THE DEVELOPMENT OF DURABLE HIGH PERFORMANCE CONCRETE IN VIETNAM

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SUMMARY

The recent development in the field of high-performance concrete (HPC) have been a giant step in making concrete a high-tech material with enhanced characteristics and durability. They have even led to it being a more ecological material in the sense that the component admixtures, aggregates and water are fully used to produce a material with a longer life cycle.

Achieving high-performance is not done with a casual approach; all ingredients must be carefully selected. High-performance concrete is very sensitive to plastic and autogenously shrinkage, so that their use demands an immediate water curing. High-performance concrete is definitely more durable the usual concrete. Its increased use will be more often linked to its durability than its high strength. Durability will become a key issue because we will become more and more concerned with sustainable development.

In this paper, the basic characteristics of high-performance concretes are described and discussed.

Keywords: *High-performance concrete, component, characteristic, durability*.

GENERAL INFORMATION

The high performance concrete concept if translated into technical terms for cement-based composites means:

- such a consistency in the fresh mix that its workability, flowability, mobility, compactability, pumpability and finishability ensure good results of execution without much effort from workers or an excessive expense of energy.
- excellent behaviour of materials in their hardened state, i.e. strength and deformations satisfying standard requirements imposed by the applications.
- relatively high strength at an early age.

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- acceptable behaviour in the long-term, i.e. durability adequate to requirements during the forecast life of the structure, low maintenance costs and relative facility of repair works.
- Good aspect of the structure during its service life, i.e. without visible cracks, voids and spellings, excessive defections, etc.

The concepts of high strength and high performance concrete varied over time. The compressive strength of ordinary concrete increased from about 15 MPa to 40 MPa. At present, high performance concretes (HPC) of $f_{28} \geq 60$ MPa and very high performance concretes (VHPC) with $f_{28} \leq 120$ MPa are conventionally distinguished.
In the performance approach to concretes the main questions which are formulated by on parties involved in the construction process are answered – the contractor who takes care of production, transportation, casting and curing of the fresh mix, the investor, the owner of the structure and the general public. All of them are interested in a low general cost for the structure, its long-term serviceability and safety. The users are less aware of various physical and chemical properties, but the overall performance is of primary importance. The scope of application of HPC and VHPC is determined by their improved properties with respects to ordinary concretes and by the technical and economic advantages which may be obtained as a result.

Photo 1: Viet Nam My Thuan bridge was built by high performance concrete

A COMPOSITE MATERIAL

High Performance Concrete are made with basically the same components as ordinary concretes but without the application of special technologies. The composition of HPC is characterized with respect to ordinary concretes by:
- Increased fraction of fine and very fine grains;
- Lower w/c ratio and use of superplasticizers (also known in this context as High-Range Water-Reducing Admixtures-HRWRA);
- Smaller fraction of coarse aggregate and smaller maximum grain dimension.

In the design of HPC composition two main groups of problems need to be solved in a well coordinated way. The first one covers the chemical and physical properties of all component, their compatibility and synergisms, together with their particular roles in the material structures. The second group of problems concerns the feasibility of using the designed material in local conditions and at a reasonable cost. Usually, the required strength is also attained when these problems are solved.

The examples of the composition of HPC and VHPC presented in Table 1 show the features listed above.

Table 1 Examples of high and very high-performance concretes

High-performance concretes							Very high-performance concretes		
		(1) (kg)		(2) (kg)		(3) (kg)		(4) (kg)	(5) (kg)
Gravel	12.5/20	852	10/20	698	5/16	955			
Gravel	5/12.5	267	6/14	465	2.5/6.3	217	2.5/10	1076	1094
Sand	0/5	765	0.1/2.5	738	0/2.5	934	0/5	753.9	772.6
Cement		425		425		425	cement	502.6	506.6
Water		150		160		160	Water	115.6	115.4
Superplast		6.4		8.5		12.8	Superlast	12.1	21.1
Retarded		1.7		1.7		1.7	Silica fume	50.2	50.7
Slump(mm)		180 - 250		110 - 190		200 - 210	Slump(mm)	230	230
		(MPa)		(MPa)		(MPa)		(MPa)	(Mpa)
fc_1		17.8		36.2		57.7	fc_{28}	120.7	120
fc_2		60.6		68.3		57.7			
fc_{28}		74		75.9		67.2			
fc_{90}		82.5		81.5			d (kg/m^3)	2510	2 560
ft_{28} (split)		5.3		4.5			E (MPa)	49 751	50 314
w/c		0.35		0.38		0.38	w/c	0.21	0.21

