CONCRETOS DE ALTO COMPORTAMIENTO: PROPIEDADES MECANICAS Y ASPECTOS SOBRE LA DURABILIDAD

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R. Pleau, M. Pigeon, A. Delagrave y M. Azabi

Sinopsis: Este trabajo presenta algunos hallazgos de la investigación desarrollada recientemente el la Universidad de Laval, sobre las propiedades del concreto de alto comportamiento (HPC). Se cubren diferentes aspectos del HPC incluyendo la estructura capilar de los poros, su resistencia a la compresión, su resistencia al congelamiento y descongelamiento; la influencia del envejecimiento en su permeabilidad al ion cloro, así como su resistencia al ataque químico. Los resultados reportados aquí ilustran no sólo las ventajas ofrecidas por el HPC en relación con la resistencia mecánica, sino que también las relacionadas con la durabilidad de la estructura del concreto. Se encontró que las propiedades del HPC estaban íntimamente relacionadas con la superficie interna del poro. La selección de los materiales, en particular los cementantes y del agregado grueso, parecen ser de particular importancia. Los resultados de los ensayes también indican que una diferencia relativamente pequeña al decidir sobre el tipo y dosificación de los aditivos o en el método de mezclado, pueden ser los responsables de grandes discrepancias en las propiedades del concreto endurecido. Por lo tanto, se debe tener especial cuidado al diseñar y fabricar el HCP para poder producir un material de alta calidad con propiedades repetibles y reproducibles.

Palabras clave: Concreto de alto comportamiento, poros capilares, resistencia a la compresión, cemento, microsílica, durabilidad al congelamiento, permeabilidad al ion cloro, ataque químico.

HIGH PERFORMANCE CONCRETE: MECHANICAL PROPERTIES AND DURABILITY ASPECTS

by

R. Pleau, M. Pigeon, A. Delagrave, and M. Azabi

Synopsis: The paper presents some findings of the research carried out recently at Laval University on the properties of high-performance concrete (HPC). Different aspects of HPC are covered including their capillary pore structure, their compressive strength, their resistance to freezing and thawing, the influence of ageing on their chloride ion permeability, and their resistance to chemical attack. The results reported here well illustrate the advantages offered by HPC not only as regards with the mechanical resistance, but also as regards with the durability of concrete structures. The properties of HPC were found to be closely related to their internal pore structure. The choice of materials, especially the cementitious materials and the coarse aggregate, appears to be particularly important. Test results also indicate that relatively small differences in the choice and dosage of admixtures, or in the mixing method can be held responsible for large discrepancies on the properties of hardened concrete. Consequently, a great care must be taken in the design and making of HPC in order to produce a high quality material with repeatable and reproducible properties.

Keywords: High-performance concrete, capillary pores, compressive strength, cement, silica fume, frost durability, chloride ion permeability, chemical attack.

Richard Pleau is an Associate Professor at the School of Architecture at Laval University in Québec City, Canada. His research interests are in the field of air entrainment, frost durability, high-performance concrete, and high-performance micro-reinforced cementitious composites.

ACI Fellow **Michel Pigeon** is a professor of Civil Engineering at Laval University, Québec, Canada. His research interests are mainly in the field of concrete durability, concrete repairs and high-performance concrete. He is a Principal Researcher of the Canadian Network of Centres of Excellence on High-Performance Concrete and a member of ACI Committee 201, Durability of Concrete.

Anik Delagrave is a Ph.D. student at Laval University. Her research interests are in the field of microstructure of cement paste, transport phenomenon, nuclear waste management and long-term durability of high-performance concrete.

Maha Azabi is a Ph.D. student at Laval University. Her research interests are in the field of durability of micro-reinforced high-performance cementitious composites.

INTRODUCTION

The advent of commercially available superplasticizer admixtures in the late seventies is mainly responsible for the rapid development of high-performance concrete (HPC) in the last decade [1, 2]. HPC was first used to take advantage of its higher compressive strength but it also offers many other advantages like a higher modulus of elasticity, a higher hydration rate, reduced drying shrinkage and creep deformations and, especially, a better durability [3, 4]. HPC is no longer considered as a laboratory material and its use is expected to grow rapidly in the next years for a wide range of applications.

This paper summarizes the results of some experimental studies carried out recently at Laval University on the mechanical properties and durability of a wide range of high-performance concrete mixtures.

CAPILLARY PORE STRUCTURE

High-performance concrete is obtained by reducing the water to binder[1] ratio (W/B) in order to produce a stronger and less porous cementitious matrix. The improved mechanical resistance of HPC and its higher durability are both closely related to the reduction of the capillary pore volume. But the lowering of the W/B ratio do not only reduces the total pore volume; it also yields to a more finely divided pore network. In ordinary cement pastes (W/B ≥ 0,45), many spaces located between cement particles are never filled with hydration products and thus remain as large capillary pores. For pastes having low W/B ratios, the cement particles are closer together and the reduction of the porosity is mostly achieved to the detriment of these larger pores [5].

