FLEXURAL STRENGTH AND MICROSTRUCTURE OF CEMENT BINDERS REINFORCED WITH WOLLASTONITE MICRO-FIBRES

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ABSTRACT

An investigation of cement composite behaviour showed that a flexural strength in excess of 28 MPa (4080 psi) can be readily attained in normal cement paste by incorporating an optimum amount of silica fume and 11.5% by volume of natural wollastonite micro-fibres. Systematic experimentation showed that modification of the flexural strength and the microstructure in hydrated cement and cement-silica fume matrices by addition of natural wollastonite micro-fibres is strongly controlled by the proportion of the various components. A discussion based on results obtained in bending tests, mercury intrusion porosimetry, helium gas pycnometry, and isopropyl alcohol saturation measurement, is presented in terms of composite theory and difference in observed properties.

Introduction

In an earlier study, it was reported that the flexural strength of the hydrated cement-water and the cement-silica fume-water systems can be significantly enhanced by incorporating natural wollastonite micro-fibres in the cement matrix. The addition of wollastonite micro-fibres with the cement matrix improved the flexural strength characteristics and resulted in a significant beneficial modification of the pre-peak and post-peak load behaviour as demonstrated by load-deflection curves [1]. Wollastonite is a natural mineral, calcium meta-silicate (β - CaO-SiO2), and is generally available in the shape of acicular particles for commercial applications. Natural wollastonite micro-fibres are very fine fibres with diameters mostly in the same range of the cement particles (about 25-40 µm); the fibre length is about 0.4 - 0.6 mm. Because this material is a natural mineral and is readily available in the market for commercial applications, it is a potential material for the development of high performance cement and concrete products. Furthermore, natural wollastonite micro-fibres are considerably less expensive than steel or carbon micro-fibres. The latter are effective in improving the strength characteristics of cement paste [2,3,4]. Wollastonite micro-fibres have been used in the pottery industry and in the cement product industry for the manufacturing of cement board and tile [5,6]. A systematic study has been carried out to examine modification of the flexural strength and microstructural characteristics of high performance cement composite systems employing both silica fume and natural wollastonite micro-fibres. The experimental results obtained in the study are presented in this paper.

Experimental

Materials

Type 10 Portland cement* was used as the base component. The natural wollastonite micro-fibres which appeared in the shape of acicular particles were obtained from a local supplier**. The size of most of the fibres is estimated in the range of about 25-30 µm in the transverse dimension and the length is in the range of about 0.4 - 0.6 mm. The silica fume*** was confirmed to be an amorphous material by X-ray diffraction analysis. The superplasticizer solution**** is made up of about 48% solids and 52% water.

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* Type 10 Portland cement was supplied by the St. Mary's Cement Co., Quebec, Canada.
** The natural wollastonite micro-fibres were of the NYAD G grade and obtained from Prescott & Co., Mississauga, Ontario, Canada.
*** The silica fume containing 95.2% SiO_2, 1.6% carbon, 0.27% K_20, and 0.10% Na_20 was supplied by the SKW Co., Montreal, Quebec, Canada.
**** The superplasticizer solution was the Atlas Mighty 150 RD2 grade.

Specimen Preparation

Five separate series of composite specimens were prepared. The first series of specimens was prepared from a mixture of cement and silica fume. The amount of silica fume mixed with the cement matrix was increased from 0 parts to 20 parts in 5 parts increments. The second series of specimens was prepared from mixtures of cement and wollastonite. Seven different concentrations varying from 2% to 15% by volume of wollastonite micro-fibres were mixed with the cement matrix. The third, fourth, and fifth series of specimens were prepared from mixtures of cement, silica fume and wollastonite. In the last three series of specimens, seven different concentrations of wollastonite micro-fibres were mixed with the cement-silica fume base matrix. The amount of silica fume used in each series varied from 5 parts to 15 parts.

