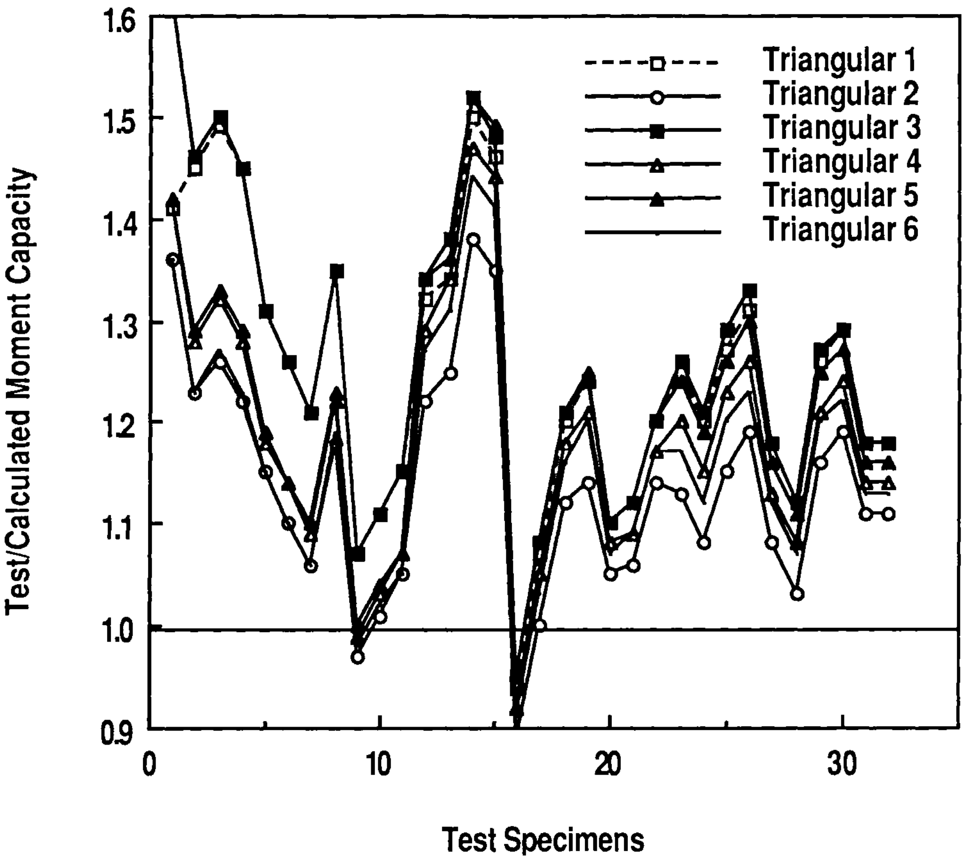

Fig. 7--Flexural strength predicition by triangular stress blocks

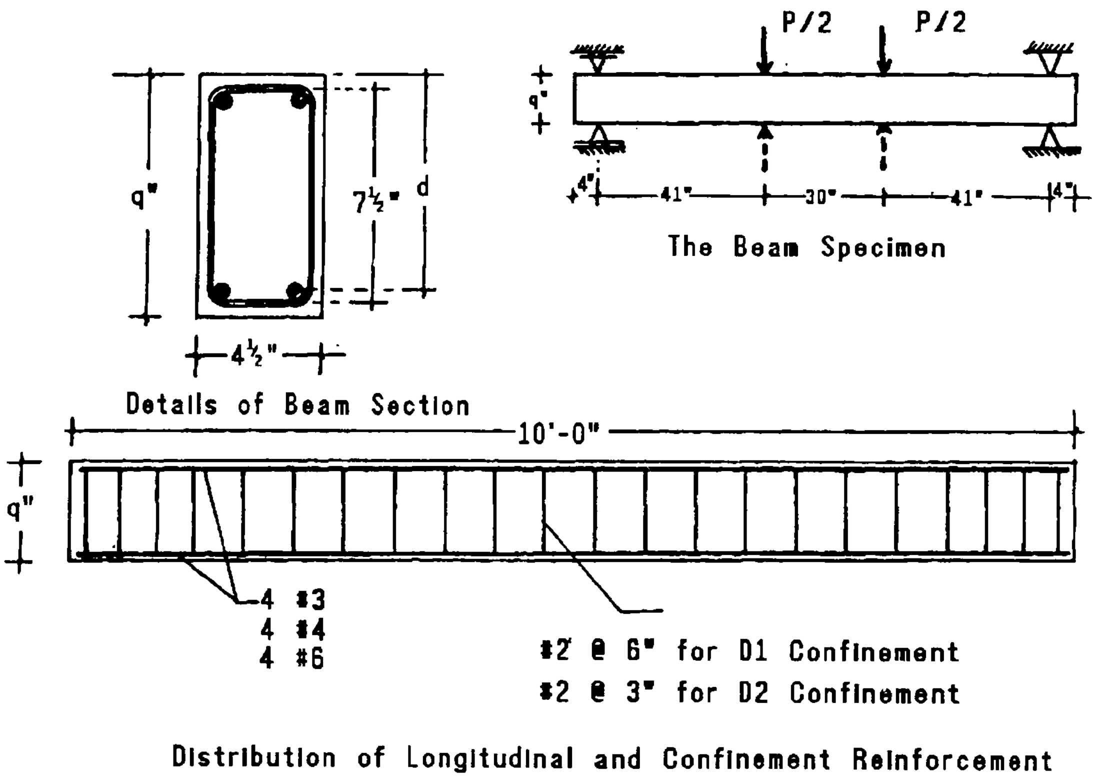