Portland cement

Ordinary Portland cement of good quality may be used for HPC. A high content of tricalcium silicate C_3S and bicalcium silicate C_2S (alite and belite) is favoured together with a low content of tricalcium aluminate C_3A. Because of the low values of water/cement ratio required, a relatively high amount of Portland cement is used 400 kg/m^3 and more. The amount of cement may be reduced by blending with order micro-fillers like fly ash or high purity silica with grains of about 4μm in diameter.
A Portland cement of rather fine grain is preferred, but not too fine, so as to avoid excessive acceleration of all processes. The compatibility with other components should be verified as well as low shrinkage and heat from hydration.

Admixtures and additives

Two main groups of admixtures are considered to be very important component of HPC – superplasticizers which improve the workability of the fresh mix with low values of water/cement ratio, and micro-fillers to increase the density of the hardened material.
There are several kinds of superplasticizers available. They belong to two main groups' sulphonated melamine-formaldehyde condensates and sulphonated naphthalene-formaldehyde condensates. Their action is explained by the absorption of polyanions on the surface of cement grains and by the generation of negative potential which eliminates the attraction and coagulation of the grains. As a result, a decrease of internal friction is obtained and the workability expressed for example by slump of 180 – 250 mm is ensured for 1 – 1.5 hours. The correct selection of a superplasticizers for other mix components is important. Usually superplasticizers are added as 2 – 4% of cement mass, according to the producer's prescription. With higher dosages some delay may occur in hydration and hardening together with the apparent early setting of the fresh mix.

When Portland cement is partly replaced by fly ash or blast-furnace slag, then better flowability of the fresh mix is usually obtained and lower dosages of superplasticizers are possible. This is quite profitable from the economical viewpoint: superplasticizer is an important part of cost of the concrete components.
The compatibility of superplasticizers with cement as well as their efficiency, duration of the fresh mix fluidity, sensitivity to ambient temperature and other factors should be verified by experiments executed in local conditions.
Fly ash, silica fume and other silica products are used as micro-fillers. They are furnished as powder or slurry with grains of one or two orders smaller than Portland cement. They enter into the voids between the cement grains and by acting as water-redactors enhance the efficiency of the superplasticizers. By their addition, the contacts between aggregate grains of bleeding and segregation of the fresh mix during transportation and casting.
The pozzolanic properties of silica fume result in a slow hydration process and in more efficient gel development. Silica fume considerably improves the performance of the binder phase and increases its bonding action with the aggregate and reinforcement. The highly porous interface is the weakest element in the structure of an ordinary concrete and its strengthening is decisive for HPC.
The application of silica fume is not necessary for concrete of compressive strength up to 60 MPa, but it is considered as a compulsory component of VHPC. However, in HPC and ordinary concrete silica fume also improves their density and durability.
According to the optimum content of silica fume is 7 – 15 % of cement mass. A higher dosage may increase brittleness and influence unfavourably the total cost of the final composite material.

W/ c ratio

The reduced amount of water and low value of the w/c ratio are necessary for the high strength and low porosity which characterize HPC. The excellent workability of fresh mix required is ensured by admixtures. W/c ratio remains between 0.25 and 0.30 and between 0.30 and 0.35 for HPC, probably for higher percentage of hydration of Portland cement. Also, lower dosage of superplasticizer might be possible for required workability.
Because of the pozzolanic properties of microfillers, it is common to also calculate the water to cement and microfiller ratio: w/(c+m).

