cement Specification.^{8,9} All is not yet known about cement. Low C_3A , high C_2S , low fineness reportedly yield higher strength to some degree. The effects need to be controlled, especially in conjunction with the use of admixtures.

(6) Longer Curing Period. Cure with water if possible. Wet (ponding) can increase strength 1000 psi (6.89 Mpa) at a W/C of 0.30.¹⁸ Why not specify a strength at 6 months or 1 yr if such will meet job requirements?

(7) Compaction by pressure.¹⁷ It may be practical in precast or prestress plants to pressurize the concrete up to 100 psi (0.69 Mpa). For each 1 percent of voids removed, a 5 percent increase in strength may be realized. Thus, removal of 2 percent entrapped air could mean a 10 percent increase in strength.

(8) Closer Control; Faster Placement. With the use of less workable mixtures and special processes, a need for even more control over the operation will develop. Faster placement, probably with on-site mixing, will likely be required. It may not be possible to place in hot weather even if ice or cooled materials are used. Organization and timing will be critical.

(9) Develop Multiaxial Strength.^{4,17} A concrete which is restrained or confined in two directions will develop a compressive strength on the third axis of four times the unconfined strength. Of course, this is sort of a back door approach; however, some attempts have been made to utilize the triaxial strengths such as spiral reinforcement in columns. Steel forms on columns or rib arches on bridges may also be used to develop additional strength through confinement.

(10) Polymer Materials. The American Concrete Institute defines three categories of concretes which contain polymers: Polymer-impregnated concrete (PIC), polymer concrete (PC), and polymer-portland cement concrete (PPCC). PIC is a hydrated portland cement concrete that has been impregnated with a monomer and subsequently polymerized insitu; PC is a composite material formed by polymerizing a monomer and aggregate mixture;

and PPCC is produced by adding either a monomer or polymer to a fresh concrete mixture, and subsequently curing and polymerizing the material in place.¹⁹ Obviously polymer concrete is a very complicated field; however, we do not have the time to even begin to discuss polymers here. They have been used to date primarily for repair and restoration, resistance to chemical attack or erosion, and in precasting. Polymers have definite physical and economical constraints, but they are fascinating materials. The concrete technologist should become familiar with the materials and applications. Information on polymers may be found in ACI SP-40, Polymers in Concrete, 1973, and ACI Committee 548 Report, Polymers in Concrete, 1977.

In order to advance the practical use of high-strength concrete, research is needed in many areas:

(1) Shrinkage, creep, bond, deformation properties.²¹ We can postulate that creep should be less, that bond is proportional to strength, etc., for high-strength concrete. However, work in these areas is needed as design aids for the engineer contemplating the use of this material.

(2) Testing - Mechanism of Failure.²⁰ High-strength concrete fails in a compression test by splitting vertically as contrasted to the conical break for conventional concrete. Are we, in effect, determining a somewhat different property? Do we need to evaluate the test configuration and the apparatus more closely, especially with respect to the end conditions of the test specimen?

(3) Notch Sensitivity.^{2,20} Stress concentrations are known to be more evident in brittle materials. Do we try to correct for these or design around them?

(4) Improved vibration or compaction procedures.^{17,22} High cement contents result in gummy, sticky mixtures. What consolidation improvements are required to overcome this? More powerful vibrators? All frequency vibrators? Ultrasonic vibration?

(5) Temperature Considerations.^{3,21} Although the detrimental effects of heat on strength, workability and volumetric stability of concrete have been known for many years, we are only now getting the tools in the form of computers to enable us to look at the many ramifications

of the heat problem. This is the thrust of the work now underway at the WES. We are looking at cement replacements of up to 50 percent in 10-bag mixtures with conventional and high range water reducing admixtures. The idea is to develop data from which mixtures can be selected which will give maximum strength at particular ages with a minimum of heat generation.

(6) Use of artificial aggregates.¹⁷ Up to now we have made a preponderance of 3000-psi (20.7-Mpa) concrete with 20,000- to 30,000-psi (137.8- to 206.7-Mpa) aggregate. Now that we are entering the high-strength realm, we are facing shortages of high quality aggregate. There has been some work on fabrication of artificial aggregates - small vacuum processed cubes have been investigated. This procedure would be expensive, but it would allow one to attack the aggregate-paste interface problem which is the weak link in the concrete strength chain. An interesting area for research would be the aggregate interface on chert aggregate. A polymer coating on very strong natural rock may well result in a ultra-high strength concrete.

(7) Improved tensile, flexural strength. High-strength concrete has a lower tensile-compression ratio than conventional concrete. An appreciable increase in tensile or flexural strength of high-strength concrete would allow for consideration in members other than compression members. Latex polymers may re-enter the picture. Suitable latex formulations greatly improve the shear, bond, tensile, and flexural strength of cements and mortars. Latexes may in fact be ideal for high-strength concrete since they are normally more effective in richer mixtures. They cannot, at present, be used successfully in all environments, however.

(8) Discontinuous Reinforcement. Although fibers have not proven beneficial to compressive strength, there is some indication that high fiber loading (up to 4 percent) will increase tensile and compressive strength if the process of incorporating them in the mixture can be perfected. A high fiber loading could possibly be combined with a reduced amount of reinforcement to make the combination attractive for flexural members.

