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HIGH PEFORMANCE IN SITU CONCRETE: CHOOSING SUITABLE MATERIALS AND METHODS

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ABSTRACT

Concrete properties are known to closely tied to choices of materials and production methods. High performance concrete can be enhanced by choosing suitable materials and methods fulfilling performance indicators including strength, durability, workability, and dimensional stability. In this work, the main interests is to evaluate the influence of adding different mineral additives such as silica fume, nano silica, fly ash, and slag towards enhancement of performance. In addition, an evaluation is also made upon the impact of production methods towards performance indicators. The aim is to enrich our knowledge especially for in situ high performance concrete construction, especially from the perspective of concrete and admixture producers. The materials are all known to improve strength and durability but giving different effect in terms of workability. A relatively novel developement is the utilization of nano material of amorphous silica produced locally in Indonesia. The roles of compaction and curing are of paramount importance in producing high quality concrete. Concrete producers are aware that high quality mix materials alone cannot guaranty the production of high quality in situ concrete without proper curing and compaction. Maximum degree of compaction and sufficient curing period must be guaranteed in order to achieve a satisfactory result. The relative contributions of the two aspects of production and the materials are discussed for each of the performance indicators.

INTRODUCTION

Concrete members can be made in situ or precast, depending on the design and construction requirements or project owner preferences. The challenges and obstacles in building a concrete structure using in situ and precast concrete are different. While factors such as mix materials and design can be common in the two products, in situ concrete often requires more rigorous curing and placement methods in order to satisfy design requirements. Meanwhile precast concrete, being cured and placed in a controlled manner, tends to conform more easily to the same requirements. In many cases, when building a concrete structure, the risk of obtaining non-conforming concrete product is greater when using in situ concrete. The risk is even more pronounced when the structure is designed using high performance concrete or HPC.

It is generally recognized that in situ concrete offers versatility in geometrical shapes and is applicable for almost all types of detailing and joints. Meanwhile, precast product is limited to certain types of connection details, types of construction equipment and space which sometimes makes it difficult to conform to code requirements such as seismic provision.

In general, HPC differs from normal concrete or NC because the former is required to have high in situ strength and durability or permeability. Both of these are associated with porosity and hydration states. Either HPC or ordinary concrete properties rely on the maximum states that can be achieved through field curing and compaction. Concrete producers or contractors normally have some standard procedures developed from years of experience for placing and curing of ordinary concrete with satisfactory result, but not with HPC. It is the objective of this paper to highlight methods of designing and producing in situ HPC. From the material point of view, the emphasis will be on the utilization of standard mix materials that are common in many parts of Indonesia combined with the use mineral and chemical admixtures.

PRODUCER'S PERSPECTIVE

Benefits of Using HPC

Benefits of utilizing HPC on enhancing the performance include, Kosmatka et al (2011):

- Ease of placement and consolidation without affecting strength
- Long-term mechanical properties
- Early high strength
- Toughness
- Volume stability
- Longer life in severe environments

Other benefits may also include: use of less material, use of fewer beams/girders for bridges, weight to strength ratio comparable to steel, reduced maintenance, extended life cycle, improved aesthetics.

Usage of HPC had begun since as early as 1940s in Japan, in late 1980s in Norway. HPC have even become mandatory for bridge structures in some countries like United Kingdom, France, Germany, Japan and United States since 1990s. Economic benefits of using HPC for bridge structures include (FHWA, 2013):

- High compressive strength at transfer and high allowable tension at service stage.
- Maximum spans increased up to 45 percent
- Use of 15.2 mm strand for higher strengths.
- Strength of the composite deck had little impact.
- HSC allowed longer spans, fewer girder lines, or shallower sections.
- Maximum useful strengths:
  - ✓ I girders with 12.7 mm strand - 69 MPa
  - ✓ I girders with 15.2 mm strand - 83 MPa
  - ✓ U girders with 15.2 mm strand - 97 MPa

Production

Normally, schemes and equipment for producing, handling and transporting high performance/strength concrete are not much different to those used for conventional concrete. Some changes, refinements, and emphasis on critical points are usually necessary. Depending on the condition and capacity of the production facility and transportation fleet, some adaption may be required. Producers that are already dedicated to supplying quality concrete routinely should have few difficulties producing and delivering high-strength concrete.

