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An Analysis on Various Mechanical Properties and Applications of High Performance Concrete: A Historical Perspective

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Abstract – The focus on High Performance concrete (HPC) has immensely increased due to utilization of large quantity of concrete, thereby leading to the development of infrastructure Viz., Buildings, Industrial Structures, Hydraulic Structures, Bridges and Highways etc. This paper includes the detailed study on the recent developments in High Performance Concrete, stressing more on the earthquake prone areas. It highlights the advantages and importance of High Performance concrete over conventional concrete and also includes effect of Mineral and Chemical Admixtures used to improve performance of concrete.

This paper deals with the development of engineering database on the changes in the mechanical properties of high performance concretes mixtures when exposed to high temperature up to 1000oC. The results of an experimental investigation in to the effects of high temperature on the residual compressive and tensile strengths for high performance concretes made with ordinary Portland cement are presented. Concrete specimens were heated in an electric furnace to varying temperatures up to 1000oC and the change in compressive and tensile strength, weight, ultrasonic pulse velocity and rebound number were determined. The heated specimens were subjected to sudden cooling in water and to slow cooling in air. The results showed that the compressive and tensile strengths, pulse velocity and rebound number were decreased with the increase in exposed temperature. The weight loss from concrete increased non-linearly with the maximum exposed temperature. Sudden cooling caused reduction in concrete strength.

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INTRODUCTION

Concrete is the most widely used construction material in India with annual consumption exceeding 100 million cubic metres. Also, the recent earthquakes in different parts of the world have once again revealed the importance of design of structures with high ductility. The strength and ductility of structures mainly depends on proper detailing of reinforcement in beam-column joints. Under seismic excitations, the beam-column joint region is subjected to high horizontal & vertical forces whose magnitudes are much higher than those within the adjacent beams & columns.

Conventional Ordinary Portland Cement Concrete which is designed on the basis of compressive strength does not meet many functional requirements as it is found deficit in aggressive environments, time of construction, energy absorption capacity, repair and retrofitting jobs etc. and loses its tensile resistance after the formation of multiple cracks. So, there is a need to design High Performance Concrete which is far superior to Conventional Concrete, as the Ingredients of High Performance Concrete contribute most efficiently to the various requirements.

The attribute “High Performance” implies an optimized combination of structural properties such as strength, toughness, energy absorption capacity, stiffness, durability, multiple cracking and corrosion resistance, taking into account the final cost of the material and above all, of the produce manufactured. Generally speaking, high performance is meant to distinguish structural materials from the conventional once, as well as to optimize a combination of properties in term of final application in civil engineering.

HPC concretes are usually designed using materials other than cement alone to achieve these requirements, such as Fly Ash (from the coal burning process), Ground Blast Furnace Slag (from the steel making process), or Silica fume (from the reduction of high quality quartz in an electric arc furnace). Different amounts of these materials are combined with Portland cement in varying percentages depending on the specific HPC requirements.

Though there are many definitions for High Performance Concrete (HPC), the most widely-accepted one is that given by the American Concrete Institute (ACI), which states; “High Performance

Concrete is concrete that meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and normal mixing, placing and curing practices.” It is not possible to give a unique definition of HPC without determining the performance requirements of the intended use of the concrete.

The requirements may involve enhancement of characteristics such as placement and compaction without segregation, long-term mechanical properties, and early age strength or service life in severe environments. Concretes possessing many of these characteristics often achieve High Strength, but High Strength concrete may not necessarily be of High Performance.

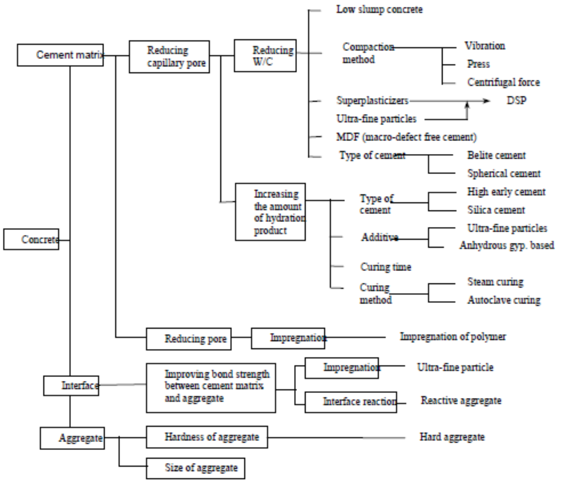
Concrete, a composite consisting of aggregates enclosed in a matrix of cement paste including possible pozzolans, has two major components – cement paste and aggregates. The strength of concrete depends upon the strength of these components, their deformation properties, and the adhesion between the paste and aggregate surface (Berntsson et al., 1990). With most natural aggregates, it is possible to make concretes up to 120 MPa compressive strength by improving the strength of the cement paste, which can be controlled through the choice of water-content ratio and type and dosage of admixtures (Mehta and Aitcin, 1990). However, with the recent advancement in concrete technology and the availability of various types of mineral and chemical admixtures, and special superplasticizer, concrete with a compressive strength of up to 100 MPa can now be produced commercially with an acceptable level of variability using ordinary aggregates. These developments have led to increased applications of high-strength concrete (HSC) all around the globe.