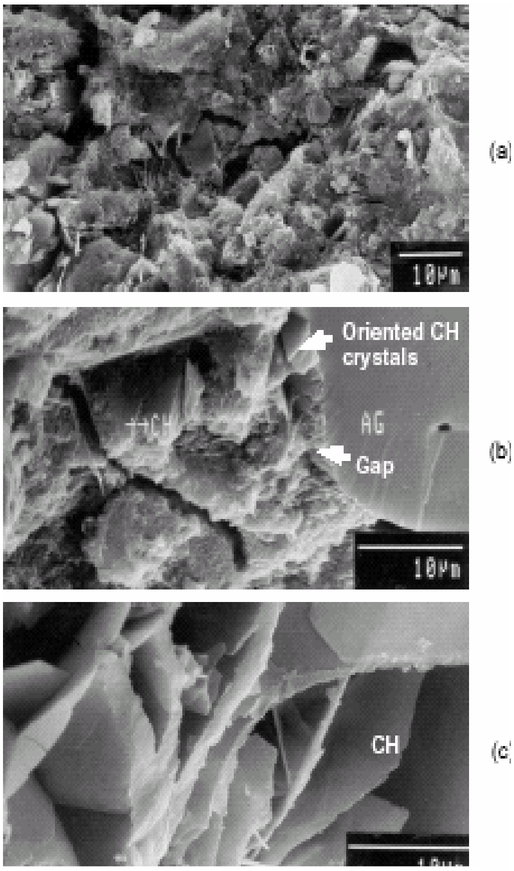

Figure 1. Microstructure of high water/cement ratio concrete: (a) high porosity and heterogeneity of the matrix, (b) orientated crystal of Ca(OH)2 on aggregate, (c) CH crystal [2]

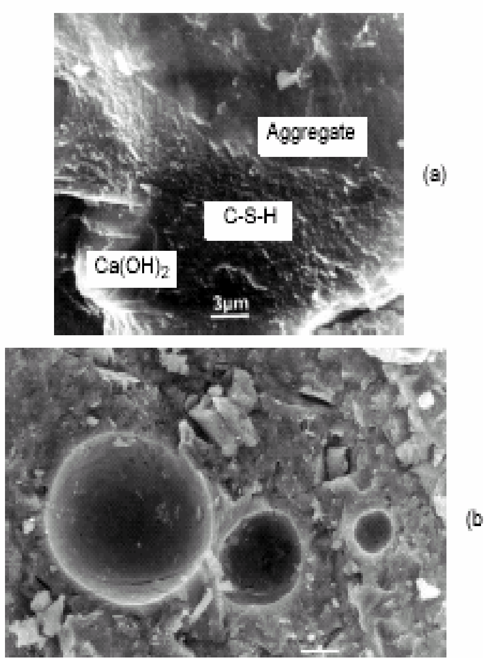

Figure 2. Microstructure of a high performance concrete: low porosity and homogeneity of the matrix [2]

Aggregate

The properties of aggregate are important and for HPC they should satisfy several different requirements. First of all, good workability must be ensured and for that reason continuous sieve distributions are preferred.

Maximum grain diameter should be limited in order to improve workability and to reduce discontinuities and stress concentrations. According to the grains should not exceed 25 mm, 20 mm is indicated and certain authors even propose 10 mm as aximum grain diameter.

Grains of spheroidal shape are preferred and natural gravel is considered better than crushed aggregate for improved workability and lower requirement.

The appropriate sieve distribution and packing of aggregate grains, together with other particles, in the mix is the direct and classic way to ensure the high density of the hardened concrete. In practice, the composition of grains obtained from quarries should be improved, but such modifications can be expensive. In other situations, the correct proportions of grain of different diameter are furnished on request.

The quality of sand seems to play a smaller role and requirement as for ordinary concrete apply. Continuous sieve distribution is also favorable and mineralogical composition should be similar to that of the coarse aggregate.

TECHNOLOGY

The methods of production of HPC are basically the same as in the case of ordinary concretes. A high quality of components and their prescribed proportions should be maintained in the fresh mix. The quality of components and of the final product should be controlled at all stages of execution.

The main reason where by HPC is accepted and fully supported by contractors and investors is the excellent workability of the fresh mix obtained by the appropriate application of superplasticizers which are either added to the water before mixing or, when the mix is transported over a longer distance are added in two portions – before mixing; and after transportation, directly before casting. The facility to fill the moulds or forms by the fresh mix and its pumpability is ensured when sufficient slump of the Abrams cone and the coherence of the mix are maintained during the full amount of time required for both transportation and casting.
The slump of the Abrams cone is not the best measure of the consistency of HPC and other methods are available. However, these methods are not generally approved and standardized and specialized equipment varies in different countries. That is why the Abrams cone is still used.