It is generally accepted that high strength concrete (HSC) should be produced to the design water to binder ratio (w/b), not consistency. Consistency should only be adjusted using water-reducing or high-range water reducing admixtures. With the exception of controlled and pre-compensated amounts of wash water, no water whatsoever should be added to high-strength concrete once batched. All sampling and testing practices, whether for constituent materials or mixed concrete should be performed strictly according to applicable standards, which in most cases is stipulated in ASTM C 94, or similar standard specifications for ready- mixed concrete.

For producing HSC, batching plants with a central, stationary drum integral to the plant are preferable over the so called transit mix facilities that introduce the materials into a truck-mounted drum that provides all of the mixing action. This is does not mean that HSC cannot be successfully produced at a transit mix facility, just that a greater batch-to-batch variability should be anticipated. Central mix plants have one mixing drum operated by one individual. Factors that can influence batch-to-batch consistency when producing HSC include differences in mixing and agitation speed, number of revolutions during mixing and agitation, and mixer efficiency. Factors influencing the mixing efficiency of concrete drums include blade configuration, drum geometry and size, cleanliness, internal wear, and mixing capacity.

APPROACH AND METHODS

Overall, the approach in finding suitable materials and method for obtaining HPC can be subdivided into three tasks. First, is to establish some concrete performance measures as well as important parameters representing the production stages. The next task is to propose materials and mix design suitable for HPC. While there is a large body of literature on materials and mix design for HPC, we should opt to use commonly available materials and adopt rather simple mix design methods. The last task is to ensure that the right procedure is done in the field by proposing some technical specifications.

Characteristics of HPC

In a broader sense HPC can be considered as concrete in which certain characteristics are developed for a particular application and environments including: ease of placement, compaction without segregation, early-age strength, good long term mechanical and transport properties (compressive strength, elastic moduli, tensile strength, fracture toughness, permeability, durability), low risk of cracking, good dimensional stability.

Key features of HPC include usages of low water to binder ratio (w/b), optimal use of silica fume (and/or other mineral admixtures), smaller aggregates and fine sand, sufficient dosage of superplasticizers, occasional specialized treatments and application of pressure especially for ultra high strength concrete after mixing (at curing stage).

Performance measures and parameters that represent important aspects of HPC products can be studied by observing the macroscopic and microscopic behaviour including:

a) Mechanical and physical properties (compressive and tensile strength, modulus of elasticity, fracture toughness, resistance to abrasion & wear, porosity, density)
b) Transport properties (permeability, sorptivity, chloride and sulphate penetration resistances)
c) Dimensional stability (thermal, shrinkage and creep)
d) Workability

Tab. 1: Microstructural parameters and their roles

Microstructural Parameters	Role/effect	Macroscopic Behavior (NC)
Solid phase of hydrated paste (C-S-H gel)	Binder, load bearing	Strength, toughness, stiffness
Interface transition zone (ITZ)	Non uniform pores and hydration products	Strength, toughness
Capillary pores	Water filled space	Shrinkage, transport
Gel pores	Intrinsic pore in gel	Shrinkage, creep
Voids	Water filled space	Internal curing, shrinkage
Aggregate	Filler, load bearing	Strength, toughness, stiffness

Mechanical properties are responsible for high load bearing and mechanical resistance capabilities of RC or plain concrete members. Meanwhile, transport properties are tied closely to durability performance of concrete against penetrations of chloride and sulphate ions, leaching, etc. High stability against thermal, shrinkage and creep-induced deformations are desired for structural members to maintain their shapes and avoid additional stresses. In general, microstructure controls the macroscopic behaviour of hardened concrete (points a, b, and c above). Therefore, observing HPC microstructure will lead to enhanced understanding on how characteristic behaviour of HPC can be controlled. Workability is considered important as production and placement of well compacted and non-segregated fresh HPC require sufficient consistency and flow. Microstructural parameters and their roles are summarized in Table 1.