Fig. 8--Reversed cyclic loading test setup

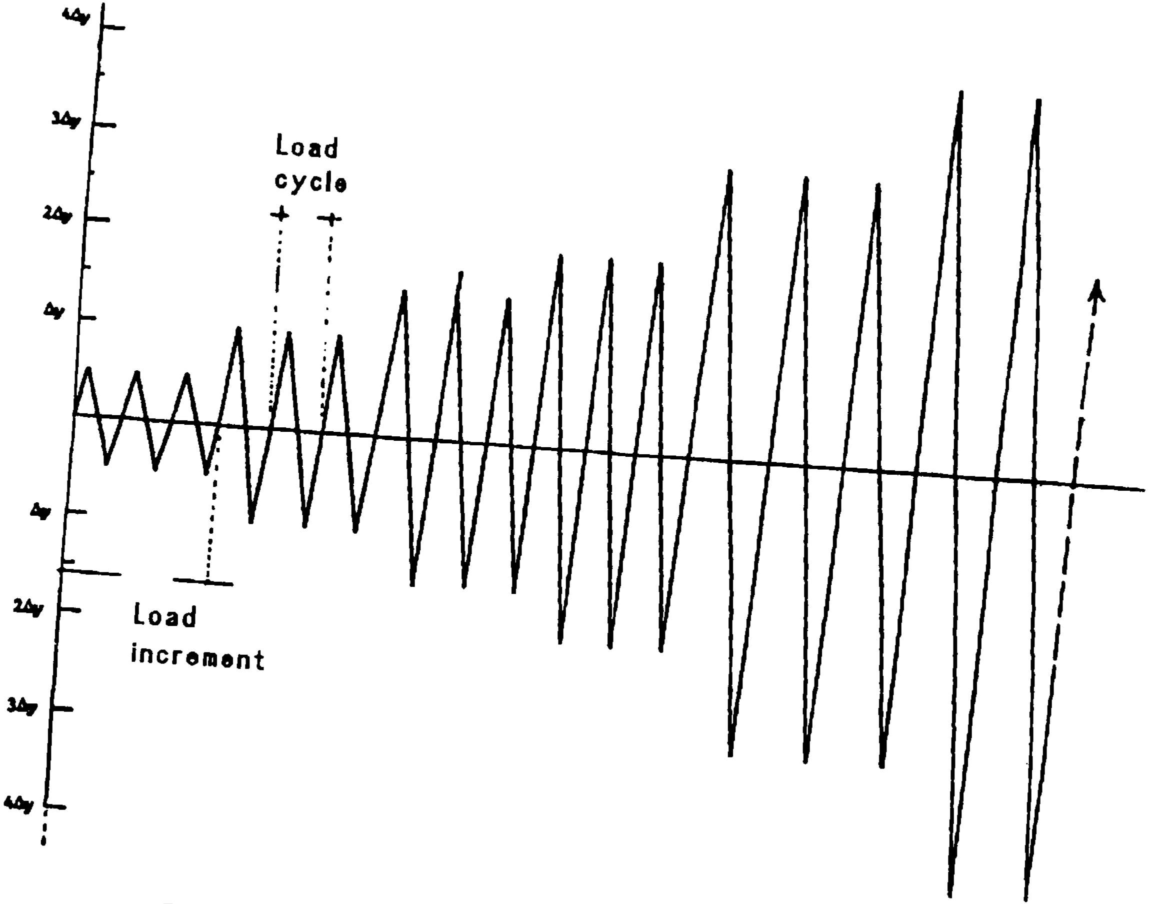

Fig. 9--Deformation sequence for reversed cyclic loading tests