If vibration of the fresh mix is necessary, then the characteristics of the equipment used should be adapted with regard to its frequency and amplitude.
When a micro-fillers is used for HPC like silica fume or fly ash, the prescribed way of adding it to the mix and the correct sequence of adding other components should be carefully executed. The good dispersion of silica fume is particularly important because its effects result from combined physical and chemical mechanisms.

The cure of HPC after casting is different than in the case of ordinary concretes. There is no need to maintain high humidity over a long time period because of the high rate of increase of strength. In order to avoid microcracking on the surface, it is advised that any evaporation of water during the first few hours should be prevented, e.g. by perfect sealing. Furthermore, to prevent stress induction due to the characteristic ability of HPC for self-desiccation, curing in water is not advised, because non-uniform swelling may occur due to the characteristic ability of HPC for self-desiccation, curing in water is not advised because non-uniform swelling may occur due to the low permeability of HPC. The absence of bleeding in HPC is the reason why the humidity of the fresh mix should be maintained immediately following casting. Sufficient curing should allow the chemical mechanism to develop its full effect.

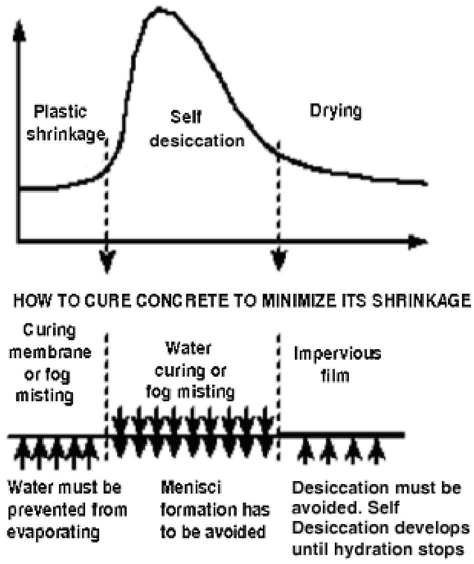

Figure 3 The most appropriate curing regimes during the course of the hydration reaction [3]

