RELATING THE STRUCTURE OF CONCRETE TO MECHANICAL BEHAVIOUR

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Synopsis

In recent years a considerable degree of effort has been employed on understanding the mechanism of hydration, the resulting morphology of the hydrated products of cement and the overall structure of concrete. The aid of transmission electron microscopy and scanning electron microscopy have been fairly successful in proposing a mechanism for the hydration of cement.

A fair understanding of the structure of concrete has enabled to explain the strength of concrete in terms of fracture mechanics parameters. The toughness, slow crack growth, stress-strain characteristics and the effect of water/cement ratio on tensile strength can be thus explained.

1. Introduction

It is a well-known fact that even though concrete has been in use for a very long time and in very large quantities little is still known about its structure compared with equally popular materials such as steel.

Failures of concrete structures are not too many but when a failure occurs it leads to enormous expense. It is very often difficult to identify the exact cause, i.e. whether it is the fault of the material itself or of poor designing practice. However, one very good example of a case in which the cause has been identified is high alumina cement. In this case sudden failures of structures were chiefly due to material itself. At the beginning of the century high alumina cement was used in order to obtain high early strength. This material was used at first without proper understanding of its structure. Recent studies have revealed that the structure of high alumina cement paste changes with time, often accelerated by certain environmental conditions. The transformed structure gives rise to a porous material with low strength. This case serves as a good example to illustrate the importance of scientific understanding of the structure of concrete and its relation to strength.

A substantial degree of research on concrete has been carried out at a phenomenological level. In order to improve an existing material or develop a new material, the use of ad hoc methods, even though they may lead to limited success in some cases, most often lead to enormous wastage of resources, in terms of both human effort and money. However, with the increased knowledge of the structure of concrete it is now possible to direct research more scientifically and less empirically.

2. Structure of Concrete

Knowledge of the structure of materials plays a vital role in understanding its behaviour. It can be viewed on an atomic, microscopic, or macroscopic scale. Since concrete is a multiphase material with differing size fractions, it may be that its macrostructure controls the strength. Nevertheless, knowledge of atomic and microstructures are essential in the understanding of the overall structure of concrete, as they will certainly influence the macrostructure.

Concrete can be considered as a composite with its aggregates bonded by a cement paste which acts as a matrix. Therefore the structure of cement paste must be first examined before dealing with the overall structure of concrete.

2.1 Structure of Cement Paste

Only in recent years has any considerable degree of effort been employed on understanding the mechanism of hydration and the resulting morphology of the hydrated products of cement. The work of Doubble and Hollawell (1, 2) who, with the aid of transmission microscopy, have been fairly successful in proposing a mechanism for the hydration of cement.

The chemistry of the changes that take place during hydration of cement is fairly well known. The main
product of hydration is calcium silicate hydrate (C-S-H) which is referred to as cement gel. This compound is only partially crystalline and may be considered amorphous. About 70 per cent of cement paste consists of this gel. The second major compound present is calcium hydroxide, about 20 per cent, which is crystalline. The chemical reactions are given by

\[ C_2S + H_2O \rightarrow CHS + Ca(OH)_2 \]
\[ C_3S + H_2O \rightarrow CHS + Ca(OH)_2 \]

Dicalcium silicate (C₂S) and tricalcium silicate (C₃S) are the main constituents of cement. The other hydrated products that are likely to be present are ettringite and calcium aluminate monosulphate hydrate, which are both crystalline. Cement paste will also contain the unreacted cement.

Any model which attempts to describe the mechanism of hydration must necessarily tie the sequence of events observed in the hydration process. During the setting of cement there is a sudden rise of temperature at the beginning which increases gradually to a peak and finally tails off exponentially at long time intervals. This is due to the exothermic nature of the reaction.

The sudden rise of temperature or the release of heat at the beginning of hydration can explain the formation of the gelatinous coating around the cement particle. This layer will now inhibit the reaction of cement inside with water outside, hence the reaction is a diffusion-controlled one. This leads to a "dormant" period corresponding to the gradual increase of temperature. The rate of reaction starts increasing after about 3 hours and reaches a peak after about 8 to 10 hours of hydration, corresponding to the peak temperature. During this period the second stage of the reaction commences. First, the initial coating of gel is broken through at many points on the coating to form protrudes (see Figure 1). These protrudes grow into fibrils and lend to a network of intertwining fibres of adjacent cement grains. This network forms a rigid matrix (cement gel) which bonds aggregate and unreacted cement. Figure 2 shows a scanning electron micrograph of a fracture surface showing a network of cement gel fibres. Such observations are also noted by others (3, 4). Double and Hallawell (1, 2) showed that the morphology of the gel fibres consists of hollow tubes. These tubes show no faceted appearance—a common feature observed in crystal growth of metals from aqueous solutions—thus confirming the amorphous state of hydrated gel. A parallel to the above behaviour is the formation of "silica gardens" when aqueously soluble salts such as Co(NO₃)₂ is brought into contact with sodium silicate solution.

Calcium hydroxide is precipitated during the formation of cement gel. Figure 3 shows a scanning electron micrograph of a fracture surface showing hexagonal platelets of calcium hydroxide which is consistent with its crystal structure. The platelets correspond to the basal planes and are also the cleavage planes for the calcium hydroxide structure. Since calcium hydroxide cleaves easily, the strength of cement paste is controlled to a great extent by its presence. On the other hand, in concrete, the proportion of calcium hydroxide is too small to control its strength.

2.2 Pores and Cracks in Concrete

The strength of concrete depends very much on the size of pores and cracks present in it. The network of fibrils is surrounded by water, hence the spaces containing water fall into two types: capillary and gel pores.
Capillary pores are referred to as original water-filled spaces in the fresh concrete, while within the gel itself there exist interstitial voids, which are termed gel pores.