All sample preparations were processed in a similar manner. Silica fume was first manually blended with cement in a steel mixing bowl until a uniform mixture was obtained by visual inspection. When wollastonite micro-fibres were used, the fibres were also manually blended with the cement or the cement-silica fume mixture until a uniform solid solution was obtained. When silica fume alone was used, the amount of superplasticizer solution equivalent to about 0.3% by weight of the solid mixture was added to the water solution gauged to provide a water/solid ratio of 0.35. When both silica fume and wollastonite micro-fibres were used, the amount of superplasticizer solution equivalent to about 1% by weight of the solid mixture was added to the water solution also gauged to provide a water/solid ratio of 0.35. The liquid water containing the superplasticizer solution was first placed in the mechanical blender and mixed for about l minute. The dry mix solids were then added to the water solution and blended for a period of about 4 minutes. The cement composite mixture was then cast into a plastic mould which measured about 40 x 130 x 4 mm. The cement mixture was allowed to harden in a moisture controlled room at saturation for a period of 24 hours. The hardened cement specimen was then demoulded. After the de-moulding process, the specimens were kept in a calcium hydroxide solution to continue the normal hydration for a total period of 28 days. After every 7 days of hydration, a composite slab was removed from the calcium hydroxide solution and sliced into small beams measuring about 4 x 65 x 4 mm. These small beam specimens were used for flexural strength test measurement and then for microstructure characterization.

Test Measurements

The flexural strength of each composite beam specimen was determined by a three-point loading test method using a computer controlled Material Testing System[#]. Prior to the bending test, each beam specimen was maintained in the calcium hydroxide solution after the slicing operation. During test, the excess water on the surface of the specimen was removed by a water absorbent type paper and the specimen was installed on the specimen support. A total of 5 or 6 specimens was tested for each test condition and the average result was used.

Subsequent to the bending test, a representative fractured beam specimen from each series of composite mixtures was selected for porosity measurement using the helium gas pycnometry method. After the pycnometry measurement, the beam specimen was broken into two portions of approximately equal size and weight. One portion was prepared for the mercury intrusion porosimetry measurement and one portion was used for the isopropyl alcohol saturation measurement. All specimens selected for porosity evaluations employing the three different methods were oven-dried at 105 °C for a period of at least 72 hours.

For the helium gas pycnometry measurement, the true volume of the whole beam specimen was accurately measured and repeated 5 or 6 times until a consistent value was obtained. For mercury intrusion measurement, the portion of each specimen was first broken into 7 to 8 small pieces and the small pieces were then inserted into the specimen container of the porosimeter. The mercury porosimeter[##] was operated at pressures up to a maximum of 414 MPa (60,000 psi) and the helium gas pycnometer[###] was operated at a gas pressure of about 0.21 MPa (30 psi). For isopropyl alcohol saturation measurement, the portion of the specimen was first weighed accurately to obtain a dry weight of the specimen. All specimens selected for evaluation were then dried by a vacuum method at ambient temperature for a period of about three hours inside a closed desiccator. After the vacuum drying process, isopropyl alcohol was allowed to flow into the desiccator to saturate the specimens. The specimens were immersed in the isopropyl alcohol liquid for a period of three hours. The saturated weight of the specimen was obtained and the amount of isopropyl alcohol entered into the specimen was determined. The volume of the isopropyl alcohol entered into the specimen with respect to the geometric volume of the specimen was considered to be the porosity of the specimen.

[#] The Material Testing Systems is the MTS Model 810 apparatus manufactured by MTS Systems Corp., Mpls, MN, U.S.A.

[##] The mercury porosimeter is the Model 60,000 psi Porosimeter manufactured by American Instrument Co., Maryland, U.S.A.

[###] The helium gas pycnometer is the Beckman 930 Comparison Pycnometer manufactured by Beckman Instrument, Inc., California, U.S.A.

Results and Discussion

Flexural strength and microstructural characteristics of cement composite containing silica fume and wollastonite micro-fibres were observed to vary significantly depending on the composition of the mixtures. The amount of the silica fume and the amount of the wollastonite micro-fibres in the composite mixtures were observed to be the determining factors in modifying the mechanical and physical properties of the hydrated cement matrices. The experimental results are analyzed and discussed in terms of flexural strength, total porosity, port size distribution, and threshold pore diameter in the various composite systems.