Concrete microstructure can be described in terms of hydrated cement paste or binder, pore systems and interfacial transition zone (ITZ), and aggregate/filler. Pores and their network can be interconnected or isolated. ITZ refers to the boundaries between the cement paste, and aggregates or particles of admixtures. The roles of these parameters are described in Table 1. Normal concrete or NC consists of cement, aggregate and water, and often without any mineral admixtures. Hydrated cement paste of NC is dominated by amorphous C-S-H gel, which is intrinsically porous, while its porosity is contributed by gel pores, capillary pores and voids. Furthermore, C-S-H gel is a low density phase which is space filling, but strength controlling. For concrete with strength below 50MPa, the increase in strength is primarily attained by reducing the capillary porosity alone. However, reducing the capillary porosity alone is not enough to generate a concrete strength above 50MPa. The gel porosity should also be reduced together with the capillary pores so that there is a substantial reduction in the total porosity of concrete. Further reductions in gel porosity require a change in chemistry to convert C-S-H to more crystalline phases, which eventually leads to the production of HPC (Buyukozturk and Lau, 2007, and Young, 2000). Other contributing factors to strength are of course the strength, toughness, texture, gradation and fineness of aggregates.

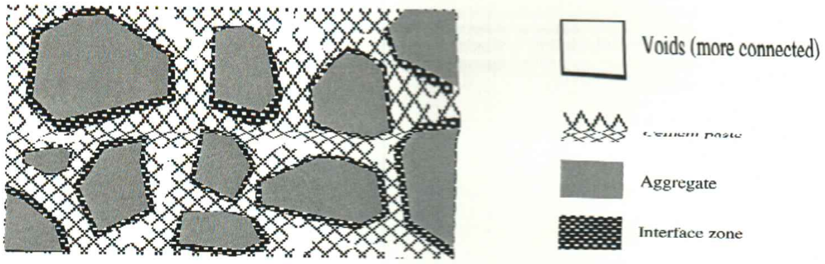

Fig. 1: Microstructure of normal concrete (NC)

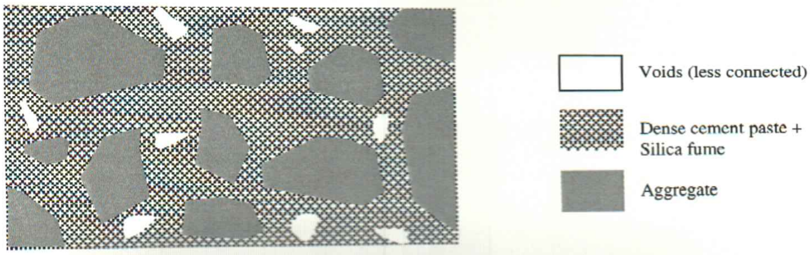

Fig. 2: Microstructure of high performance concrete (HPC)

While total porosity of the cement paste matrix has a great influence on the strength of concrete, the pore structure and its connectivity have a significant impact on permeability. A high permeability usually means low durability as the inner part of concrete is more readily to be attacked by surrounding chemicals. However, with a high permeability, the concrete can get a higher early strength using suitable curing process because continuous hydration can be carried out with the permissible flow of water within the pore network. The porosity and the pore connectivity of NC are usually higher than that of HPC due to the absence of fine particles (see Figure 2).

A zone adjacent to the surface of fillers such as aggregates and steel fibers, has a modified structure when compared to C-S-H gel. This is better known as the interfacial transition zone (ITZ). It is usually more porous than the bulk paste matrix as a result of poor packing of cement particles adjacent to the embedment surface. The higher porosity around ITZ is subjected to accumulation of water leading to a locally higher water-to-cement ratio in these regions (internal bleed water). Therefore, ITZ in NC may be weaker than other regions in the concrete system. In NC, ITZ is considered the weakest load bearing part. As a result, bond cracking along the boundaries of aggregates under external loading initiates from and propagates around ITZ.