The bottom range of the strength of HSC varies with time and geographical location depending primarily on the availability of raw materials and technical know-how, and the demand from the industry. Concretes that were considered to be high strength 50 years ago are now regarded as low strength. For instance, concrete produced with compressive strength of 30 MPa was regarded as high strength in the 1950’s. Gradually, concretes with compressive strength of 40-50 MPa in the 1960’s, 60 MPa in the 1970’s, and 100 MPa and beyond in the 1980’s have evolved and used in practical structures. In spite of the rapid development in concrete technology in recent years, concrete with compressive strength higher than 40-60 MPa is still regarded as HSC. In the North American practice (ACI 318, 1999), high strength concretes are those that attain cylinder compressive strength of at least 41 MPa at 28 days. In the FIP/CIB (1990) state-of-the-art report on high strength concrete, it is defined as concrete having a 28-day cylinder compressive strength of 60 MPa.

HSC offers many advantages over conventional concrete. The high compressive strength can be advantageously used in compression members like columns and piles. Higher compressive strength of concrete results reduction in column size and increases available floor space. HSC can also be effectively used in structures such as domes, folded plates, shells and arches where large in-plane compressive stresses exist. The relatively higher compressive strength per unit volume, per unit weight will also reduce the overall dead load on foundation of a structure with HSC. Also, the inherent techniques of producing HSC generate a dense microstructure making ingress of deleterious chemicals from the environment into the concrete core difficult, thus enhancing the long-term durability and performance of the structure. Since the introduction of concrete with a compressive strength of 62 MPa in columns, shear walls and transfer girders of the Water Tower Place in Chicago in 1975, many applications of HSC in projects, ranging from transmission poles to the tallest building (KLCC Twin Tower in Kuala Lumpur, Malaysia) on earth, with concrete strength reaching up to 131 MPa in the Union Square building in Seattle, Washington have been reported. ACI 363 (1992), CEB-FIP (1994), FIP/CEB (1990) and Russell (1994) have summarized worldwide development and use of HSC to demonstrate its versatility and wide ranging application potentials.

Production of HSC may or may not require special materials, but it definitely requires materials of highest quality and their optimum proportions (Carrasquillo, 1985). The production of HSC that consistently meets requirements for workability and strength development places more stringent requirements on material selection than that for lower strength concrete. However, many trial batches are often required to generate the data that enables the researchers and professionals to identify optimum mix proportions for HSC. Practical examples of mix proportions of HSC used in structures already built can also be the useful information in achieving HSC. The various techniques of producing HSC, as summarized by Nagataki and Sakai (1994), are presented in Fig. 1.

In this paper eight numbers of trial mixes have been considered, following the reviewed information, in order to achieve concretes with compressive strengths from 60 MPa to as high as 130 MPa. The information obtained from literature as well as the results of experimental work described herein will be beneficial to researchers and engineers dealing with HSC.



(Note: DSP = Densified Systems of homogeneously arranged ultra-fine Particles)

Fig. 1. Various techniques for achieving high strength concrete.