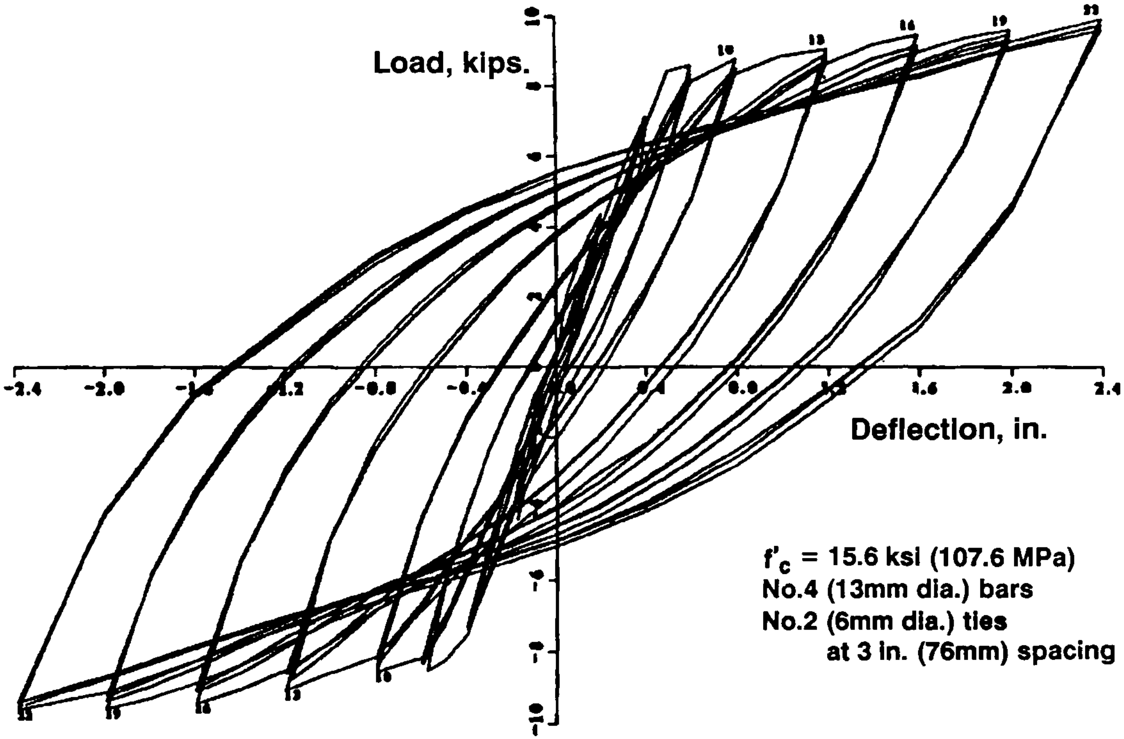

Fig. 10--Hysteretic load-deflection curve of specimen tested under reversed cyclic loading