[A] Flexural Strength

The flexural strength of the reference Portland cement paste prepared with a water/cement ratio of 0.35 and a superplasticizer (solution equivalent to about 0.3% of the solids) increased gradually in the range of 10.3 - 13.7 MPa (1500 - 1990 psi) after hydration in calcium hydroxide solution for a period varying from 7 to 28 days. The flexural strength of a cement-silica fume paste prepared with similar water content and hydration treatment, however, decreased significantly as the amount of the silica fume in the cement matrix was increased. The flexural strength was observed in the range of 8.7 - 9.8 MPa (1230 - 1420 psi) for the cement-silica fume mixture consisting of 95 parts cement and 5 parts silica fume. It was in the range of 6.4 - 9.2 MPa (930 - 1330 psi) for the mixture consisting of 90 parts cement and 10 parts silica fume and in the range of 4.1 - 8.5 MPa (580 - 1230 psi) for the mixture consisting of 85 parts cement and 15 parts silica fume. It was in the range of 5.7 - 8.2 MPa (900 - 1200 psi) for the mixture consisting of 80 parts cement and 20 parts silica fume. The change of flexural strength with the increase of silica fume in the composite mixture is evident. Extending the hydration period in calcium hydroxide solution from 7 to 28 days generally resulted in a slight increase of flexural strength with hydration period for the cement-silica fume system.

Addition of wollastonite micro-fibres to cement paste significantly modified the flexural strength characteristics of the cement-wollastonite composite system after normal hydration. The flexural strength was observed to vary from 10.7 MPa (1550 psi) to 22.60 MPa (3150 psi) depending on the mixture composition and the hydration period. Extending the hydration period from 7 days to 28 days also resulted in an increase of the flexural strength with the hydration period for the cement-wollastonite system. However, a relatively large and almost linear increase in the flexural strength was observed when the amount of wollastonite micro-fibres incorporated into the cement matrix was increased from 2% to 11.5% by volume. A maximum flexural strength in the composite system was observed when the mixture contained about 11.5% by volume of the wollastonite micro- fibres. Further increase of the wollastonite micro-fibres in the cement matrix up to 15% by volume resulted in a slight reduction in the flexural strength of the composite system. This trend was observed to prevail for specimens tested after 7 days hydration up to 28 days.

Incorporation of wollastonite micro-fibres into a matrix consisting of cement and silica fume particles was also observed to have similar enhancement on the flexural strength. However, the trend of variations in the improvement of the strength characteristics after hydration was observed to be complex. The modification of the flexural strength is dependent not only on the amount of the silica fume mixed with the base cement matrix but also on the concentration of the wollastonite micro-fibres in the composite mixture. In the cement-silica fume-wollastonite composite system, seven different concentrations of wollastonite micro-fibres were mixed with the cement-silica fume matrix. The flexural strength was observed in the range of 12.1 - 28.1 MPa (1760 - 4080 psi) for the composite mixture containing 5.2% silica fume, in the range of 10.9 - 26.5 MPa (1590 - 3845 psi) for the composite mixture containing 10.2% silica fume, and in the range of 5.4 - 24.0 MPa (780 - 3480 psi) for the composite mixture containing 17.6% silica fume. Figure 1 shows the variation of flexural strength with the silica fume content for the various cement composite systems containing different amounts of wollastonite micro-fibres after 28 days of hydration.

When different concentration (from 2% to 15% by volume) of wollastonite micro-fibres was incorporated into the cement or the cement-silica fume matrix, a maximum flexural strength in each composite system was generally observed. This maximum flexural strength occurred at one specific wollastonite concentration in the composite system. For the four composite systems investigated, the maximum flexural strength was observed at 11.5% in the cement-wollastonite system containing no silica fume and in the cement-silica fume-wollastonite system containing 5.2% and 10.2% silica fume in the cement matrix. When the silica fume content in the composite mixture increased to 17.6%, the maximum flexural strength occurred at the mixture composition containing 12.5% by volume of wollastonite micro-fibres. This appears to suggest that more wollastonite micro-fibres are required in order to compensate for the presence of more silica fume particles in the composite matrix. Figure 2 shows the variation of the flexural strength at 28 days with the concentration of wollastonite micro-fibres in the composite system containing different amount of silica fume.