Acceptance of high performance concrete by the construction industry contributed to the economical construction of high-rise buildings and long spans bridges. The use of high water reducing admixtures (HRWRA) and silica fume has resulted in producing workable high strength concrete, having the compressive strength over 100 MPa. Most specifications for high performance concrete require the desired strength at the ages of 56 or 90 days, instead of the conventional age of 28 days. This allows the concrete producers to utilize one or more of the supplementary cementing materials, such as fly ash, ground granulated blast furnace slag and silica fume in the high performance concrete mixtures. The risk of exposing high performance concrete structures to high temperatures increases with the increase in usage of high performance concrete by the construction industry. Therefore, it becomes necessary that the properties of high performance concrete subjected to high temperatures be clearly understood. The previous investigations reported that up to 300oC, concrete with the initial compressive strength of 52 MPa, retained more than 80% of its initial strength but after 300oC, the residual strength fell markedly. The porosity studies indicated an increase in the total pore distribution as well as in the pore dimensions. The concrete retained 46% of its initial strength when it was exposed to 600oC. Aim of this study was to evaluate the effects of high temperatures on the properties of high performance concrete, having the compressive strength of about 80 MPa. The parameters studied were maximum temperature up to 1000oC, ordinary Portland cement with 35% fly ash were used in the concrete mixtures. The following properties of concrete were determined before and after heating: water content, compressive strength, indirect tensile strength, ultrasonic pulse velocity and rebound number.

APPLICATION AREAS OF HIGH-PERFORMANCE CONCRETE

Major applications of high-performance concrete in the field of Civil Engineering constructions have been in the areas of long-span bridges, high-rise buildings or structures, highway pavements, etc. Some of the application areas are discussed in brief below :

1. Bridges

The use of high performance concrete would result in smaller loss in pre-stress and consequently larger permissible stress and smaller cross-section being achieved, i.e. it would enable the standard pre-stressed concrete girders to span longer distances or to carry heavier loads. In addition, enhanced durability allow extended service life of the structure. In case of pre-cast girders due to reduced weight the transportation and handling will be economical. Concrete structures are preferable for railway bridges to eliminate noise and vibration problems and minimize the maintenance cost (Dr. R. B. Khadiranaikar).

2. High Rise Structures

The reasons for using the high strength concrete in high-rise buildings are to reduce the dead load, the deflection, the vibration and the maintenance cost.

3. Highway Pavements

High Performance concrete is being increasingly used for highway pavements due to the potential economic benefits that can be derived from the early strength gain of high performance concrete, its reduced permeability, increased wear or abrasion resistance to steel studded tires and improved freeze-thaw durability.

A durable concrete known as fast track concrete designed to give high strength at a very early age without using special materials or techniques has been developed. *Fast Track Concrete Paving (FTCP)* technology can be used for complete pavement reconstruction, partial replacement by an inlay of at least one lane, strengthening of existing bituminous or concrete pavements by a concrete overlay, rapid maintenance and re-construction processes. The benefits of applying FTCP technology in such applications are : (a) a reduced construction period, (b) early opening of the pavement to traffic, and (c) reducing the use of expensive concrete paving plant.

BASIC CONSIDERATIONS FOR THE MIX DESIGN OF HIGH STRENGTH CONCRETE

The mechanical properties of the concrete can be improved by obtaining a denser packing of the solids. The paste-aggregate bond can also be improved. The first effect might be explained by so-called ‘DSP-concrete’ (Densified Systems containing homogeneously arranged ultra-fine Particles). Larger amounts of silica fume (SF) (more than 10% of the cement weight) are used to ‘refine’ the particle structure and thereby reduce the total pore volume and the average pore size. The size and spherical geometry of SF particles allow them to fill effectively the voids between the larger and angular cement grains. Extreme dosages of dispersing agents are used to overcome the surface tensions, permitting dense particle packing. Very low water demand is obtained and, thus, pastes of very low water-cement ratios can be produced. The SF eventually also contributes to the formation of CSH-gel through pozzolanic reactions, causing a denser and more homogeneous gel structure.

A dense cementitious matrix is not sufficient by itself to obtain HSC since the aggregate-matrix bond may not be strong enough. In NSC the interfacial zone is often a weak link, since it tends to be more porous and heterogeneous than the bulk paste matrix. The addition of SF can drastically change the microstructure of the paste at the interface, causing it to be as dense as that of the matrix. This provides a much more efficient bond between the aggregate and the matrix. This effect of SF is associated with its ability to pack densely at the aggregate surface, as well as to reduce the internal bleeding of the concrete. Due to these interfacial effects, the aggregates in high strength silica fume concrete are becoming active load-bearing components in the concrete, contributing to the overall strength, and not just inert mechanical fillers as in NSC. Therefore, the pillars of practical mix design for HSC are:

(i) Reduced water-cement ratio.

(ii) Extensive use of plasticizers.