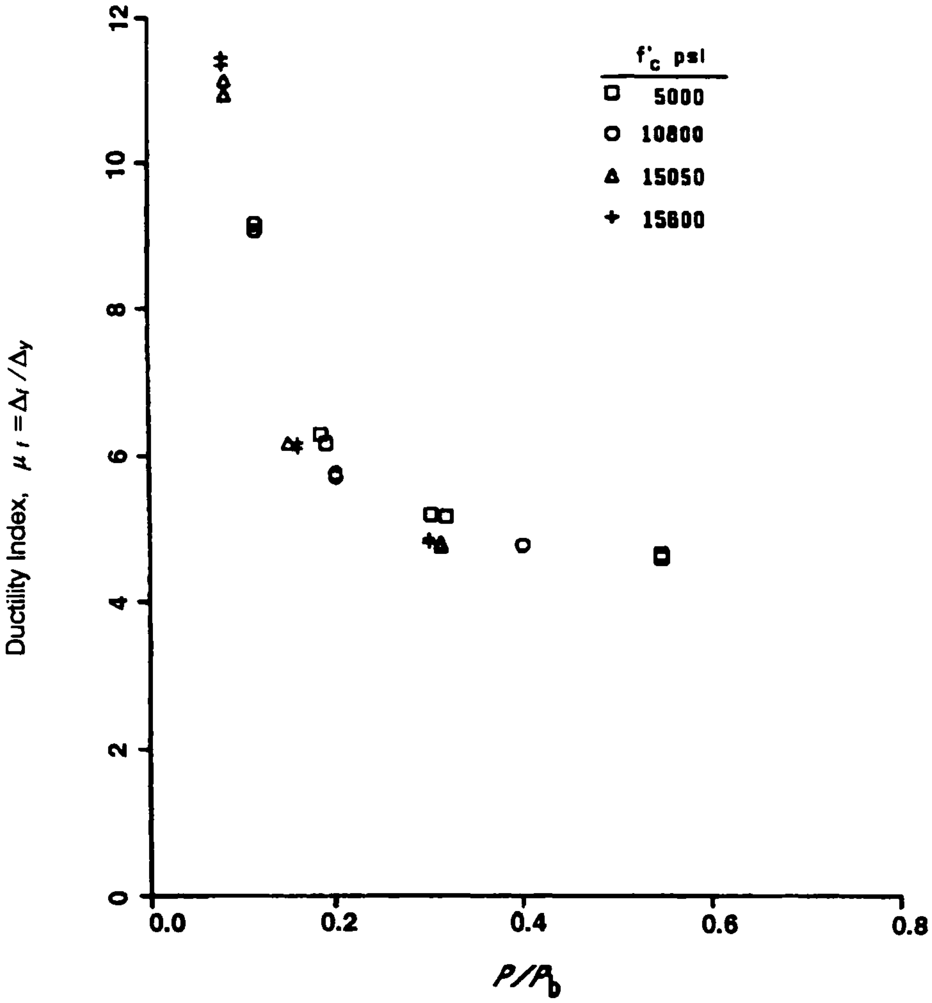

Fig. 11--Flexural ductility, as defined by Eq. (3), under reversed cyclic loading - upward deflection

