Fracture Mechanics of Concrete Structures
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REDUCTION IN STRENGTH IN HIGH STRENGTH MORTARS AT LONG AGES

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Abstract

The development of strength of mortars with an exremely low water:cement ratio was investigated, being related to the characteristics of microstructure of them. A considerable reduction of strength occurred in the mortars at long ages even when the mortars were continuously cured in water. Microcracks were found in mortars along with the decreases in microhardness in the cement paste matrix during the periods. However, the mortars showed no shrinkage. A mechanism of deterioration of the hardened cement paste phase at microscopic scale seems to lead to the reduction in strength at long ages in the high strength mortars. Delayed interaction between unreacted cement particles and diffused water might be responsible for the degradation of ultra high strength mortars.

Key words: high strength mortar, microcracking, microhardness, late hydration

1 Introduction

For the past decade, concrete technology has greatly progressed, e.g. the development of high performance concrete. At the present, concretes with a strength greater than 100 MPa is used at practical construction sites. Such a high performance concrete is expected to have good performances in durability as well as mechanical properties compared to conventional concrete.

Properties of concrete are generally closely related to its characteristics of microstructure, especially to the pore structure of mortar matrix (Mehta and Aitcin 1990). Various strength characteristics and durability of concretes can be interpreted from the features of microstructure in the concretes. High strength in concrete attained by reducing water:cement ratio results from the formation of very dense microstructure. However, the lack in water for the completion of cement hydration in concrete with an extremely low water:cement ratio results in conspicuously different microstructure from that in normal strength concrete. In such a case, the relationships between the microstructure and mechanical properties established in conventional concrete may not be simply applied to the system of ultra high strength concrete. Therefore, it is significant to reveal the relationships between long-term strength and characteristics of microstructure formed in ultra high strength cementitious materials.

The objective of this study is to precisely pursue the development of strength of mortars with an extremely low water:cement ratio. Durability problem in the ultra high strength system is discussed with a mechanism of alteration of the microstructure formed in the mortars.

2 Experimental

2.1 Materials and mix proportion of mortars

The cement used was ordinary Portland cement. Fine aggregates used were natural river sand and high - carbon ferrochromium (FCr) slag which is a by-product of ferrochromium alloy. Physical properties of these aggregates are given in Table 1. A commercial silica fume with the specific surface area of 20.0 m^2/g and SiO_2 content of 90.8% was used. Superplasticizer was of

Table 1. Physical properties of aggregates

	Density(g/cm^3)	F.M.
River Sand	2.64	2.49
FCr Slag	3.09	3.36

Table 2. Mix proportion of mortars

W/C (%)	Cement	: Silica Fume	: Fine Aggregate	Superplasticizer (% wt. Binder)	Type of Aggregate
24	1	: 0	:1	4	River Sand
24	0.9	: 0.1	:1	4	River Sand
24	0.9	: 0.1	:1	4	FCr Slag

the polycalboxylic acid type. Mix proportions of the mortars are given in Table 2.

2.2 Mechanical strength tests

2.2.1 Compressive strength

Cylindrical specimens with 50 mm in diameter and 100 mm in height were cured in water at 20℃ up to 182 days immediately after demolding. At the prescribed ages, compressive strength test was carried out according to JSCE G505-1995.

2.2.2 Flexural strength

40 × 40 × 160 mm prisms were prepared and cured under the same condition as the specimens for compressive strength test. Flexural strength test of three-point bending was carried out according to JIS R 5201.

2.2.3 Compact tension test

Compact tension specimens (Fig.1) were produced. Splitting force was given to the specimens by wedge loading at prescribed ages. Fracture toughness was calculated using Eq.(1).

$$K_{eff} = \frac{P}{B\sqrt{W}} Y(\frac{a}{W}) \qquad (1)$$

where the shape factor Y(a/W) given in a handbook, was used.

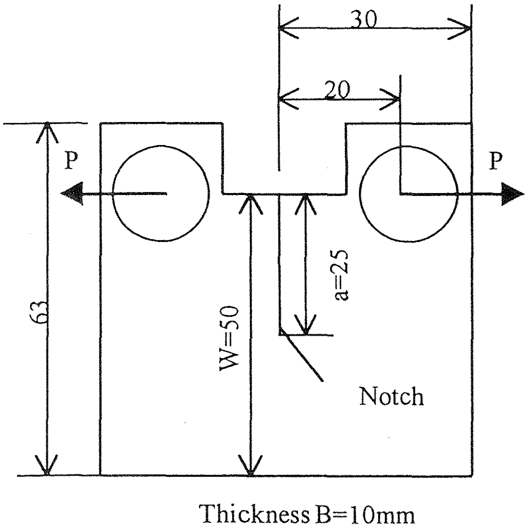

Fig.1 Compact tension specimen

2.2.4 Microhardness test

Small prismatic specimens,

30 × 30 × 20 mm, consisting of the cement paste of 90% and aggregate of 10% by volume were produced for this test. These specimens were stored at the same curing condition as the specimens for other mechanical strength tests. At the prescribed ages, a slice was cut from the portion up to the depth of 5 mm from the surface of specimen using a low speed diamond wheel saw. The surface was polished with silicon carbide paper and diamond slurry. Microhardness in the interfacial zone around aggregate particles and the bulk cement paste phase were measured by the use of the Vickers testing apparatus.