A series of laboratory tests was carried out in our laboratory to study the influence of W/B ratio on the capillary porosity of cement paste. Four different binders were tested: a normal (ASTM Type I) and a high early strength (ASTM Type III) Portland cements with and without silica fume (6% in weight) used as a partial replacement for Portland cement. A granitic sand and a crushed limestone were used as fine and coarse aggregates in a 40/60 relative proportion (in weight). Concrete mixtures were made with three W/B ratios (0.45, 0.35, and 0.25), and their compositions were chosen in order to keep the volume of cement paste almost constant (approximately 35% of the total volume). All mixtures were submitted to the ASTM C 642 water absorption test method and to the AASTHO T227 rapid chloride ion permeability test method after respectively 7 and 28 days of moist curing at 23°C.

Table 1 shows the volume of permeable pores (i.e. pores containing evaporable water) obtained from the water absorption tests. This volume roughly corresponds to the total capillary porosity and, as Table 1 indicates, it decreases with the advance of cement hydration and the lowering of the W/B ratio. The values reported in Table 1 clearly show that Type III Portland cement is more reactive than Type I cement and thus yields a less porous cementitious matrix. Similarly, Table 1 indicates that the presence of silica fume also promotes the hydration process and reduces the total porosity, especially for concretes made with Type I cement and tested at early ages (7 days).

Table 2 summarizes the results of the rapid chloride ion permeability tests. It gives the electrical charge (expressed in Coulombs) passing through concrete specimens submitted to a 60 volt potential during a 6 hour period[2]. Table 2 shows that the chloride ion permeability also decreases with the advance of hydration and the lowering of the W/B ratio. Concretes made with Type III cement are less permeable than those made with Type I cement and the use of silica fume significantly reduces the chloride ion permeability, especially at later ages (28 days).

The chloride ion permeability per unit volume of capillary pores can be easily obtained by dividing the charge passing through concrete (Table 2) by its capillary pore volume (Table 1). This parameter is a good index of the fineness of the pore network because the chloride ion permeability is related not only to the total pore volume, but also to the spatial distribution of capillary pores. For a given pore volume, the mobility of ions, and consequently the chloride ion permeability, will be reduced if this volume is more finely subdivided. Figures 1 and 2 show the relationship between the charge per unit pore

[1] The term "binder" includes Portland cement and other cementitious materials used as a partial replacement of Portland cement such as silica fume, fly ash, or blast-furnace slag.

[2] One side of the concrete specimen is in contact with a 3% NaCl solution and the other side with a 0.3N NaOH solution.

volume and the W/B ratio for concretes made with and without silica fume after 7 and 28 days of moist curing. The curves shown on these Figures clearly illustrate the refinement of the pore network with the advance of hydration (7 vs 28 days of moist curing) and the lowering of the W/B ratio. It is interesting to notice that mixtures made with Type III cement have a slightly finer pore network than those made with Type I cement probably due to the higher fineness of the cement particles (The Blaine fineness was 545 m²/kg for Type III cement compared to 383 m²/kg for Type I cement).

The comparison between Figures 1 and 2 indicates that the presence of silica fume reduces very significantly the chloride ion permeability per unit capillary pore volume. This reduction can be due in part to the lower ionic content of the capillary pore water which increases the electrical resistance of concrete. But the main difference is most probably simply due to the refinement of the pore structure provided by the presence of the silica fume particles. It must be remembered that these particles are about 100 times smaller than cement grains which confer them a great ability to fill small spaces and act as nucleus for hydration products. It is interesting to notice that the presence of silica fume tends to increase the difference between 7 and 28 days of moist curing. It is also very significant to observe that, at 28 days, all silica fume concretes show extremely low values of permeability no matter the type of cement or the W/B ratio.

COMPRESSIVE STRENGTH

The compressive strength of HPC was the object of a large number of research studies reported in the technical and scientific literature. Among the many factors which influence the strength of HPC, the choice of materials is particularly important. Portland cements with a high fineness and a high early strength (such as ASTM Type III) generally provide the best results because they produce a less porous and more finely divided cementitious matrix as described in the previous section. Although it is not absolutely essential, most of the HPC contain silica fume because it significantly improves the quality of the cement paste as well as the quality of the bond at the paste–aggregate interface, and it generally have a beneficial effect on the rheological properties of fresh concrete. The choice of the coarse aggregate is certainly one of the key factor in the production of very high strength concrete. At very low W/B ratios the performance of HPC is often governed by the characteristics of the coarse aggregate which is rarely the case for normal strength concrete. The stronger aggregates are not necessarily the best ones because they are often too stiff and their high modulus of elasticity creates harmful stress concentrations at the paste–aggregate interface.

