CONCRETE DURABILITY AS INFLUENCED BY DENSITY AND/OR POROSITY

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ABSTRACT

The presence of capillary pores and air voids influences concrete permeability to a large extent. Concrete density is inversely proportional to its porosity. The ingress of aggressive agents into the pore structure is responsible for various durability problems in concrete structures. Therefore, a durable concrete should have low permeability. Permeability of concrete increases with the increase in porosity of concrete. Various factors such as water to cementitious materials ratio, degree of hydration, air content, consolidation, mineral admixtures, aggregates, reaction between aggregate and cement paste, pozzolanic admixture, etc., affect concrete porosity. The effects of these factors on concrete porosity and density are discussed in this paper.

Previous investigations relating concrete porosity to permeability, and other durability-related properties are also briefly addressed. Theoretical and empirical models representing relation
between porosity and concrete strength properties

are described.

INTRODUCTION

Concrete density depends upon volume fractions of constituent materials and their
densities, and the volume of voids present in the concrete. Concrete can be divided into two
major phases at a macroscopic level; these are coarse aggregates and matrix (i.e., mortar,
hydrated cement paste and sand). Each of these phases is also a composite material. The
region between the aggregates (coarse or fine) and hydrated cement paste (hcp) is more
porous than the hcp; and, it can be considered as a third phase at a microscopic level.

The aggregate phase is largely responsible for the unit weight and dimensional stability
of concrete. These properties are dictated by bulk density and strength of the aggregate.
The volume, size, and distribution of pores present in the aggregate control
these properties to a large extent. In order to produce dense concrete, the porosity of the
aggregate should be kept low. The shapes and sizes of the aggregate can also influence concrete properties. Classification of aggregates is done according to size, bulk density, or source. The coarse aggregates are composed of particles greater than 4.75 mm, and fine aggregates contain particles of less than 4.75 mm. Based on bulk density, coarse aggregates are classified into three categories: normal weight aggregate (1520 to 1680 kg/m$^3$), lightweight (1120 kg/m$^3$), and heavyweight (above 2080 kg/m$^3$).

Coarse aggregates are relatively more impermeable than the hydrated cement paste. The hcp is composed of solids and voids. The major solids are crystals of calcium silicate hydrates (C-S-H), calcium hydroxide (Ca(OH)$_2$), calcium sulfoaluminates (C$_6$AS$_3$H$_32$), and unhydrated portland cement clinker grain. The volume occupied by these crystals varies from 50 to 60% for C-S-H, 20 to 25% for Ca(OH)$_2$, and 15 to 20% for calcium sulfoaluminates of total volumes of solids in a completely hydrated cement paste (Mehta 1986).

The C-S-H crystals (C-S-H gel), being the major component of solids, play a great role in influencing concrete properties. The solid-to-solid distance between the C-S-H layer (gel pore) is found to vary between 5 to 25 Å (1 Å = 10$^{-5}$ mm). Due to their size and very
low interconnectivity, these pores are relatively impermeable to water. However, water removal from these pores can influence drying shrinkage and creep behavior of concrete (Mehta 1986). Compared to C-S-H crystals, greater pore sizes are observed between the solid of Ca(OH)$_2$ and calcium sulfoaluminate crystals.

Capillary voids, voids created by water particles movements and space not occupied by solid components, are known to make a major contribution to porosity of the concrete. The size of capillary voids is much larger at the interfacial zone (i.e., the region at the interface of the aggregate and the hcp) compared to the bulk cement paste. The size of capillary voids can range from 10 to 50 nm (1 nm = 10$^{-6}$ mm) in low water to cementitious materials ratio pastes while for high water to cementitious materials ratio paste, capillary pores are relatively larger (up to 3 to 5 $\mu$m). Additional concrete porosity results from both entrapped and entrained air voids. Entrapped air voids (as large as 3 mm) are larger in size compared to entrained air, 50 to 200 $\mu$m, (1 $\mu$m = 0.001 mm). The dimensional ranges of solids and voids are shown in Fig. 1.