2.2.5 Fluorescence microscope examinations

The same cylindrical specimens as the compressive strength test were produced and cured in water. At the prescribed ages, a disk with about 10mm in thickness was cut out from the middle of a specimen. The disk was placed in ethanol for at least 24 hours, and then was impregnated with the epoxy resin containing a fluorescence dye. After the resin hardened at room temperature, the specimen was polished with a SiC paper and diamond slurry for fluorescence microscopy.

2.2.6 Shrinkage test

Gauge plugs were attached to the end of mortar prisms of 40 × 40 × 160 mm. The initial length of mortar prisms was measured immediately after demolding. Those specimens were cured in water at 20℃.

3 Results and Discussion

3.1 Time-dependent changes in mechanical strength of mortars

Fig.2 shows the compressive strength of mortars with and without silica fume. Silica fume-bearing mortars, particularly FCr slag mortars have a greater compressive strength than silica fume-free mortars until the age of 28days. Greater compressive strength of FCr slag mortar can be attributed to the greater bond strength due to pozzolanic reaction and the improved mechanical interlocking of the slag particles (Igarashi et al. 1997). Taking into consideration for the less water available for the reaction of silica fume at an extremely low water: cement ratio and the early ages, such a higher compressive strength in the silica fume-bearing mortar suggests the microfiller effect of silica fume in the development of strength in the mortar (Goldman and Bentur 1994). Namely, extremely fine particles of silica fume may fill the small voids of rough surfaces of

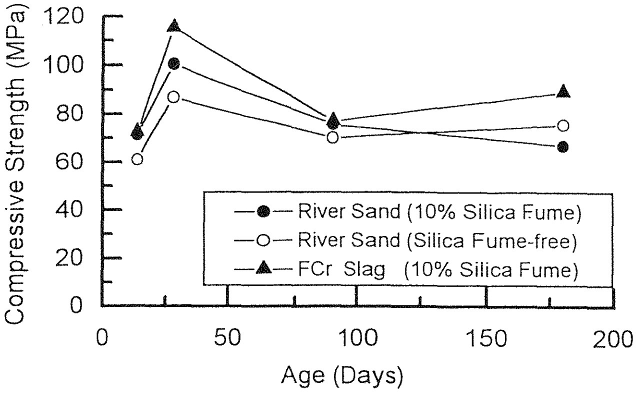

Fig.2 Compressive strength of high strength mortars

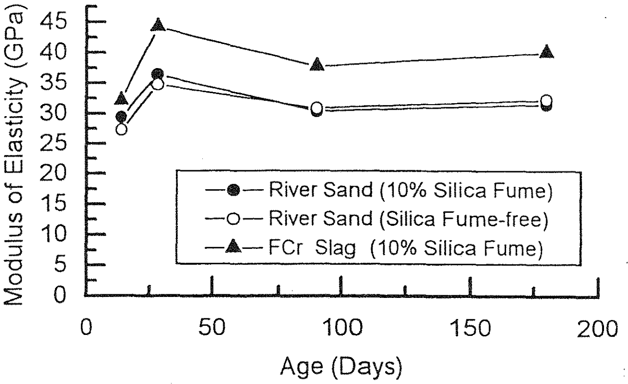

Fig.3 Modulus of elasticity of high strength mortars

the FCr slag particles so that the bond between the reinforcing particles and the matrix is effectively increased. However, the compressive strength of those mortars remarkably decreased during the period of 28 to 90 days. The improvement in strength by silica fume was almost lost at long ages. Fig.3 shows the modulus of elasticity of the mortars measured at the compressive strength test. There is little difference in modulus of elasticity between the river sand mortars with and without silica fume. On the other hand, modulus of elasticity of FCr slag mortar was much greater than that for river sand mortars because of harder slag grains contained. However, the modulus of elasticity also decreased with time during the period of 28 to 90 days. Time dependent changes in flexural strength are shown in Fig.4. Contrary to the compressive strength, the