As reported in the earlier study [1], incorporation of wollastonite micro-fibres into the cement matrix modified the pre-peak and post-peak load behaviour of the load-deflection curve in the bending test. Similar load behaviour was also observed in the cement-silica fume-wollastonite composite systems and the characteristics were observed to be independent of the amount of silica fume in the cement matrix. As explained in the previous paper [1], fracture and total failure in a plain hydrated cement matrix generally occur abruptly with a straight drop in the load-deflection curve. Fracture and failure in the cement composites reinforced with wollastonite micro-fibres occur gradually and the drop in the load-deflection curve occurs in a steady manner showing higher ductility characteristics.

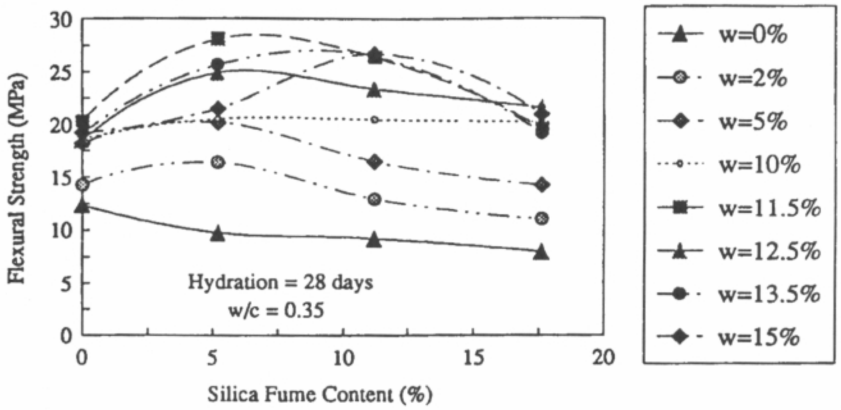

Figure 1. Variation of flexural strength with silica fume contents for cement composite systems containing different amount of wollastonite micro-fibres in the base matrix.

[B] Total Porosity

The total porosity in hydrated cement and cement-silica fume matrices reinforced with wollastonite micro-fibres was observed to display complex variations depending on the amount of the silica fume, the amount of wollastonite micro-fibres and the method used in determining the porosity parameter. Specimens selected for porosity characterization were all hydrated for a period of 28 days. Most of these samples had the highest value of flexural strength for each composite system studied. In the porosity evaluation process, the wollastonite micro-fibres are assumed to be non-porous and the porosity is concentrated only in the cement paste matrix. It should also be pointed out that all samples prepared in the present investigation were based on a water/cement solids ratio of 0.35. As a result, the effect of water content on the pore formation process is assumed to be similar for all composite systems studied. The results are discussed in terms of the porosity values determined by the method of measurement.

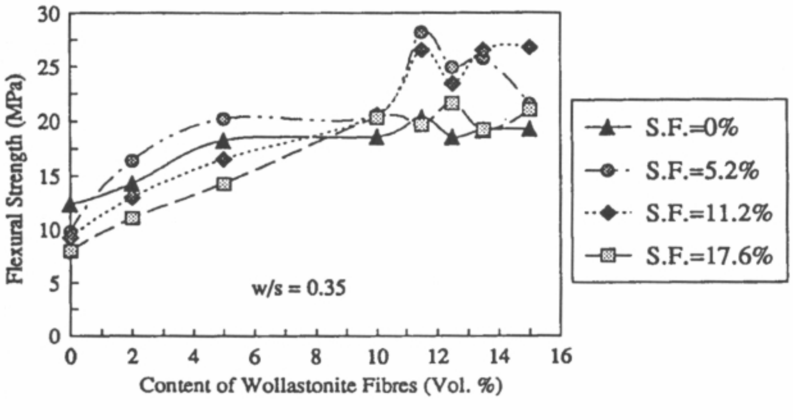

Figure 2. Variation of flexural strength with concentration of wollastonite micro-fibres for cement composite systems containing different amount of silica fume in the base matrix.