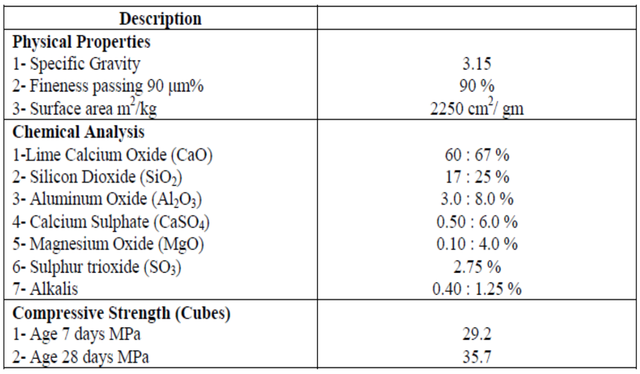
(iii) Application of cement with a high strength potential.

(iv) Application of pozzolans and in particular SF.

METHODOLOGY

Material Preparation and Characterization-

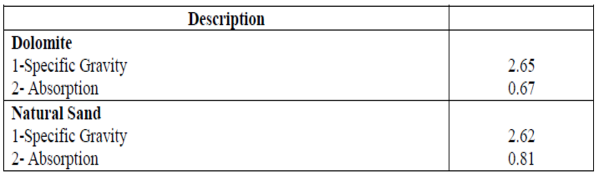
Portland Cement-Ordinary Portland cement, from Helwan Factory in Cairo were used, their physical properties and chemical analysis as follows in table 1



Description	
Physical Properties	
1- Specific Gravity	3.15
2- Fineness passing 90 µm%	90 %
3- Surface area m^2/kg	2250 cm^2/ gm
Chemical Analysis	
1-Lime Calcium Oxide (CaO)	60 : 67 %
2- Silicon Dioxide (SiO_2)	17 : 25 %
3- Aluminum Oxide (Al_2O_3)	3.0 : 8.0 %
4- Calcium Sulphate ($CaSO_4$)	0.50 : 6.0 %
5- Magnesium Oxide (MgO)	0.10 : 4.0 %
6- Sulphur trioxide (SO_3)	2.75 %
7- Alkalis	0.40 : 1.25 %
Compressive Strength (Cubes)	
1- Age 7 days MPa	29.2
2- Age 28 days MPa	35.7

Table 1: Properties of used Portland cement.

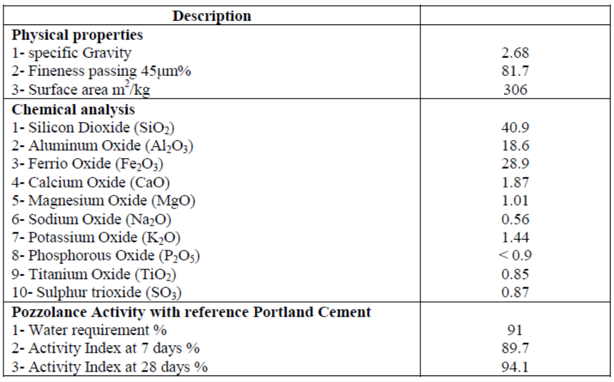
Aggregates - Crushed dolomite (specific gravity of 2.65) having the maximum aggregate size of 10 mm was used as the coarse aggregate and local natural sand as fine aggregate (specific gravity of 2.62). To keep the grading uniform for mixtures, both the fine and the coarse aggregates were separated into different size fractions that were then recombined to a specific grading.



Description	
Dolomite	
1-Specific Gravity	2.65
2- Absorption	0.67
Natural Sand	
1-Specific Gravity	2.62
2- Absorption	0.81

Table 2: Physical Properties of used aggregates.

Fly Ash - The physical properties and chemical analysis as follows in table 3



Description	
Physical properties	
1- specific Gravity	2.68
2- Fineness passing 45µm%	81.7
3- Surface area m^2/kg	306
Chemical analysis	
1- Silicon Dioxide (SiO_2)	40.9
2- Aluminum Oxide (Al_2O_3)	18.6
3- Ferrio Oxide (Fe_2O_3)	28.9
4- Calcium Oxide (CaO)	1.87
5- Magnesium Oxide (MgO)	1.01
6- Sodium Oxide (Na_2O)	0.56
7- Potassium Oxide (K_2O)	1.44
8- Phosphorous Oxide (P_2O_5)	< 0.9
9- Titanium Oxide (TiO_2)	0.85
10- Sulphur trioxide (SO_3)	0.87
Pozzolance Activity with reference Portland Cement	
1- Water requirement %	91
2- Activity Index at 7 days %	89.7
3- Activity Index at 28 days %	94.1

Table 3: Properties of used fly ash.