Both capillary voids and air voids influence concrete impermeability and strength to a
large extent. Fluids can flow more easily through large capillary pores and air voids compared to gel pores found in the solid crystals. The voids/flaws present in the concrete reduces the mechanical strength of the concrete due to the stress concentration effects. Thus, porosity of concrete composed of large pores has detrimental effects on both impermeability and strength of the concrete.

Concrete durability-related properties are known to be negatively affected due to expansions that result from factors such as freezing and thawing actions, alkali-aggregate reactions, sulfate attack, corrosion of the reinforcement, etc. Such expansions depend, to a large extent, upon ingress of water, gases, and aggressive chemicals into the concrete; which, in turn, depend upon permeability (which depend upon porosity). Therefore, permeability of concrete can be used as a measure of concrete durability. Thus, porosity affects can be related to concrete durability.

**FACTORS AFFECTING CONCRETE POROSITY/DENSITY**

For given constituent materials, the porosity of the hcp depends upon several factors
including the following:

1. Water to cementitious materials ratio.
2. Degree of hydration.
3. Air content.
5. Admixtures.
6. Aggregates.
7. Reaction between aggregate and cement paste.
8. Mixture proportioning.

**Water to Cementitious Materials Ratio**

For a given cementitious material content of a concrete mixture, the space occupied by the hydration product increases with increasing water content. However, the volume of the hydration product will remain constant irrespective of the water content of the mixture at a particular degree of hydration. Consequently, unfilled spaces, i.e., gel pores and capillary voids,
will increase with the increase in water to cementitious materials ratio. Therefore, an increase in water to cementitious materials ratio will cause an increase in porosity and a decrease in density of concrete.

In a freshly mixed concrete, water films are formed around the aggregate. As a result, a higher water to cementitious materials ratio is present in the interface region compared to the bulk cement paste. This condition also favors formation of larger crystals of calcium hydroxide and ettringite. This results in a higher porosity and lower density in the interface region relative to the bulk cement paste. Also, in such regions, the crystals of Ca(OH)$_2$ tend to form oriented layers, with the C-axis perpendicular to the aggregate surface. A general schematic description of the interfacial zone formation is depicted in Fig. 2.

Degree of Hydration

The degree of hydration increases with age. Both gel pores and capillary pores volume and pore size decrease with an increase in the degree of hydration due to the formation of increased amounts of hydration products. This leads to improved (i.e., denser) microstructure
of the concrete. In order to obtain improved internal structure of concrete, adequate curing
conditions should be maintained. A combination of relative humidity, time, and temperature
should be selected so as to obtain denser microstructure and to avoid microcracking of concrete.

**Air Content**

In order to ensure freezing and thawing durability of concrete, adequate entrained air
voids are provided. An increase in air content (either entrained or entrapped) causes increase

**Consolidation**

Compaction of freshly mixed concrete allows elimination of entrapped air pockets and
placement of concrete at a low water to cementitious materials ratio. Compaction/consolidation
also decreases capillary pores. Consequently, proper compaction causes reduction in porosity
and increase in density. This effect is more pronounced in the interface region where packing
of cement particles is inefficient.
Admixtures

Inclusion of reactive pozzolanic additives such as fly ash, slag, silica fume, natural pozzolans, and rice husk ash improves concrete microstructure. This happens due to the densification of the microstructure that occurs as a result of the production of pozzolanic C-S-H.