(1) Mercury Intrusion Porosimetry

Some workers have questioned the validity of the mercury intrusion porosimetry method in quantifying the true total pore volume in hydrated cement matrices because of the possibility of causing damage to the pore structure [7]. In spite of this caution, mercury intrusion porosimetry measurements were observed to provide some informative characteristics of the pore structure in the various composite systems. The total porosity determined by the mercury intrusion measurements in this investigation is corrected for the concentration of the wollastonite micro-fibres mixed with the base matrix for each composite system.

Measurements showed that the total pore volume in the hydrated cement matrix varied significantly depending on the composition of the mixture. The total porosity in the reference hydrated cement paste prepared with a water/cement ratio of 0.35 and hydrated for 28 days was about 24.8%; however, the total porosity in the cement-silica fume system decreased substantially when the amount of silica fume mixed with the cement matrix was increased. Results showed that the total porosity in the cement-silica fume system was about 21.6%, 18.1%, 19.0% and 15.8% respectively when the composite mixtures contained about 5.2%, 10.2%, 17.6% and 25% of silica fume in the base matrix.

The total porosity in the composite mixtures containing wollastonite micro-fibres alone was observed to vary depending on the amount of wollastonite micro-fibres incorporated into the base matrix. In the cement-wollastonite composite system without the presence of silica fume, the total pore volume was observed within the range of 22-26% and it increased slightly when the wollastonite micro-fibres in the composite mixture increased from 2% to 15% by volume. When silica fume was mixed with the cement, the total porosity in the cement-silica fume-wollastonite system was observed to increase slightly as the concentration of the wollastonite micro-fibres increased from 2% to 15% by volume in the composite mixtures. Measurements showed that the total pore volume in the cement-silica fume-wollastonite systems was within the ranges of 22-26%, 21-25% and 21-24% respectively when the composite mixtures contained about 5.2%, 10.2% and 17.6% silica fume. It was noted that the change of the total pore volume in the cement-silica fume-wollastonite composite system containing different amounts of silica fume in the mixture was less pronounced when compared to that observed in the cement-silica fume system without the presence of the wollastonite micro-fibres.

(2) Helium Gas Pycnometry

The total porosity determined by helium gas pycnometry was observed to be significantly lower than values determined by the mercury intrusion porosimetry. This observation was noted in all four composite systems studied. No systematic variation of the total porosity with change of the concentration of wollastonite micro-fibres was observed, but a systematic variation with change of the amount of silica fume in the composite mixture was evident. Measurements showed that the total porosity was in the range of 12.6% - 19.3% for the cement-wollastonite composite system and in the range of 2.4% - 7.8%, 0.8% - 2.7%, and 4.3% - 1.6% for the cement-silica fume-wollastonite composite system containing 5.2%, 10.2% and 17.6% silica fume in the mixture respectively. It seems apparent that helium gas does not infiltrate into all pore space in systems containing a relatively high amount of silica fume. A correlation between the porosity values determined by the mercury intrusion porosimetry and the helium gas pycnometry methods is shown in Figure 3. The experimental results observed in the study suggest that mercury at high pressures damages the microstructure of the hydrated cement matrix and enters into space which is inaccessible to helium. This effect appears to be less pronounced for the two component cement-wollastonite system containing no silica fume. Addition of wollastonite micro-fibres and addition of silica fume appears to have the same effect of promoting pore discontinuity.