It is very difficult to assess the quality of an aggregate on the sole basis of its mineral composition. The best way (and certainly the safer) is to identify the good quality aggregates available in the local area and to test them in the laboratory. Such an exercise was done with a number of aggregates of the Québec City area. Concretes with low W/B ratios were made with 6 different coarse aggregates (with a 14 mm maximal nominal size) by using always the same materials in the same proportions. A Type I Portland cement containing 6 to 8% of silica fume was used in conjunction with a granitic sand and a

naphtalene based superplasticizer admixture. The composition and properties of concrete mixtures are given in Table 3. Table 4 summarizes the compressive strength obtained after 48 hours and 28 days of moist curing at 23°C (each number represents the average value obtained for three 150 x 300 mm cylinders). This Table indicates that the best results were obtained with a dolomitic limestone (aggregate C) and the worst ones with a granite (aggregate D) and a limestone (aggregate A). It is funny to notice that aggregate A is the most commonly used by the local concrete producers. For the 0.22 W/B ratio a difference of about 20 MPa is observed between the stronger and weaker aggregate which is quite a significant difference. Figure 3 shows the relationship between the compressive strength and the water-binder ratio for three of these aggregates (A, B, and C). This Figure shows significant differences between the strength obtained with these three aggregates. The reversed order of strength obtained with aggregates A and B at 48 hours and 28 days well illustrates the importance of the paste-aggregate interfacial bond at early ages (a lot of debonding and few broken particles were observed on the ruptured surfaces).

The materials which yields higher compressive strengths are not necessarily the more appropriate ones. Many other factors have to be taken into account such as the workability of fresh concrete, the loss of slump with time, the heat of hydration, the unit cost of concrete, bleeding and segregation, creep and shrinkage, etc. The compatibility between the cement, the superplasticizer, and the other chemical and mineral admixtures was found to be of a major concern and worth a particular attention from the concrete producer [6, 7]. When crushed particles are used as coarse aggregate, the reduction of the maximum nominal size often provides higher compressive strengths probably because the aggregate particles are less affected by the microcracking induced by the crushing process.

HPC is much more sensitive to little differences of mixture composition, mixing procedures, or weather conditions than normal strength concrete, and thus requires a more rigorous control. For example, a series of tests was carried out to study the influence of the superplasticizer (both its nature and its dosage) and the influence of the mixing sequence on the properties of a high performance concrete made with a W/B ratio of 0.35. Concrete mixtures having the same composition (i.e. about 150 kg of water, 425 kg of Type I Portland cement, 772 kg of granitic sand and 1090 kg of coarse aggregates for each cubic meter of concrete) were made with two coarse aggregates (a dolomitic limestone and a granitic gneiss) and three superplasticizers (a melamine and two naphtalene) used at different dosages. Two mixing sequences were tested. The first one consists to mix cement, sand, water, and superplasticizer until the obtention of an homogeneous mortar and to later add the coarse aggregates. In the second method dry materials (cement, sand, and coarse aggregates) were first mixed before the adding of the water and superplasticizer. The results obtained are summarized in Table 5. The 28 days compressive strengths reported in this Table range from 41 to 68 MPa which is quite a large difference for concrete mixtures supposedly similar ! The average resistance is around 60 MPa and it can be reached with all the three superplasticizers used with both coarse aggregates although the data are quite scattered (particularly for the two naphthalene-based superplasticizers). Let us consider, for example, the mixtures made with the dolomitic limestone and the superplasticizer N2. It is surprising to observe that two identical mixtures made with the same dosage of superplasticizer (6.5 L/m³) and the same mixing sequence (A) yields compressive strengths as different as 44 and 53 MPa. Mixtures made with the granitic gneiss and the superplasticizer N1 provide another good example. In that case, the compressive strength vary by about 17 MPa due solely to the mixing sequence used (the results were repeated twice for each mixing sequence). The reason for these discrepancies is still disputed. It was suggested that some internal bleeding beneath the coarse aggregates, or a poor distribution of water through the cement paste could be held responsible for some exceptionally low compressive strengths. This would be mainly observed for concrete mixtures with very high slump values. It is also interesting to notice that, in all cases, a much higher dosage of superplasticizer is required to obtain the same slump value when mixing sequence B is used instead of the sequence A. Further research is still need to better understand, and control, this particular behavior of HPC. However the results reported in Table 5 well emphasize the great care that concrete producers must give to the mixture design and the making of HPC in order to deliver a high quality construction material with always the same properties.