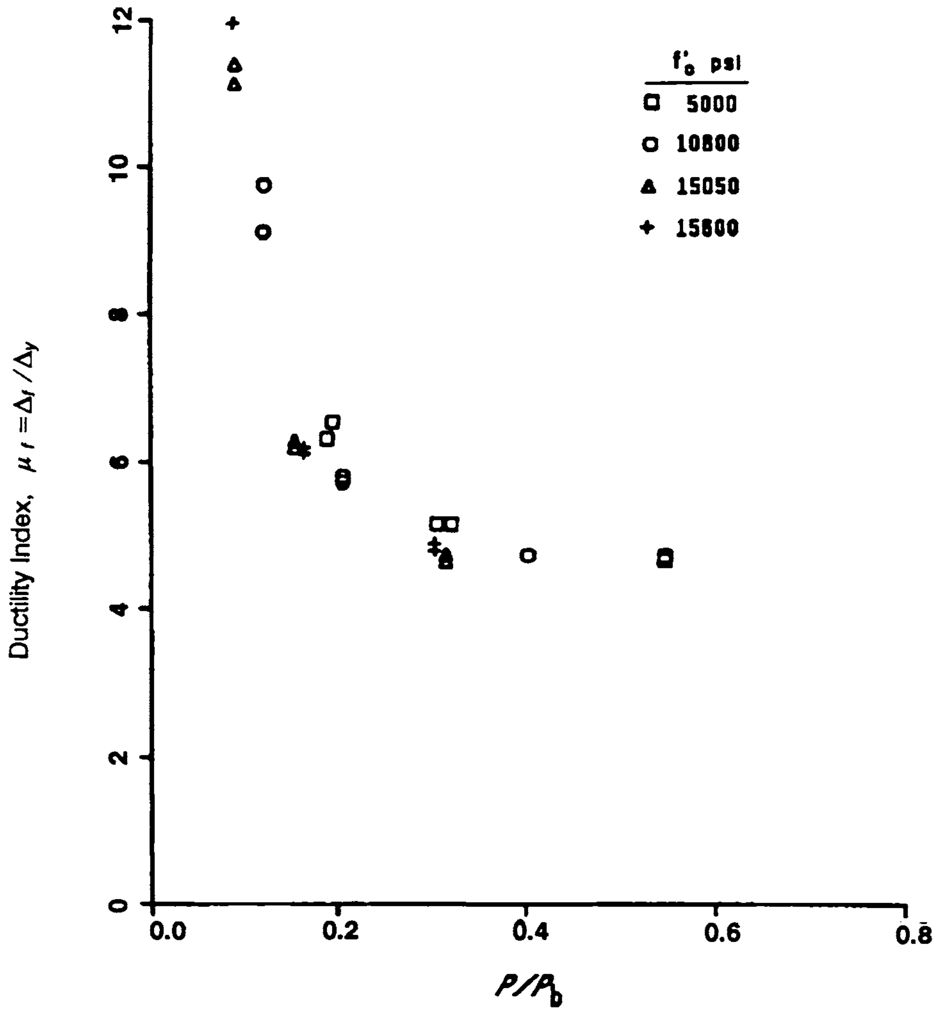

Fig. 12--Flexural ductility, as defined by Eq. (3), under reversed cyclic loading - downward deflection

SP 121-14

Microstructural Basis of Selection of Materials and Mix Proportions for High-Strength Concrete

by P. K. Mehta and P. C. Aitcin

Synopsis: During the 1980's, the use of high-strength concrete has gained wide acceptance. The materials and mix proportions for making high-strength concrete are selected empirically by extensive laboratory testing since there are no accepted procedures, such as the ACI method of proportioning normal concrete mixtures. For someone who, for the first time, would like to make high-strength concrete from local materials, the problem is complicated by the fact that a variety of newly developed chemical and mineral admixtures may have to be incorporated simultaneously into the concrete mixture. The published literature has enough information on the new admixtures but is essentially of little help in selecting the type and optimum dosage of these admixtures.

In this paper, the authors have attempted to address the problem of selection of materials and mix proportions for high-strength from a microstructural standpoint. Principles underlying the strength of brittle solids are discussed and important features of concrete microstructure, which influence the strength, are described. Microstructural considerations are used as a basis for the selection of materials and for establishing guidelines that are helpful in the development of a simple procedure for concrete mix proportioning.