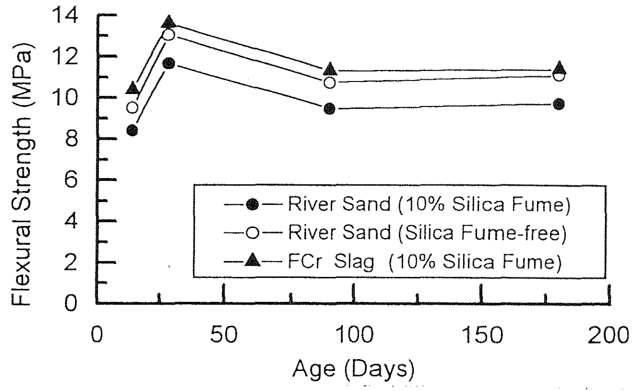

Fig.4 Flexural strength of high strength mortars

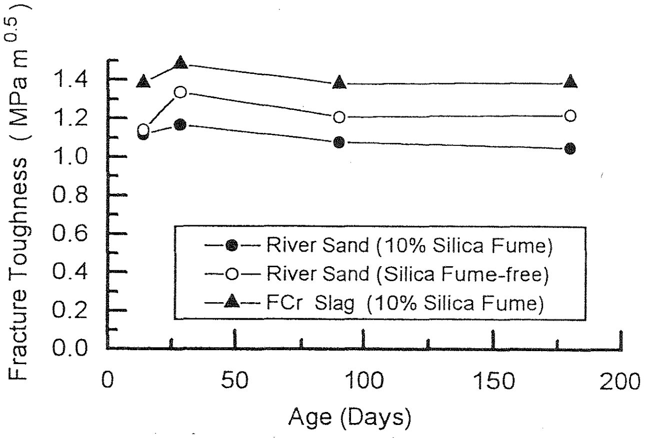

Fig.5 Fracture toughness of high strength mortars

flexural strength of the river sand mortars with silica fume was smaller than the silica fume-free mortars. Furthermore, there was little difference in flexural strength between the FCr slag mortar with silica fume and the river sand mortar without silica fume. The addition of silica fume did not increase flexural strength of mortars at a low water:cement ratio. A great reduction in the strength was also found at long ages in mortars. The results of fracture toughness of the mortars are given in Fig.5. Only a little variation in effective fracture toughness with time was found, especially in the mortars with silica fume. However, fracture toughness of these high strength mortars also followed the same tendency of reduction as other mechanical properties.

As shown in Figs. 2 to 5, all mechanical properties of mortars with a low water:cement ratio of 0.24 degraded during the period of 28 to

90 days. The high strength mortars with an extremely low water:cement ratio were not stable in water. The decreases in mechanical strength and modulus of elasticity may be related to some changes in the cement paste matrices with a low water:cement ratio during the period of 28 days to 90 days, being independent of the presence of silica fume.

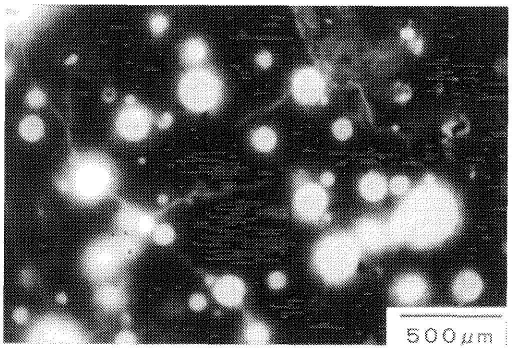

Fig.6 Microcracks observed at the cement paste phase in a FCr slag mortar with silica fume at 28 days

3.2 Fracture at microscopic scale

Fig.6 is a fluorescence micrograph for the polished surface of mortar specimens at 28days. Microcracks were found on the whole area of mortar matrix. However, it should be noted that any reduction in strength did not occur in the high strength mortars up to the age of 28days. In other words, occurrence of those microcracks shown in Fig.6 did not directly relate to the decrease in strength of mortars.

Fig.7 shows changes in microhardness with time in the hardened cement pastes with and without silica fume. Generally, the hardened cement paste with silica fume has a slightly smaller microhardness than

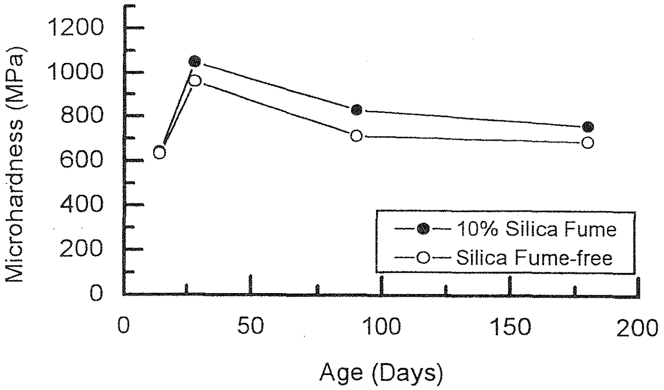

Fig.7 Vickers microhardness of hardened cement paste phases in high strength mortars