The total porosity in the hardened cement paste depends on the initial water/cement (w/c) ratio and the degree of hydration. It is known (5) that one volume of cement when fully hydrated produces 2.68 volumes of gel. By knowing the volumes of other hydrated products it is possible to obtain the minimum amount of water at 100% hydration so that all the hydrated products occupy all the water-filled spaces in the cement paste. Such a process is not, however, practically possible since it becomes increasingly difficult for hydration to take place. Because of this reason and also of the necessity to have a 'workable' mix higher w/c ratios are generally used in the preparation of concrete. It must be noted that the higher the w/c, the greater the amount of water-filled spaces in the final hardened structure. This means that we expect a lower strength from cement pastes with high w/c ratios.

Pores also result when concrete is badly compacted. It must be emphasised that poor compaction leading to about 5 percent voids (air trapped inside) can reduce the concrete strength by about 50 percent (6). Bleeding can produce voids in concrete. In this instance the rising water can get trapped on the underside of a coarse aggregate, producing large voids in the hardened concrete.

There are a number of ways in which cracks can originate in concrete but in this paper the discussion is restricted only to the important ones, i.e., due to the shrinkage of concrete. Cracks are present even prior to loading, at the interface between the coarse aggregate and cement paste. These are due to the shrinkage of cement paste. Shrinkage results due to the drying of cement paste. When water evaporates from gel pores there is an increase in the Van der Waals forces which draws the paste structure together, giving rise to shrinkage. Since the aggregates themselves do not shrink and if the bond between the cement paste and aggregates is maintained, then shrinkage of cement paste is inhibited. Thus it produces an interface stress which when exceeds the bond strength will produce large shrinkage cracks at the interface. Plastic shrinkage in fresh concrete can also produce surface cracks but this effect is usually very small.

3. Strength and Toughness of Concrete

3.1 Fracture Toughness

Tough materials are generally preferred to brittle materials in constructional work. Therefore it is important to estimate the fracture toughness parameter for this system in order that it can be compared with the values for other materials. Kaplan (7) was one of the first to apply fracture mechanics to studying the fracture of concrete. If fracture mechanics principles are applicable, then strength can be related to flaw size. In the case of concrete because of the aggregates, the system must be treated similar to a composite.

Of the flaws that are likely to control the strength are large voids resulting from entrapped air, capillary pores and shrinkage cracks. Capillary pores are of the order of 1.5 µm and are usually interconnected. The size of shrinkage cracks depend at the matrix aggregate interface is obviously limited by the size of the aggregate. The path of crack propagation in concrete is usually along the cement-aggregate interface.

When a fracture toughness test is performed on a monolithic brittle solid, the material fractures in a catastrophic manner once the load reaches a critical value. However, in concrete, because of its complex structure, slow crack extension prior to application of final failure load is observed. This is a characteristic phenomenon in concrete. The coarse aggregates help in arresting catastrophic crack growth. The toughness increases with the increase in the proportion of coarse aggregates in concrete.

Subsidiary cracks, or branching of cracks from the original cracks can occur, or the crack may circumscribe the aggregate particles. It therefore means that the effect of slow crack growth leads to higher toughness values. The reason for higher toughness values being observed in concrete compared with mortar, and in mortar compared with cement paste should now become clear.

The onset of cracking in cubic specimens subjected to uniaxial compression showed that it takes place at about 35 percent of the ultimate load. In the case of flexural testing it takes place at about 70-80 percent of the ultimate load. These results were obtained by an ultrasonic testing device.

3.2 Effect of w/c ratio

The water/cement ratio has been a convenient parameter for characterising concrete. The fact that the strength decreases with increasing w/c ratio may be explained by Griffith’s theory of crack propagation (8). The tensile strength, \( \sigma \), can be expressed in the form

\[
\sigma = \sqrt{\frac{2EY}{\pi a}}
\]

where \( E \) and \( a \) are Young’s modulus, work of fracture and semi-crack size respectively. \( Y \) is a geometric factor which depends on the specimen geometry. For an infinite body in tension \( Y = 1 \).

The effect of \( Y \) is difficult to calculate but one may estimate intuitively that it is most probable that with greater density of the gel net work at lower w/c ratios, the work of fracture may increase. If, on the other hand, there were not a network of fibrillar gel but a monolithic mass, then \( Y \) would depend mainly on the surface energy component. \( E \) too increases at lower w/c
3.3 Stress-Strain Curve

As a direct result of the slow crack growth phenomenon, the stress-strain curves of concrete and, to a lesser extent, mortar specimens, under load, show inelastic behaviour. This is most obvious in compression testing and, to a lesser extent, in flexural testing. A typical stress-strain curve is shown in Figure 4. It must be noted that the additional strain due to creep is not considered. The unloaded curve is shown by the broken lines. In practice the unloading curve does not come back to the origin, due to creep and structural damage. The reasons for the curvature in the loading curve is due to slow crack growth. If there was no crack growth during loading, then the curve is a straight line. In other words the compliance of the specimen changes during the slow crack growth period.

4. Concluding Remarks

The structure of concrete is discussed at three levels: atomic, micro and macro. Due to the presence of a number of phases in concrete, it has been difficult to relate the structure to the strength, even though an attempt is made in this paper. The influence of pore size distribution, the interconnection of pores, and the presence of interfacial cracks between the aggregate and cement paste matrix on the strength should be better understood in order to propose a mechanism of failure. Then it may be possible to develop, on a scientific basis, a new type of concrete with better properties. It must be mentioned that lack of understanding of the structure of high alumina cement concrete led to many disasters. This emphasises the fact that it is essential to understand the structure of a new material before it is used on a wide-scale.

References