(3) Isopropyl Alcohol Porosity Measurement

The total porosity determined by the isopropyl alcohol saturation measurement was observed to be significantly higher than values determined by the helium gas pycnometry measurement but the values are close to those obtained by the mercury intrusion porosimetry measurement. Again, no systematic variation of the total porosity with change of the concentration of wollastonite micro-fibres was observed, but a systematic variation with change of the amount of silica fume in the mixture was also evident. Isopropyl alcohol saturation measurements showed that the total porosity was in the range of 25.7% - 28.2% for the cement-wollastonite composite system and in the range of 22.5% - 24.0%, 17.3% - 20.6%, and 20.8% - 23.2% for the cement-silica fume-wollastonite composite system containing 5.2%, 10.2% and 17.6% silica fume in the mixture respectively. These results clearly indicated that isopropyl alcohol infiltrates into all pore space in all composite systems including those containing a relatively high amount of silica fume. Figure 4. shows a correlation of the total porosity values determined by the mercury intrusion porosimetry and the isopropyl alcohol saturation methods. The experimental results observed in the study suggest that the liquid diffusion process of isopropyl alcohol into the microstructure of hydrated cement matrix under a low vacuum condition is more efficient than the diffusion of helium gas. The observation of higher porosity in both cement-wollastonite and cement-silica fume-wollastonite composite systems by the isopropyl alcohol saturation method might be a result of more energetic entry into restricted pore entrances due to the surface wetting process. A small degree of chemical reaction with the surface of hydrated calcium silicate might also contribute to this effect [8-10].

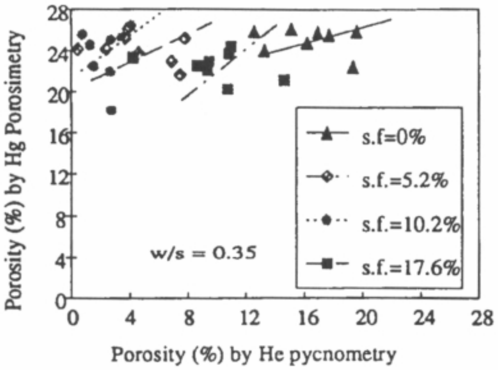

Figure 3. Porosity of cement composite systems containing various amount of silica fume and wollastonite micro-fibres. Values determined by Hg intrusion porosimetry versus values determined by He gas pycnometry are plotted.

[C] Pore Size Distribution

The distribution of pore sizes expressed as % pore volume versus pore diameter was observed to show complex variations for each composite system depending on the composition of each composite mixture. The pore size distribution curve for the reference cement paste appeared to show a large percentage of pores in the range of 0.05 - 0.10 µm. As the amount of silica fume mixed with the cement matrix was increased, the pore size distribution curve showed that the pores are concentrated in the range of 0.005-0.01 µm. Furthermore, total pore volume is decreased as the amount of silica fume in the composite mixture was increased, as shown in Figure 5.

The pore size distribution curves in the cement-wollastonite composite system showed that the pore diameters in the 0.5 - 0.1 µm range increased gradually as the content of the wollastonite micro-fibres in the composite was increased from 0% to 15% by volume. Pore sizes in the range of 0.01 - 0.1 µm appeared to increase in a manner independent of the concentration of the wollastonite micro-fibres. Figure 6 shows the pore size distribution curves for the cement-wollastonite composite system. For clarity, the pore size distribution curves for three composite mixtures were omitted.

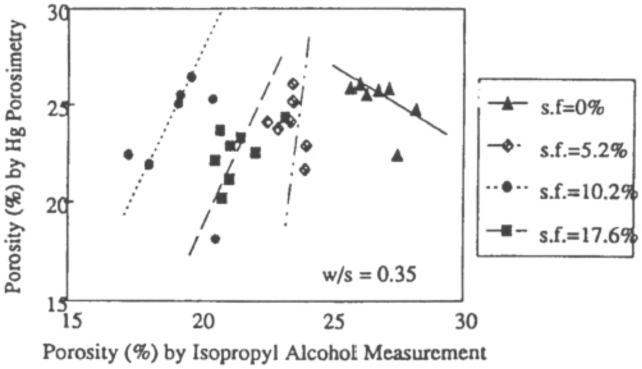

Figure 4. Porosity of cement composite systems containing various amount of silica fume and wollastonite micro-fibres. Values determined by Hg intrusion porosimetry versus values determined by isopropyl alcohol saturation.