The use of pozzolanic additives is essential for densification of the interface region, in production of high-strength and/or high-performance concretes. Use of high-range water-reducing admixture (HRWRA), also called superplasticizer, results in the production of the desired consistency of the concrete at a low water to cementitious materials ratio for a given water content. This causes reduction in the amount and size of gel and capillary pores. As a result, a denser concrete microstructure is produced, which in turn, improves concrete strength and impermeability. Therefore, HRWRA is needed in production of high-quality, high-strength, and/or high-performance concretes.
Aggregates

The size and shape of coarse aggregates can affect concrete microstructure to a large extent. In general, an increase in the maximum size of aggregate or amount of flat particles tends to increase the amount of water in the vicinity of the aggregate. As a result, the water distribution in the mortar matrix becomes non-uniform. This occurs due to bleeding and the wall effects around aggregates that prevent packing of cement grains of large size (10 \( \mu m \) or more). Therefore, shape, size, and amount of flat aggregates permitted should be judiciously selected to avoid increase in porosity or decrease in density of concrete.

Reaction between Aggregate and Cement Paste

Chemical composition of the aggregate can influence the porosity of the interface region (Bentur and Odler 1996). When the aggregate (e.g., calcite and dolomite) reacts with the
cement paste, formation of compounds such as carboaluminates or calcium carbonate-calcium hydroxide complex occurs in the interface region. This can result in increased density and decreased porosity of the interfacial region of concrete.

Effect of Mixture Proportioning

The mixture proportioning plays a significant role in packing of cement particles near the interface region. In general, a low water to cementitious materials ratio and a high aggregate/cement ratio promotes packing of cement particles in the interfacial region (Scrivener and Pratt 1996). Improved packing results in decreased porosity of concrete and increased density of concrete.

PREVIOUS INVESTIGATIONS

In accordance with ACI Committee 201, durability of concrete is defined as its ability
to resistant weathering action, chemical attack, abrasion, or any other process of deterioration.

This means that a durable concrete will maintain its original form, quality, and serviceability when exposed to various environmental conditions. The movement of water or other fluids through concrete can carry aggressive agents which create various types of durability problems for concrete construction. In fact, permeability controls the rate at which aggressive agents such as gases (CO$_2$, SO$_2$, etc.) and liquids (acid rain, sea water, sulfate rich water, salt-bearing snow/water, groundwater, etc.) can penetrate into concrete. Therefore, in order to avoid permeation of these agents, permeability of concrete must be reduced by decreasing porosity and/or increasing density of the concrete.

**Effect of Porosity on Concrete Permeability**

In general, permeability decreases with an increase in porosity up to a certain level, and then the influence of porosity on permeability is negligible. A strong correlation between porosity and permeability is reported by a number of investigators (Powers, et al. 1954; Naik,
et al. 1993; Naik, et al. 1996; Mehta 1986; Massazza 1996). Researchers (Powers, et al. 1959; Costa and Massazza 1985) have indicated that when volume fraction of porosity is less than 35%, the permeability becomes negligible. The same trend was also observed by Mehta (1986) at a porosity of 30%. This may be attributed to the fact that at a low porosity, there is a large reduction in size and amount of capillary pores, and interconnection between them.

Concrete porosity is maximum at the interfacial region of concrete (Fig. 2) A relation between permeability and capillary porosity is presented in Fig.3.

A variation in paste permeability and porosity with time is shown in Fig. 4. A large number of studies (Ozyldirin and Halstead 1988; Naik, et al. 1992; Thomas and Mathews 1992; Torii and Kawamura 1992; Naik, et al. 1993; Bilodeau, et al. 1994; Naik, et al. 1996) have reported decreases in permeability of concrete due to inclusion of pozzolanic admixtures. The decrease in permeability was attributed to improvement in the concrete microstructure, especially in the transition zone.