Keywords: admixtures; aggregates; C_3A; high-strength concretes; microcracking; microstructure; mineral admixtures; mix proportioning; plasticizers; strength; workability

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INTRODUCTION

Most structural concrete elements are made with 20 to 40 MPa* concrete. However, for a variety of reasons, the use of high-strength concrete is gaining wider acceptance for some applications. In 1965, a 50 MPa concrete was industrially produced for the first time in the United States for making columns of the Lake Point Tower building in Chicago. Again in Chicago in 1970's, a 60 MPa concrete was used for fabricating columns of 28 lower stories of the 79-story Water Tower building and a 75 MPa concrete was used in River Plaza. A 100 MPa concrete was used in 1982 in the Chicago Mercantile Building and more recently one experimental column at 225 W. Wacker Dr. in Chicago, reportedly contains 117-MPa concrete. During the 1980's, some high-rise buildings in New York and Texas contained structural members made with 50-80 MPa concrete. The Nova Scotia Plaza building in Toronto and the Two Union Square building in Seattle contain 95- and 120-MPa concrete elements, respectively.

It may be noted that the high-strength concretes mentioned above were made with industrially available materials, using conventional concreting practice. Reports in the published literature show that using synthetic materials, such as an aggregate composed of carefully graded particles of calcined bauxite, and special processing technology (viz. thermal curing and pressure), concrete specimens with up to 260 MPa compressive strength have been produced in the laboratory.

High-strength concrete mixtures are generally characterized by low water/cement ratio, high cement content, and presence of several admixture types, such as water-reducing, set retarding, and mineral admixtures (viz. fly ash, ground blast-furnace slag, and condensed silica fume). From the literature review it is concluded that the materials and mix proportions are selected empirically by extensive laboratory testing. This means that for someone who, for the first time, would like to make high-strength concrete from locally available materials, there are no guidelines similar to the ACI 211 Recommended Practice for Selecting Proportions for concrete mixtures. How then should one proceed to determine the approximate quantities of cement, water, coarse aggregate, fine aggregate, and the type and dosage of water-reducing admixtures as well as mineral admixtures for the first trial batch?

In this report the authors have attempted to address the question of making of high-strength concrete mixtures from a fundamental standpoint. General principles underlying the strength of brittle solids, such as concrete, are discussed. Important features of the concrete microstructure that are relevant to high strength are described, and guidelines for selection of materials are given. Finally, a simple

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*Unless otherwise specified, the term "strength" is used to describe the 28-d uniaxial compressive strength of standard-cured, 100 by 200 mm concrete cylinders.

approach for proportioning of high-strength concrete mixtures is proposed. Using this approach, it is determined that the recommended mix proportions for the first trial batch compare well with the accumulated field and laboratory experience of many reseachers.

PRINCIPLES GOVERNING THE STRENGTH OF BRITTLE SOLIDS

Microstructure-property relations are at the heart of modern materials engineering. Due to the highly complex microstructure, such relations are not fully developed for concrete. However, fundamental principles governing the behavior of brittle solids such as ceramics, which show certain microstructural similarities to concrete, can be usefully applied to control the microstructure and properties of concrete.

The porosity dependence of the tensile strength of single-phase crystalline materials is generally expressed by the exponential relationship: $S = S_o e^{-bP}$, where S is the tensile strength of the material which contains a volume fraction porosity P, S_o is the intrinsic tensile strength at zero porosity, and b is a factor depending on the size and shape of pores. Studies involving microstructure-strength relations in ceramics have shown that, besides porosity, **grain size and presence of inhomogeneities** are the other important factors which control the tensile strength.

The compressive strength of brittle materials is much greater than the tensile strength because in tension the material can fail by rapid propagation of a single flaw or microcrack. Since a number of tensile cracks must coalesce together to cause a compressive failure, in compression much more energy is needed for the formation and extension of the microcrack system. Assuming the compressive failure to be a multiple of several tensile failures, the Griffith tensile fracture theory and concepts of continuum mechanics can be used to predict that the compressive strength of a homogeneous ceramic is eight times the tensile strength. Besides this, there has been no attempt to specifically derive a theory of the microstructural dependence of compressive strength of porous materials. However, from empirical compressive strength studies many researchers have reported that the experimental data can be fitted to the equation: $C = C_o(1-P)^m$, where C is the compressive strength of the material containing the volume fraction porosity P, C_o is the intrinsic compressive strength at zero porosity, and m is a factor depending on intercrystalline bonding in the solid, shape and size of pores or flaws, grain size, and presence of impurities. In general, **compressive strength decreases with increasing pore size** and **increases with decreasing grain size.**