The distribution of pore sizes in the cement-silica fume-wollastonite composite system was observed to vary significantly depending on the amount of silica fume in the base matrix and the concentration of the wollastonite micro-fibres in the composite mixture. For composite mixtures containing similar amount of silica fume, the pore size distribution curves showed that pores larger than 0.10 µm increased as the amount of wollastonite micro-fibres added to the cement-silica base matrix increased. The increase of pore volume toward smaller pore diameters in the region of 0.01-0.10 µm appeared in two stages with a rapid rise and then leveling off for the cement-silica fume-wollastonite composite system containing 5.2% silica fume. The pore size distribution curves for the composite system containing 10.2% silica fume appeared to display two curvatures in the region of 0.005-0.05 µm. The pore size distribution curves showed a steep rise in the same region for the composite system containing 17.6% silica fume. Furthermore, pore volume in the region 0.05-0.1 µm for the composite system containing 17.6% silica fume showed a significant increase as the concentration of the wollastonite micro-fibres in the composite mixture increased. Figures 7 - 9 show the pore size distribution curves for the three series of composite mixtures containing different amounts of silica fume in the cement-silica fume-wollastonite composite system.

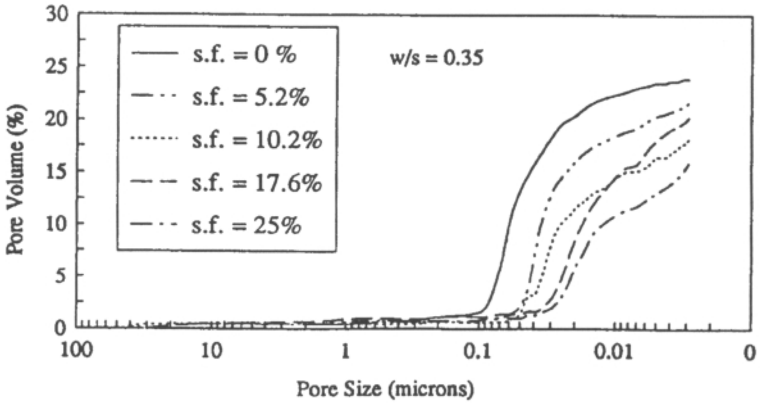

Figure 5 Pore size distribution in the cement-silica fume composite system.

Observation of the large increase of pore volume in the legion of 0.5-0.1 µm in the present study was found to be very similar to the study of cement mortars [11]. In that study, it was reported that large pores are formed at the interface between the sand particle and the cement paste and the pore volume generally increased with the change of the sand-cement ratio in mixes with and without the presence of silica fume. Silica fume addition to mortars was also observed to result in an increase of large pores in this range at the sand-paste interface. Silica fume addition to mortars therefore had the general effect of increasing the volume of coarse pores. Similar behaviour appeared to occur in the cement-silica fume-wollastonite composite systems.

Processes associated with transition zone formation in the vicinity of inclusions such as wollastonite micro-fibres affect the deposition of cement reaction products (such as CH, C-S-H, and ettringite) in this region. The pore structure in this region is generally coarser and is affected by the quantity, size and nature of the inclusion [12]. Inclusions can affect the rate and extent of hydration in addition to CH formation and matrix permeability [13]. Silica fume reacts with CH. The removal of CH from the matrix interface decreases the permeability of the system. Low permeability is achieved despite higher porosity due to a higher degree of discontinuity in the pores [14]. The effect of wollastonite micro-fibres on the pore structure of cement matrices described above also appears to account for the strain-softening behaviour described earlier.

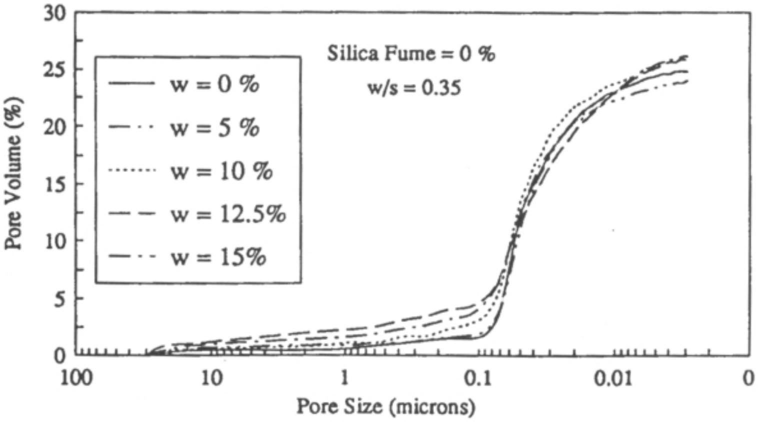

Figure 6. Pore size distribution in the cement-wollastonite composite system.