Incorporation of reactive pozzolans such as fly ash, natural pozzolans, silica fume, and rice husk fly ash causes both grain and pore refinements. This occurs primarily due to
production of pozzolanic C-S-H and efficient packing of cementitious materials particles, leading to improved concrete microstructure. An increase in reactive mineral admixture may or may not decrease total porosity. But it decreases the fraction of total capillary pores with increased discontinuity between pores (Young 1988; Marsh, et al. 1985; Moukwa 1993)

Due to slow pozzolanic reaction of many fly ashes, a greater curing time is required for fly ash concrete compared to concrete without fly ash. The beneficial effects of curing temperature on the pozzolanic reactions of fly ash and slag has been observed in the past (Naik, et al. 1993; Naik, et al. 1994 a,b,c) In general, concrete permeability decreases with increasing strength (Fig. 5). Naik, et al. (1996) reported optimum cement replacement with fly ash in the range of 35 to 55% with respect to air, water, and chloride permeabilities. At a very high replacement of cement with fly ash, concrete microstructure was adversely affected due to the dilution effects. Silica fume is a more efficient pozzolanic material than natural pozzolans or fly ash. Consequently, lower amounts of silica fume can be used to obtain the beneficial effects of pozzolanic reactions (Naik, et al. 1994c ); however, at a possibly increased cost of the concrete. An optimum dosage of silica fume should range between 5-10% of the total
cementitious materials for improving concrete impermeability with favorable economics.

The use of chemical admixture in cement-based materials results in changes in pore size distribution (Manmohan and Mehta 1981; Young 1988). Generally, addition of high-range water-reducing admixture (HRWRA) reduces water demand for a given consistency of fresh concrete. This, in turn, reduces size of capillary pores and total porosity of the concrete. Consequently, permeability of superplasticized concrete is lower compared to unsuperplasticized concrete. The incorporation of calcium chloride enhances amount of fine capillary pores in cement paste (Manmohan and Mehta 1981). This causes reduction in permeability of cement-paste.

Other Durability-Related Properties

A few investigations have attempted to establish a relation between porosity, strength, and durability-related properties. Brunauer (1965) observed a non-linear relationship between
compressive strength and density (Fig. 6). In general, as expected, compressive strength increased with density. A linear relation between compressive strength and log of porosity has been reported for up to 700 MPa of cement pastes (Fig. 7). One percent increase in porosity causes a reduction in concrete strength in the 5 - 6% range (Massazza 1996).

Due to relatively high porosity of the interfacial zone compared to other regions, it becomes a weak link in the concrete structure. As a result, concrete strength and durability-related properties are dictated by the properties of the interface region to a marked extent. In order to improve concrete durability, it is essential to improve strength and durability of the interfacial region. In general, attempts have been made to improve properties of the interfacial region through the use of mineral additives and chemical admixtures. Recent investigations (Naik, et al. 1994 a,b; Gjørv 1994) have shown reduction in the size of interface through the use of mineral additives and HRWRA at a very low water to cementitious materials ratio.

A special class of concrete, called high-performance concrete (HPC), is proportioned
to eliminate the negative effects of the interfacial regions. This type of concrete is made with very high quality constituent materials, and requires special mixture proportioning and production technique. A number of investigations by Naik and his co-workers (Brand 1992; Patel 1992; Naik, et al. 1994 a,b,c; Olson 1994; Beffel 1995) and others (Aitcin, et al. 1987; De Larrand, et al. 1990; 1987; Gjorv 1994) have been directed toward development of HPCs for strengths ranging between 50 and 150 MPa. These concretes have exhibited excellent durability properties, including high resistance to freezing and thawing, alkali-silica reaction, abrasion, chloride-ion penetration, etc.

MODELS RELATING STRENGTH PROPERTIES AND POROSITY

It is well accepted that mechanical and elastic properties of solids are adversely affected by the presence of pores or voids in the materials (Mackenzie 1950; Krstic and Erickson 1987;
Pani and Niyogi 1987; Wang 1987). Mackenzie (1950) was probably the first to propose theoretical models for the shear and bulk modulus for solids containing spherical holes.

These models are written as:

\[
G_o = G \left[ 1 - 5 \frac{3K + 4G}{9K + 8} V_{vo} \right] \\
K_o = \frac{4KG (1 - V_{po})}{(4G + 3V_{vo} K)}
\]

where \(G_o\) and \(K_o\) are shear modulus and bulk modulus of porous solids, and \(G\) and \(K\) refer to shear and bulk moduli of non-porous solids; and \(V_{vo}\) is the volume fraction of voids present in the solid.