In order to improve the concrete performance without disregarding the economical consideration, the following aspects are considered: (a) the hydrated cement paste should be strengthened, (b) the porosity in concrete should be lowered, (c) the interfacial transition zone should be toughened, (d) aggregates must be well graded, well textured and provide sufficient toughness, (e) workability must be improved to achieved higher degree of compaction, and (f) curing must be improved in order to allow maximum degree oh hydration. The first three aspects are evaluated one by one as follows. Corrective actions relevant to the aforementioned aspects can be found in Table 2.

According to Table 2, HPC with very fine admixture, such as silica fume or fly ash has denser hydrated paste and ITZ. The pore connectivity in HPC is also lowered because the very fine particles effectively block the capillary network. Thirdly, the interfacial transition zone can be toughened by lowering the locally high water-to-cement ratio and by improving the particle packing in this zone. The role of superplasticizer is to enable mixes with very low water-to-cement ratio (less than 0.25) to be adopted. Hence, its microstructure is quite different from that of NC. Figure 2 shows the microstructure of HPC.

Tab. 2: Corrective actions for HPC

Corrective Actions	Macroscopic Behaviour	HPC Paramater	Mechanism
Strengthening of hydrated paste	Higher strength & toughness	• Mineral admixtures (fly ash, silica fume and slag) • Fibre	• Mineral admixtures (fly ash, silica fume and slag) to reduce gel porosity • Adding fibre increases toughness
Lowering porosity	Improved durability and dimensional stability	• w/b • mineral admixtures • integral waterproofing agents	• lowering w/b reduces capillary porosity • Mineral admixtures tend to "disconnect" capillary pores • Integral waterproofing agents block entrance to pores
Toughening ITZ	Higher strength & toughness	• Mineral admixtures	• Mineral admixtures densify pores around ITZ
Improving aggregate quality	Improved dimensional stability, higher strength, toughness and durability	• Coarse aggregate and sand	• Good gradation and fineness give good compactness • Tougher aggregate improves strength and toughness
Improving workability	Higher compaction factor	• Superplasticizer • Water reducer	• Superplasticizer improves workability • Workable mix optimizes compaction
Improving curing	Higher achievable degree of hydration	• Curing compound, binder	• Achieving higher degree of hydration means more hydrated paste in concrete • Curing compound allows higher degree of hydration • Reactive binder allows for rapid hydration

Identifications of Materials and Mixes

There has been numerous studies conducted about HPC. Identifications of materials and mixes commonly found in HPC have been done using relatively recent studies. One such studies comprises compilation of large amount of data (Olek et al., 2002) and is included here. Other studies are also included and comparison is made, as given in Table 3. Essentially, the result from one study is quite similar to other. Materials commonly used, apart from Portland cement and aggregate, such as silica fume, fly ash, slag, superplasticizer, and water reducer, and their suggested quantities or proportions are identified. Note that some quantities such as binder content (350-400 kg/m^3) and aggregate content are not so different from normal concrete mixes. The water to binder ratio however is consistently lower than common normal concrete mixes, around 0.3.

Tab. 3: Characteristics of HPC

Mix Parameters	Suggested quantity	Properties (28-day)	Source
w/b	0.3-0.4	Comp. strength 75-100 MPa	Olek et al., 2002
Silica fume	10-20 % binder	Elastic modulus 35-40 GPa	
Fly ash	10-20 % binder	Chloride resistance 500-1000 Coulombs[7]	
GGBS[1]	35-40 % binder	Diffusion coeff. 0.5-1 m^2/sec (x 10^{-12})	
PC[2]	400-500 kg/m^3	Vebe 10-15 sec	
Binder[4]	350-400 kg/m^3	Slump 150-200 mm	
Water	150-175 kg/m^3		
Coarse aggregate[5]	1000-1100 kg/m^3		
Fine aggregate	700-800 kg/m^3		
Air	2 %		
w/b	0.37-0.39	Comp. strength 42-65 MPa	Issa *et al*, 2008
Silica fume	15-18 kg/m^3	Flexural strength 4.6-6.5 MPa	
Fly ash (Class C)	30-102 kg/m^3	Elastic modulus 29-37 GPa	
GGBS	47-51 kg/m^3	Drying shrinkage 390-560 micron	