RESISTANCE TO FREEZING AND THAWING CYCLES

In Northern countries, repeated freezing and thawing cycles is one of the main cause of deterioration of concrete structures (along with the corrosion of steel rebars). Damages due to frost action can be divided in two categories: (1) internal microcracking caused by the hydraulic pressures resulting from the force movement of freezable water through the capillary pore structure during freezing, and (2) surface scaling due to freezing in presence of deicing salts [8]. When concrete is exposed to severe climatic conditions, air entrainment is required to protect concrete against freezing [9]. Air entrainment is achieved by adding an air-entraining admixture to the mixing water. Microscopical air voids (with diameters ranging from 10 μm to more than 1 mm) act as vessels to dissipate the internal pressures caused by the flowing of freezable water. These pressures are roughly proportional to the square value of the distance that freezable water must travel through cement paste [10]. The frost resistance is thus strongly related to the air-void spacing factor ($\bar{L}$) which is defined as the average maximum distance between the boundaries of two adjacent air voids. This spacing factor is determined by means of a microscopical examination of polished concrete surfaces according to the ASTM C 457 test method. The concrete is considered frost resistant if its $\bar{L}$ is smaller than a critical value called the critical spacing factor ($\bar{L}_{crit}$). For a given concrete mixture, the critical spacing factor is determined by submitting similar concrete mixtures with different $\bar{L}$ values to 300 repeated freezing and thawing cycles in laboratory (ASTM C 666 test method) and assessing the extent of frost damage by means of length change, resonance frequency, or pulse velocity measurements. The critical spacing factor is a function of many parameters such as the choice of materials, the mixture composition, and the curing period [11].

Table 6 gives the values of $\bar{L}_{crit}$ obtained for a number of concretes made with different binders (Type I and III Portland cement with and without silica fume) and different W/B ratios (0.50, 0.30, and 0.25) which were subjected to 300 freezing and thawing cycles in air or in water after 14 days of moist curing. Concretes having lower values of $\bar{L}_{crit}$ require a higher air content because the air voids must be more closely spaced in order to

efficiently protect them against freezing and thawing cycles. Table 6 indicates that for low W/B ratios (0.30 and 0.25), the nature of cement is of a paramount importance. For concretes made with Type III Portland cement it was not possible to determine an $\bar{L}_{crit}$ value since all the mixtures tested were found to be frost resistant (the non air-entrained mixtures have an $\bar{L}$ of about 800 μm). In fact, even non-air entrained mixtures subjected to 750 freezing and thawing cycles in water only 24 hours after casting show no signs of deterioration. Concretes made with Type I Portland cement do not have such a good frost resistance and, for these mixtures, air entrainment is still required even for very low W/B ratios (although their air content may be significantly lower than the value generally recommended for normal strength concretes). The difference between cements is mostly due to their influence on the capillary pore structure (see the previous section devoted to this topic). The lower porosity and more refined pore structure obtained with Type III cement is such that the concretes made with this type of cement contain a negligible amount of freezable water which explains their better frost resistance.

For normal strength concrete, it is generally accepted that a spacing factor lower than about 200 to 250 μm is required in order to provide a satisfactory surface scaling resistance in presence of deicer salts [9, 11]. Most of the time, scaling is a condition more restrictive than internal microcracking since many concrete mixtures with $\bar{L}$ values substantially higher than 250 μm can sustain repeated freezing and thawing cycles without internal damage (see Table 6). Laboratory test results indicate that HPC generally exhibit very low weight losses due to scaling even after 150 daily freezing and thawing cycles irrespective to the W/B ratio, type of cement, and curing period [12, 13]. It thus seems that, contrary to the normal strength concretes, the frost resistance of HPC is mainly governed by the internal microcracking instead of deicer salt scaling. It is clear that it is possible to produce highly frost resistant HPC with lower air contents than normal strength concretes. In some cases it is even possible to produce frost resistant HPC without air entrainment. However, research is still needed in order to propose new guidelines about the characteristics of the air-void system which are required to ensure the frost durability of HPC.

INFLUENCE OF DRYING ON CHLORIDE ION PERMEABILITY

Penetration of chloride ions is one of the most important cause of deterioration of concrete structures and is associated to many detrimental phenomenon such as the formation of chloroaluminates, the corrosion of steel reinforcement, and the surface scaling. Because of its very low porosity, HPC is much less permeable to chloride ions which contributes to improve its durability very significantly. Recently, a research program was carried out in our laboratory to study the influence of drying on the rapid chloride ion permeability of concretes made with four binders (Type I and Type III Portland cement with and without 10% of silica fume) used at three W/B ratios (0.45, 0.35, and 0.25) [14]. All the concrete mixtures were subjected to a 7 day initial curing period and were air-dried for 90 days at different temperature (23, 38, and 110°C) prior to testing. Drying at 23°C and 38°C corresponds to normal conditions for field concretes. Drying at 110°C, however, is