Several empirical models are available for describing elastic modulus of solids. Most widely used models are polynomial in form, containing one or more material constants (Krstic and Erickson 1987; Phani and Niyogi 1987; Wang 1984). A generalized form is expressed as:
\[ E = E_0 \exp \left[ -(aP + bP^2 + cP^3 + \ldots) \right] \]

where \( E \) and \( E_0 \) are the elastic moduli at porosity \( P \) and zero, and \( a, b, c, \ldots \) are material constants. Several forms of the above model representing modulus relation with porosity are summarized by Phani and Niyogi (1987).

Sereda, et al. (1980) reviewed various models that represent relation between strength and porosity of hardened paste. Three most commonly used regression models (Uchikawa and Okamura 1993) are:

1. \( S = S_0 \cdot (1-P)^h \) (Balsin's formula)

2. \( S = S_0 \cdot \exp(-BP) \) (Ryshkewitch's formula)

3. \( S = C \cdot \ln \left( \frac{P_{cr}}{P} \right) \) (Schiller's formula)
Where \( S \) = strength; \( S_o \) = strength at zero porosity; \( P \) = porosity; \( P_{cr} \) is zero strength porosity; \( A, B, \) and \( C \) are regression coefficients.

Akyüz, et al. (1993) developed a mathematical model to relate compressive strength with porosity or water/cement ratio (W/C). The model is of the form:

\[
f'_c = M_1 \left( 1 - \left( (1 - P)^{1+\theta_1 c} \right)^{2/3} \right)
\]

or

\[
f'_c = M_2 \left( 1 - \left( (1 - P)^{1+\theta_1 \left( \frac{W}{C} - 0.25 \right)} \right)^{2/3} \right)
\]

where \( M_1 \) and \( M_2 \) are constants which represent the theoretical compressive strength of concrete with zero porosity, \( c \) is the capillary coefficient, \( \theta_1 \) and \( \theta_2 \) are constants, and \( P \) is porosity.

The results of this investigation are depicted in Fig. 8 and 9.

SUMMARY
Concrete is a hybrid particulate composite material. It is composed of three major phases: particles (coarse aggregates), matrix (hydrated cement paste (hcp) and sand, mortar), and the interfacial region between aggregate and the hcp. The aggregates are less permeable compared to the hcp. The interface region between the hcp and aggregate is more porous and weak compared to the other two phases. Furthermore, each of these phases at a microscopic level can be treated as a multiphase material.

Concrete porosity is inversely proportional to its density. Concrete porosity is affected by a number of parameters, including water to cementitious materials ratio, degree of hydration, air content, consolidation, admixtures, aggregates, reaction between aggregate and the hydrated cement paste, mixture proportioning, etc. Of these, the water to cementitious materials ratio and degrees of hydration (curing) are the most important parameters that affect concrete porosity and thus concrete density. An increase in water to cementitious materials ratio increases porosity.

For production of low porosity in concrete, a low water to cementitious materials ratio with optimum curing is used. An increase in compaction reduces porosity. The size of
aggregates should be reduced to minimize creation and to decrease the amount and size of the interfacial region in concrete. The amount of flat aggregate should be minimized/avoided because it contributes significantly to the amount of weaker interfacial region. The introduction of pozzolanic additives, such as fly ash, natural pozzolans, slags, rice husk ash, and silica fume, cause refinement of grain and pore structures, especially in the interfacial region. Concrete permeability increases with an increase in porosity and decrease with an increase in density. For achieving high durability, concrete porosity should be kept low so as to reduce its permeability. A very high impermeable concrete will reduce or eliminate ingress of water and other aggressive chemicals and gases. This will lead to improved concrete durability due to avoided expansive reaction that can occur in presence of these aggressive agents. Various theoretical and empirical models can be used to evaluate the effects of porosity on concrete strength properties.

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