PC	316-376 kg/m^3	1009-4122 Coulombs[9]	
WR[6]	2.28-12.25 L/m^3		
HRWR[7]	2.16-11.03 L/m^3		
Coarse aggregate	974-1127 kg/m^3		
Fine aggregate	511-766 kg/m^3		
w/b	0.232-0.3	Comp. strength 59-98 MPa	Perumal & Sundararajan, 2004
Silica fume	10 % binder	Flexural strength 8.3-10.9 MPa	
PC	408-563 kg/m^3	Elastic modulus 35-44 GPa	
Binder	453-625 kg/m^3	Porosity 1.95-2.2 %	
Water	139-142 kg/m^3	Sorptivity 0.021-0.014 mm/min$^{0.5}$	
Coarse aggregate	1070 kg/m^3	Compaction factor 0.83-0.92	
Fine aggregate	644-795 kg/m^3	Vebe 11-21 sec	
		Slump 24-55 mm	

1. GGBS: ground granulated blast furnace slag
2. PC : Portland cement
3. SF : silica fume
4. PC+SF is used the most
5. Maximum size limited to 19-25 mm
6. WR : water reducer
7. HRWR: high range water reducer
8. Rapid chloride permeability test ASTM C1202
9. At 56-day

It is noticed that the admixtures and the sand present in HPC are all very fine. The small sizes of these particles are essential in generating HPC. The basic concept of adding fine particles into the concrete mix is based on packing density theory. Effective particle packing depends on the relative size of particles and the number of different sizes (Gray, 1968). In principle, calcined clays, such as metakaolin, should be able to achieve dense packing configurations. However, these materials are not as effective because of their plate morphology, in contrast to the spherical morphology of silica fume particles.

In addition to the mix materials and compositions, the performance indicators recommended as representing HPC are also identified in Tab. 3. As seen, there are wide ranges of compressive strength, the highest being 75-100 MPa. The elastic modulus of HPC of around 35 GPa is seen higher than normal concrete mixes. Some of the recommended values such as the lower limit of chloride resistance (based on rapid chloride permeability test or RCPT) of around 1000 Coulombs is quite difficult to obtain.

Effect of curing condition must be appreciated as it controls the progress of hydration and thus, the amount of hydrated paste. It can influence:

1. Strength; difference between strengths of moist and constant room temperature- cured sample (representing ideal designed concrete mix) and sealed, in situ temperature- cured sample (field-cured concrete)
   - Field cured concrete have compressive strength 7-10 % less than designed concrete mix (Glover and Stallings, 2000).
   - Field cured concrete have compressive strength 0-11 % less than designed concrete mix (Missouri DOT, 1999).
2. Shrinkage: influence of age of exposure of cured concrete to drying shrinkage at certain relative humidity and temperature.

Properties of HPC can be predicted using the forms little different from those used for NC. For instance,

- Modulus of rupture: $f_r = 0.75\sqrt{f'_c}$
- Elastic modulus: $E_c = 3500 + 4300\sqrt{f'_c}$