the silica fume-free paste at early ages (Igarashi et al. 1996). However, the silica fume paste shown in Fig.7 is found to show a greater microhardness than the silica fume-free paste even at early ages. The values of microhardness in both cement pastes with and without silica fume considerably decreased with time during periods later than 28days. The microhardness generally has a good correlation with the porosity of a material. Therefore, the decrease in the microhardness suggests the occurrence of microcracks to increase porosity in the bulk cement paste phase although such microcracks with sizes of unhydrated cement grains could not be found in microscopic examinations in this study. It is concluded from the results given in Figs.6 and 7 that the decreases in mechanical strength of the high strength mortars resulted from the occurrence of some phenomena which may be related to the decrease in microhardness in the hardened cement paste phase at long ages.

Some workers pointed out the decrease of strength in the high strength concrete system. Tazawa and Miyazawa (1992) showed that non-uniform internal stress due to self-desiccation resulted in the decrease in strength of high strength mortars. Larrard and Bostvironnois (1991) also interpreted the reduction of compressive strength in very high strength concrete with silica fume, based on a hypothesis on drying-related effects. They showed indirectly the reduction of strength in silica fume concrete at long ages. However, those results of the decrease in strength at long ages were obtained for concretes exposed to a drying condition. Therefore, it is difficult to explain the reduction of strength in mortars in this study from such a drying effect because the mortars were continuously stored in water.

Fig.8 shows the length changes of silica fume-free mortars

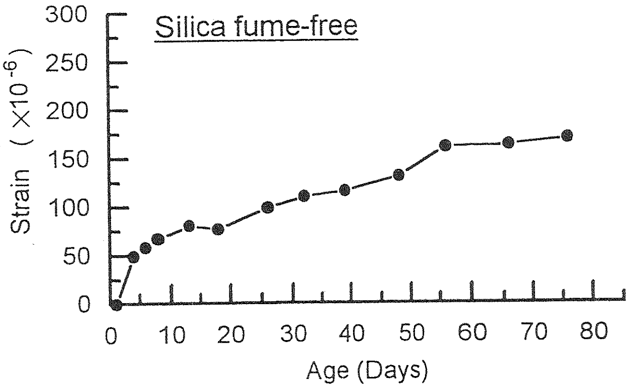

Fig.8 Length changes of silica fume-free mortars cured in water

continuously cured in water. A slight expansion was found to occur immediately after the initiation of curing in water. The swelling increased with time until at least about the age of 55 days. Then, it is likely that the internal relative humidity was not seriously declined at least in external portions of those mortar specimens (Perrson 1997). In other words, the capillary system in the external portions must have had enough water at least in early ages so that hydration was not interrupted until there was no space left to accommodate the new hydration products (Aitcin, et al. 1997). It is clearly shown from Fig.8 that any damages due to drying was not induced in those specimens during the curing in water.

As for the decrease in strength of high strength concrete, a different mechanism was also proposed (Hillemeier and Schroder 1995, Muller and Rubner 1995). As mentioned earlier, the high strength concrete system has a large amount of unhydrated cement particles. Those remnant particles can hydrate if capillary pores left after the initial hydration are occupied by water at long ages (Hellemeirer and Schroder 1995). However, enough capillary pores available for the hydration products are not remained at such later ages. As a result, the late hydration needs spaces for their hydration products although the rigid and dense microstructure previously formed impedes their new formation of products. Hellemeirer and Schroder (1995) experimentally confirmed the microcracks induced by the development of inner pressure due to the late hydration products. If such a late hydration had occurred at the mortars in this study, the reduction of microhardness may be explained from the formation of microcracks around unhydrated particles although such microcracks were not detected in this study. Such microcracks also reduced the function of unhydrated cement particles as reinforcing particles so that the microhardness in the cement paste must have been reduced. At present, an explicit explanation can not be given to the decrease in microhardness at long ages. However, the degradation of mechanical properties and the decrease in microhardness may evidence the validity of the concept of the changes in inherent microstructure of cement paste due to the delayed hydration of unhydrated cement grains.

4 Conclusions

The development in the strength of high strength mortars cured in water was investigated with emphasis on the characteristics of microstructure formed in mortars with an extremely low water:cement ratio. The strength of the mortars was considerably reduced at long ages. Such a degradation in mechanical properties of the mortars was in response to the decrease in microhardness in cement paste phase in the mortars. That degradation in mechanical properties may be related to the late hydration of unhydrated cement grains which probably gives rise to internal expansive pressure in the microstructure.

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