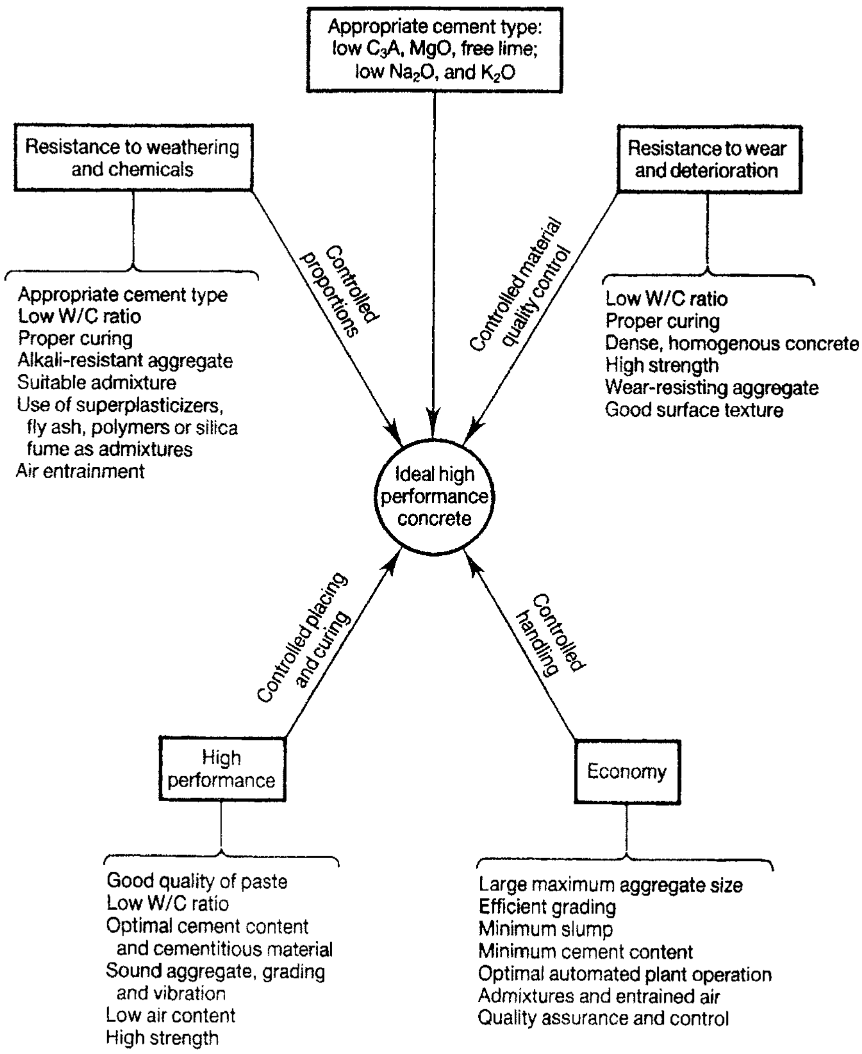

Figure 4 Principal parameters for high performance concrete [4]

The high rate of hardening and relatively high early strength after one, there or seven days enables the moulds and scaffolding to be removed earlier than in the case of ordinary concretes. That is an advantage which is used for quick re-use of moulds or for the reduction of traffic closures on structures being repaired. The fresh mix is also only exposed for a short time to possible adverse ambient factors.

In view of the large variety of possible compositions of HPC and of ambient conditions, the hardening process may develop differently depending on circumstances. That is why a detailed method of cure and the time delay for demoulding should be established following verification and observations in situ.

DURABILITY

Based on years of experience with ordinary concrete, we can safely assume that high performance concrete is more durable than ordinary concrete. Indeed, the experience gained with ordinary concrete has taught us that concrete durability is mainly governed by concrete permeability and the harshness of the environment.
It is easy to asses the harshness of any environment with respect to high performance concrete because hydrated cement paste is essentially porous material that contains some freezable water. Assessment involves simply examining how the environment affects each of these characteristics.
The durability of HPC are related to their composition and structure, characterized by a dense and strong matrix with good bonding to the aggregate grains and by an absence of excessive pores and other inhomogeneities.

The most important property of HPC is its improved durability thanks to the increased impermeability and homogeneity of the material's structure. Hydration products are in a higher degree amorphe than in ordinary concretes and capillar pores of 0.1 – 1.0 μm are considerably reduced or eliminated. Thus the material's resistance to different climatic actions and corrosive factors is enhanced. Increase capability to adopt alien (Cl^-, Na^+, K^+) and improve impermeability decrease the diffusion of chlorides improve resistance against the long-term action of sulphates and against alkali-aggregate reaction and related swelling.

The carbonation process in HPC is basically reduced because CO_2 cannot penetrate its dense structure. Accelerated tests executed showed practically no traces of carbonation. When silica fume is added as admixture for VHPC, the pH of concrete may decrease thus creating conditions more favourable for corrosion of steel-reinforcement. However, in that case the electrical resistance of the concrete is enhanced and consequently it will slow down the corrosion process.

The shrinkage of HPC develops differently than in ordinary concrete. A higher rate of autogenously shrinkage may induce additional stresses when free displacements are constrained at an early age. In contrast, drying shrinkage is less important because of the smaller amount of free water and the lower permeability of the matrix. The total strain due to shrinkage depends on the size of the elements and on the curing conditions, however, in most cases smaller values than for ordinary concretes were observed.

So-called plastic shrinkage may cause cracks in external layers of elements which appear immediately after casting. Such effects are related to local desiccation because of the dense structure of HPC and the low w/c ratio pore water does not migrate from the internal core of elements and the phenomenon of bleeding is absent. The only remedy is abundant moisturing of HPC at a very young age.

The evolution of heat during hydration of HPC should be considered carefully. The amount of heat depends on cement content and on the degree and rate of its hydration. The admixture of silica fume and low water/cement ratio result in a smaller degree of hydration and lower heat evolution. It is expected, therefore, that a smaller amount of heat is produced in HPC. However, appropriate measures should be prepared if necessary to lower the temperature of components, to evacuate heat and to allow for possible displacements, etc. furthermore, it should be bond in mind that for the appropriate action of silica fume lower temperatures are favourable. More research is needed in that area to quantify the effects of different material composition, methods of execution and ambient conditions.