Admixtures such as superplasticizer and water reducer play the roles of improving the workability of concrete mix and reduce the amount of water needed. Therefore, it enables the use of very low water-to-cement ratio. Adding superplasticizers allows to successful production of concrete having w/b as low as 0.2. Fly ash with suitable spherical morphology can improve the workability and, in some cases, permits reduction of w/b to 0.3. Fly ash also acts as the secondary binder, and concrete containing fly ash also develops a finely divided capillary pore system. Silica fume, which has a similar function as fly ash, is very effective in lowering the water-to-cement ratio needed for workable concrete in conjunction with superplasticizers because its sub-micron particle size allows it to pack between the cement grains (Kwan, 2000). The spaces between cement grains that would normally have to be occupied by water are now partially filled with other solid particles. This is the basis of castable densified with small particle (DSP) systems, which can have a water-to-cement ratio as low as 0.16 with a compressive strength more than 150MPa (Wise et al, 1985, Richard and Cheyrezy, 1995). In such a high strength concrete, the C-S-H gel method described in (Jonbi et al. 2012b) and also by adding the commercial nano silica product (Aerosil HDKN 20). The amount of nano silica added was 3, 5, 10, and 15% of initial amount of cement (or relative to 900 kg per m^3 concrete).

Tab. 5:

Materials	60R	80R	100R(a)	100R(b)
Cement type I (kg/m^3)	500	600	800	900
SF (kg/m^3)	75	120	120	120
Binder (kg/m^3)	575	720	920	1020
w/b	0.20	0.23	0.23	0.23
Sand (kg/m^3)	641	603	637	637
Coarse aggregate (kg/m^3)	1092	1119	1091	1091
Superlasticizer (lt/m^3)	3	3.6	4.8	5.4

The experimental investigation is focused on strength and durability properties. The results of compressive strength test, RCPT test, and water penetration test have been obtained for a total of 17 mixes containing nano silica. Some important correlations have been established, namely RCPT charge vs. compressive strength and water penetration depth vs. compressive strength as shown in Fig. 3 below. The strong correlations can be seen from relatively high regression number (R=0.595 and R=0.718). The plots in Fig. 3 have been added with zones indicating HPC class (shaded zone in grey blue). This zoning follows the classification suggested in Tab. 3. As seen, some mixes fall into HPC class when the compressive strength is above 75 MPa and RCPT charge of less than 1000 Coulombs (both evaluated at 28 days). Looking at this correlations, one can evaluate the concrete mix and taylor it to fulfil the requirement for HPC. About 70% of all mixes have been made using nano silica.

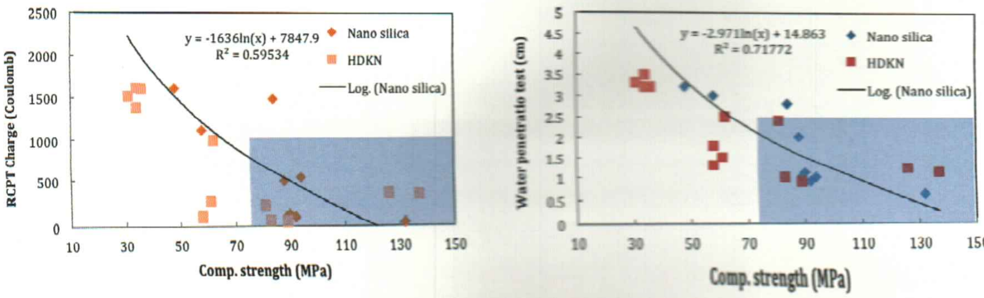

Fig. 3: RCPT charge and water penetration versus strength, and range for HPC

CONCLUDING REMARKS

This study has elaborated the characteristics of HPC and has classified or categorized its performance and mix parameters for the purpose of developing HPC product further. Efforts to achieve HPC like properties has been suggested and tables have been created as aid. The main findings are that HPC product exhibits a microstructure different from that of normal concrete. Finer pores and denser interfacial zone are among the characteristics of HPC microstructure. HPC can be achieved by ensuring good workability and hence, good compaction, optimal mix materials, and sufficient curing. It also relies on utilizations of admixtures such as superplasticizer to improve its workability, and silica fume and fly ash to improve its microstructure.

The development of HPC as also been attempted in this study. The basis of such development has been on utilization of fine pozzolans like silica fume and fly ash. This results in apparent improvement of concrete strength and durability properties. This study also shows that utilization of nano silica to produce HPC is potential and can be pursued further.