Super Plasticizer - A commercially available type-high range water reducing super-plasticizer was used. This type is dark brown in color and has 40% solids content in an aqueous solution. It is consisting of a salt of naphthalene sulphonate formaldehyde condensate.

Heating Equipment -

A ventilated oven was used to heat the concrete specimens to a temperature up to 100oC. For the temperature of 200oC and above, an electrically heated furnace designed for a maximum temperature of 1200oC was used. The furnace was heated by means of exposed heating elements laid on the refractory walls of the inside chamber, which was approximately 400 × 400 × 800 mm in dimension. The test specimens were stacked with sufficient space between two adjacent specimens to obtain a uniform heating in each specimen. Since the chamber had a limited volume the concrete specimens were heated in batches.

Concrete Mixtures –

The graded coarse and fine aggregates were weighted in room dry condition, the coarse aggregate was then immersed in water for 24 hours, the excess water was decanted and the water retained by the aggregates was determined by the mass difference. A predetermined amount of water was added to the fine aggregate that was then allowed to stand for 24 hours. The water to cementitious materials ratio and the quantities of cement, water and fly ash were kept constant 35%, also the quantity of ordinary Portland cement was kept constant 900 kg/m3. Fly ash was kept also constant 300 kg / m^3 .

The required specimens were included 150 × 300 mm cylinders, 150 × 150 ×150 mm cubes. The specimens were cast in two layers; an internal vibrator was used for compaction. After casting, all the molded specimens were covered with plastic sheets and were left in the casting room for 24 hours. Afterwards, they were remolded and transferred to the moist curing room at 100% relative humidity until required for testing and stored in water at 20^0C till the age of 28 days.

Testing of Specimens –

At the age of 28 days, the concrete specimens were removed from water and dried in air for 24hrs at the laboratory conditions with a mean relative humidity and temperature of 65% and 25^oC respectively. Then the specimens were placed in a ventilated oven at 60^oC for 24hrs before subjecting them to high temperatures in the electric furnace. This step was found to be necessary to avoid the explosion of the concrete specimens in the furnace due to the formation of steam. The rate of heating was maintained at 200^oC/hr. Once the required maximum furnace temperature was reached, the temperature was maintained until the specimens were removed. For all concrete specimens, the total duration in the furnace was 8 hrs. The maximum furnace temperatures were 200, 400, 600, 800 and 1000^oC.

Two cooling methods were employed for the heated concrete specimens. At the end of the sustained periods at the corresponding maximum temperatures, the specimens were removed from the furnace. Some of the heated specimens were quenched in water at 20oC in a very large water tank and kept in water for 48hrs prior to strength testing. The remaining specimens were cooled in air at the laboratory conditions for 24hrs, followed by placing in water for 24hrs prior to strength testing. Both water quenched and air cooled concrete specimens were tested in either compression or in direct tension. The specimens were weighted at different stages of heating and cooling. Both the ultrasonic pulse velocity and rebound number were determined using the cube specimens. All specimens for the compression testing were capped with sulphur before testing.

CONCLUSION

HSC that consistently meets requirements for workability and strength development places more stringent requirements on material selection than that for lower strength concrete. Therefore, the production of HSC may or may not require the special materials, but it definitely requires materials of highest quality and their optimum proportions. In the production of HSC, use of strong, sound and clean aggregates is essential. The basic trick then lies in reducing the capillary pores in the matrix and improving the bond strength between cement matrix and aggregate. These can be accomplished by using low water-cement ratio and incorporating ultra-fine particles (particles much smaller than the grains of cement, such as silica fume) in the concrete mix, but not at the expense of workability necessary to achieve adequate compaction.

The paper presents an overview of the concept of high-performance concrete and some of its applications in civil engineering constructions. Although high-performance concretes are made with the same components as of normal concrete, their much higher qualitative and quantitative performances make them new material for usage. On the basis of their use, they offer different advantages such as enhanced durability, reduced permeability, higher strength etc. at an economical cost. The purpose of high-performance concrete is not to produce a high cost product, but simply to provide a means for producing concrete that will perform satisfactorily with reasonable cost for intended service life.

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