(9) Interaction with the energy situation. Like almost everything else today, the concrete industry is affected by the increasing cost of energy. The cement industry is energy intensive; therefore, the cost to produce high-strength concrete will be relatively high. Ironically coarse cement, which costs less to grind, would normally be best for high-strength concrete. However, the vast majority of cement customers are accustomed to the properties associated with a Type I cement and therefore the producers will probably continue to cater to the market. Special application cements have had a history of failure in the field for a variety of reasons. The high-strength area would need to capture an appreciable part of the market, before production of a special high-strength cement could be considered practical. Another consideration is the variability of the fly ash being produced today. For efficient use in concrete pozzolans need not only to have certain properties, but they must have consistency of properties. The changing requirements of the varying loads on, and the variability of the materials being used in the participators today, can only result in large variations in the end product. This puts an additional burden on a concrete technologist trying to secure and maintain consistency in the concrete. The interaction of the energy situation and the environmental constraints could possibly be the mechanism which may cause modifications in the production of cement. It is conceivable that the result of studies like those of Professor Diamond at Purdue University would alter the cement properties to advantage for high-strength concrete. Diamond²⁶ reported strengths of up to 17,000 psi (117.1 Mpa) at 7-days age with clinker not interground with gypsum, but regulated with an admixture. Much is yet to be learned about the critical elements in production of high-strength cement.

(10) Design Considerations. Although there has been only a limited amount of design of high-strength members, the stress-strain characteristics of high-strength concrete are fairly well known. High-strength concrete is very brittle; the stress-strain curve is almost linear to failure. Also, Young's modulus reaches an upper limit of approximately 7.0×10^6 psi (48×10^3 Mpa) for 10,000-psi (68.7-Mpa) concrete and above. The ACI "Building Code Requirements for Reinforced Concrete" (ACI 318-77)

only recently recognized the existence of high-strength concrete. Prior to 1977, the Code called for a stress block which decreased in depth from 85 percent to 0 percent as concrete strength increased from 4000 to 20,000 psi (27.6 to 137.8 Mpa), an obvious fallacy. The new code limits the figure to 65 percent for all concrete of 8000 psi (55.1 Mpa) or greater. However, other suggestions have been made, including use of a triangular stress distribution²³ and application of a nonlinear computerized method.²⁴

To enter the realm of 15,000 psi (103.4 Mpa) and above one will need to employ, by our standards today, exotic materials and techniques. Such techniques might include:

(1) Low porosity paste or mortar, W/C = 0.20, 25,000 psi (172.2 Mpa). Here some of the cement acts as aggregate - a very strong aggregate if one can afford the cost. The WES has done some work in this area in an attempt to match strength of a granite rock.²⁵ A strength of 18,000 psi (124.0 Mpa) was achieved using a high range water reducer, but strength retrogression was noted after 1-yr age. Others²⁶ have reported strength of 17,000 psi (117.1 Mpa) in 7 days.

(2) Pressure combined with vibration. This process has the advantage of expelling virtually all of the entrapped air, no matter what the bubble size. Strengths in the range of 20,000 psi (137.8 Mpa) can be obtained with pressures on the order of 200 psi (1.4 Mpa) and 40,000 psi (275.0 Mpa) with 1000 psi (6.9 Mpa) of applied pressure during molding.²⁷ Other variations of this technique include the spun pipe concept,¹⁷ vacuum concrete,²⁸ and pressure combined with high temperatures.²⁹

(3) Silica-lime bond to 20,000 psi (138.0 Mpa).¹⁷ Significant strength increase can be achieved by taking advantage of the chemical bond developed between free lime in the cement and silica in fine aggregate in the presence of additional heat and pressure. Compressive strengths of 17,000 psi (117.1 Mpa) have been reported²⁸ under pressure of only 10 psi (0.07 Mpa) in an autoclave for 8 hr. Valore, et al,³⁰ reported strengths of 20,000 psi (138.0 Mpa) in 2 days for mortars containing a water-reducing admixture autoclaved 5 hr at 365F (185C).

(4) Combinations of new materials. Strength? We can, or course, only anticipate what new materials or processes will be forthcoming in

the next 20 years. Possibly extensions of some of the things we now have will prove practical for high-strength concrete. Something like a combination of discontinuous reinforcement with a polymer-portland cement matrix may come forth. In order for the high-strength field to advance beyond compression members, very appreciable gain must be made in flexural and tensile strength. There has been a new process reported whereby fibers, blown into a mixture in high concentrations, produced flexural strengths on the order of 2400 psi (16.5 Mpa).

(5) Interaction of Materials, Techniques, and Processes. Most of the present-day work deals with only one aspect of the problem, i.e., compaction, workability, aggregate paste interface, etc. But how do the effects add up? For example, if a pressurization technique adds 1000 psi (6.89 Mpa) and a water cure adds 1000 psi (6.89 Mpa), the combined effect may be only 1500 psi (10.3 Mpa) rather than 2000 psi (13.8 Mpa). These types of effects must be considered to successfully advance into the exotic area of 15,000 psi (103.4 Mpa) concrete.

Finally, a high-strength concrete placement in the year 2000 might present this type of picture: A combination of cementitious aggregates, high-strength cement, and admixtures supplied from a material truck, mixed in a high-speed mixer, placed by pumping, consolidated by ultrasonic vibration, with controlled set and cure and using discontinuous reinforcing with revised design considerations.

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