The requirements for curing HPC are likely to differ from those of normal concrete. HSC contains finer binders and thus, hydrates faster. Moist curing of minimal of 7 days is recommended. However, it remains to be further investigated whether a shorter moist curing can be applied to HSC containing finer binder. Another aspect that needs further investigation is whether curing period and conditions should be formed by conventional hydration reacts with silica fume at high temperature to form crystalline hydrate which is a dense phase without intrinsic porosity.

Specifications and Provisions for Production, Placement and Curing

Standards, specifications and codes of practice are probably not the most interesting subject for a book on advanced concrete technology. Standards, codes and specifications may take one of three approaches:

- Prescription-based
- Performance-based
- A combination of prescription and performance

The European Standard for concrete (EN 206-1, 2002) allows an essentially performance-based approach in the specification of designed concrete whereby the only information required to be specified comprises:

- Exposure class
- Compressive strength class (for structural purposes)
- Maximum nominal aggregate size
- Chloride content class (maximum permissible level of chloride in the concrete, as supplied)
- Consistency/workability class

Builder is recommended to implement a Quality Management Plan (QMP). Items addressed in a QMP should include: mix design properties, procedure for ordering concrete, various guidelines (for material handling, production, delivery, concreting under hot and cold weather, etc.), acceptance and rejection of fresh concrete, placement (compaction, finishing, and curing practices), various protocols (for material sampling, concrete sampling and testing).

A review of the predecessors to ACI 318-95 revealed that the general requirements for curing of concrete have changed very little since the first standard regulations were proposed in 1909 (Meeks and Carino 1999). The basic requirement has been to cure concrete made with normal portland cement for a period of at least 7 d and to cure high-early-strength concrete for at least 3 d. Tests reported by Price (1951) indicated that normal strength concrete that is moist cured for 7 d and then stored in air would attain approximately the same 28-day strength as if it had been continuously moist cured. These tests provide validation of the 7-day criterion in the ACI Code.

Since high-early-strength concrete will gain strength more rapidly, the Code permits a 3-day curing period. In the 1971 Code, a requirement was added to maintain the concrete temperature above 10 °C during the curing period. This addition is to ensure that sufficient strength development will occur during the prescribed minimum curing periods. In addition, a new provision was added for checking the adequacy of curing procedures based on strength tests of field-cured cylinders. Both requirements were carried over to the 1995 version of ACI 318 (ACI, 1995). The ACI Code, however, makes no distinction between strength and durability considerations with regard to curing requirements. Since ACI 318 deals primarily with structural safety, the provisions are intended primarily to ensure adequate structural capacity. The only explicit mention of durability in relation to curing is contained in the provisions (originally added in 1971) dealing with accelerated curing. It also does not address curing requirements for concretes made with other cementitious materials besides portland cement. Since the nature of the cementitious system affects early-age strength development characteristics, this omission may be a major deficiency in the current Code.

CASE STUDY

The case taken for study is the development silica fume concrete using local materials available in Indonesia. The work is detailed elsewhere (Jonbi et al, 2012a and Jonbi et al, 2012b) and is part of the dissertation work currently on progress by Jonbi. The goal here is to develop HPC mixes starting from some standard mixes utilizing silica fume as the mineral admixture. The observed properties include compressive strength and chloride resistance. The main idea is to develop mix design and to incorporate nano silica produced using local materials. Sand and silica was obtained from Bangka Island and coarse aggregate was from Rumpin. In addition, cement and silica fume were provided from respectively, Indocement and Sika. A process that involves liquid milling and polishing (Jonbi et al, 2012c) has been developed to enable production of nano silica. The result is silica powder relatively finer than commercial silica fume, comprising 50% or more particles of 70 nm size. Main concrete mixes made were listed in Tab. 5 below, where silciafume (SF) used is regular product available in Indonesia, e.g. Sika product. Additional mixes were made by modifications mixes 100R(b) by adding nano silica produced by the decided based on attainment of strength or other properties such as durability properties. As often indicated by research, the limit state of concrete performance may be governed by its durability rather than its strength.

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