On the other hand, it is not always simple to assess how easily aggressive agents will penetrate concrete. For example, water flow through a 0.70 w/c concrete is easy to measure, but water flow almost stops in a 0.40 w/c concrete, regardless of thickness of the sample and the amount of pressure applied. The gas permeability is also difficult to measure.

Despite all the criticism leveled at it, the so-called “Rapid chloride-ion permeability test” gives a fair idea of the interconnectivity of the fine pores in concrete that are too fine to allow water flow. Experience has revealed good correlation between the water permeability and rapid chloride ion permeability for concrete specimens with aggregate w/c greater than 0.40. Chloride-ion permeability is expressed in coulombs, which corresponds to the total amount of electrical charge that passes during the 6-hour test through the concrete sample when subjected to a potential difference of 50 volts.

When the rapid chloride-ion permeability test is performed on concrete samples with lower w/c, the number of coulombs passing through the sample decreases. It is easy to achieve a chloride-ion permeability of less than 1000 coulombs for high performance concrete containing about 10% silica fume and having w/c around 0.30. Much lower chloride-ion permeability values can be achieved if the w/c is reduced below 0.25. Values as low as 150 coulombs have been reported, far lower than the 5000 to 6000 coulombs reported for ordinary concrete.

The rapid chloride-ion test reveals that the connectivity of the pore system decreases drastically as the w/c decreases, making the migration of aggressive ions or gas more difficult in high-performance concrete than in its plain counterpart. The author believes that this is the best indication that the service life of high-performance concrete should exceed that of ordinary concrete cannot be readily extrapolated to include high-performance concrete. However, it can be said that some high-performance concrete structures will outlast the average life span of a human being in developed countries.

Photo 2 High performance concrete applied in construction at Viet Nam

ECONOMIC CONSIDERATIONS AND FURTHER DEVELOPMENT OF HPC

The economic questions concerning the application of cement-based composites have considerable importance for their development in various building and civil engineering structures.
The cost of HPC is not particularly high. On the contrary commercially available concrete of nearly 100 MPa costs significantly less that 3.5 times the price of ordinary 28 MPa concrete. Thus, more strength is obtained per unit cost and per unit mass, together with more stillness per unit cost and lower specific creep.
Furthermore, the specific cost of the material, calculated after the cost of components and execution, is only a small part of the total cost which also comprises maintenance costs of various kinds, including repairs, possible replacement, breaks in normal exploitation. Using high performance materials, smaller dimensions of structures are necessary and lower maintenance cost may be expected.

In the economic calculations the cost of increased control of all components and of high performance materials in subsequent stages of execution should be partly compensated by gains due to the lower mean values of their required properties. When variations of the material’s properties are reduced, then lower mean values may be designed and that aspect again allows a decrease in cost. Methods to evaluate the increase durability and other advantages of HPC are needed. These should be based on rational provision of repair and maintenance expenses during the lifetime of the designed structure. Without such calculations the investor will not be convinced that in many situations the use of HPC is the optimum solution.
Research in the field of optimization of the structure and composition of materials, is also aimed at improving the economic advantages of HPC.

Questions of economy determine the fields of application of cement matrix composites and that is the reason why ordinary concretes are still used and will continue to be used in the future for traditional plain and reinforced structures where high strength and improved durability are not necessarily required. Advanced composite materials are needed for special outstanding structures or for their specific regions, sometimes called “hot-points” like joints and nodes or for elements likely to particularly exposed to destruction.

CONCLUDING REMARKS

Notwithstanding multiple applications of HPC and VHPC, there are several important problems which should be studies further and in order that solutions may be found. These are:

- Optimization of mix composition for given requirements and conditions;
- New kinds of admixtures, microfillers and dispersed reinforcement;
- Application of lightweight aggregate;
- Thermal effects related to hydration of Portland cement;
- Possibility of decreasing the content of Portland cement
- Mechanical behaviour in various conditions, etc.

An effort is needed to further develop both structure designs with the application of HPC. Further work should be aimed at preparation of appropriate design codes and quantitative recommendations. Without any doubt, the trend towards improving the performance of concrete-like composites will also be developed in the further, corresponding to new needs in building and civil engineering structures.

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