According to Rice (1) another interesting observation from microstructure-property relations in ceramics is that, while most other properties are more closely related to averages rather than the extremes of the microstructural components, **strength and fracture depend critically on microstructural extremes rather than averages.** In other words, fracture, especially in compression, is a weak-link type process; therefore, in addition to the number, size, and shape of pores, their spatial distribution or local concentration is a major factor in failure. The ceramic literature contains numerous examples of fracture origins definitely initiating from regions of unusually high porosity (1).

In conclusion, the strength of non-metallic, brittle, crystalline solids can be improved by paying close attention to the following principles:

- Porosity: A large number of big pores or voids (viz., > 50 nm), especially when concentrated in one location, are detrimental to strength.
- Grain Size: In general, the strength of a crystalline phase increases with

decreasing grain size.

- Inhomogeneities: With multi-phase materials, the microstructural inhomogeneities are a source of strength loss.

MICROSTRUCTURE OF CONCRETE AND ITS EFFECT ON STRENGTH

For the sake of simplicity, concrete may be viewed as made up of two components, namely 65-75% aggregate and 25-35% cement paste by volume. Since the aggregate phase exercises an important restraining influence on the drying shrinkage and creep characteristics of hardened cement paste, its proportion in a concrete mixture cannot generally be reduced below about 65% without adversely affecting the dimensional stability of the concrete member.

For reasons of cost economy, natural sand and gravel or crushed rock are generally used as concrete aggregates, which consist of multimineralic particles of widely varying porosity and strength. The strength of individual aggregate particles, usually as large as 50 mm in ordinary concrete of 20-40 MPa strength, is primarily controlled by the size and distribution of pores, and presence of flaws such as microcracks and inclusion of weak minerals (e.g., clay and shale). Fine-grained igneous rocks (e.g. basalt) and dense sedimentary rocks (e.g. limestone and certain siliceous gravels) are examples of natural materials that are the general sources of high quality aggregate (typically 100-200 MPa crushing strength).

Microstructural examination of fractured samples of ordinary concrete shows that hydrated cement paste, which is the continuous phase in the two-component system, is generally the weaker component. A closer examination reveals distinct microstructural differences between the bulk cement paste in concrete and the cement paste in the transition zone--a region approximately 50-100 μm thick which lies in the immediate vicinity of the coarse aggregate particles. As will be discussed later, hydrated cement paste in the transition zone is usually characterized by high porosity and large size crystalline hydration products. From the microstructural standpoint it is helpful, therefore, to consider hardened concrete as made up of three phases, namely aggregate, bulk cement paste, and the transition zone. This is because, being the weakest element of the system, the transition zone exercises a great influence on concrete strength. Therefore, microstructure-strength relations for the hydrated cement paste and for the transition zone are separately discussed next.

The Hydrated Cement Paste

The anhydrous portland cement consists of calcium compounds which are unstable in water. When cement particles, typically 1-50 μm, are mixed with water, in the beginning the hydration takes place through solution, i.e., the liquid phase becomes saturated with various ionic species which later combine to form different products of hydration, such as calcium sulfoaluminate hydrates, calcium silicate hydrates, and calcium hydroxide. Since the products of hydration are relatively insoluble, they begin to crystalline out and start filling the space originally occupied by water, as shown diagrammatically in Fig. 1. At any point during the hydration process, the unfilled space will consist of voids or capillary pores. With increasing hydration and decreasing capillary porosity, the moisture movement in the system becomes sluggish. The subsequent hydration of the unhydrated portions of large cement particles is believed to be a slow process by solid-state reactions.

Scanning electron microscopic studies have shown that the early hydration products formed when there is plenty of water and empty space in the cement-water system, consist of flocs of large crystals, which tend to entrap a considerable