[D] Threshold Pore Diameter

The threshold pore diameter is considered to be a useful parameter in the characterization of the microstructure of hydrated cement matrices as it indicates the specific pore diameter at which the rapid increase of pore volume during the mercury intrusion process starts. The threshold pore diameter was observed to change depending on the composition of the composite system. The threshold pore diameter in the reference cement paste was observed to be about 0.116 µm and it decreased to 0.070 µm, 0.058 µm, 0.035 µm, and 0.035 µm in the cement-silica fume composite systems containing 5.2%, 10.2%, 17.6% and 25m of silica fume in the mixture respectively. The threshold pore diameter in the cement-wollastonite composite system was about 0.116 µm and remained essentially unchanged when wollastonite micro-fibres in the composite mixture was increased from 2% to 15% by volume. However, this was not the case in the cement-silica fume-wollastonite composite system. The threshold pore diameter was observed to change depending on the amount of silica fume and the concentration of wollastonite micro-fibres in the composite mixture. In the cement-silica fume-wollastonite mixture containing 5.2% silica fume, the threshold pore diameter was about 0.087 µm and remained unchanged with the change of the concentration of the wollastonite micro-fibres in the composite mixture. In the cement-silica fume-wollastonite composite system containing 10.2% silica fume, the threshold pore diameter was 0.058 µm for mixtures containing 2% and 5% by volume of wollastonite micro-fibres and increased to 0.087 µm for mixtures with more than 10% and up 15% by volume of wollastonite micro-fibres. A similar trend was also observed in the composite system containing 17.6% silica fume. In this system, the threshold pore diameter increased from 0.043 µm to 0.070 µm. Figure 10 shows the variation of the threshold pore diameter with the concentration of wollastonite micro-fibres for the four series of composite systems containing different amount of silica fume. The influence on the modification of the threshold pore diameter by the silica fume is evident. Change of the threshold pore diameter in hardened and hydrated cement paste with water/cement ratio and the specimen drying conditions has been observed in other investigation [12]. It was reported that the threshold pore diameters changed from 0.59 µm to 0.035 µm when a lower water/cement ratio decreasing from 0.80 to 0.45 was used to prepare the cement paste. All composite mixtures prepared in this investigation were based on a constant water/cement+silica fume ratio of 0.35. The modification of the threshold pore diameter in various composite systems is attributed to the solid material components and not the water component

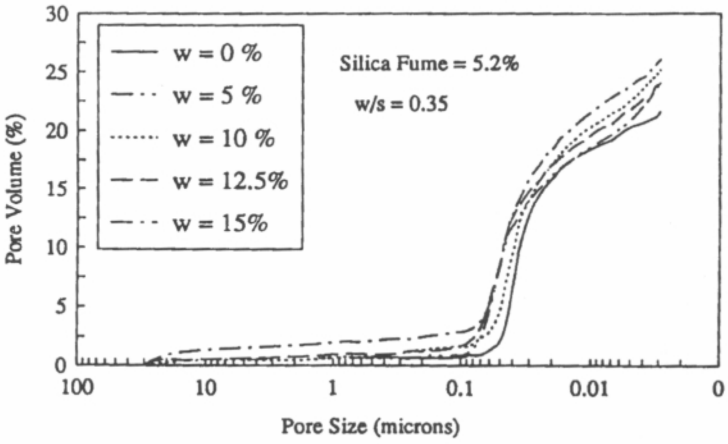

Figure 7. Pore size distribution in the cement-silica fume-wollastonite composite mixtures containing 5.2% silica fume.

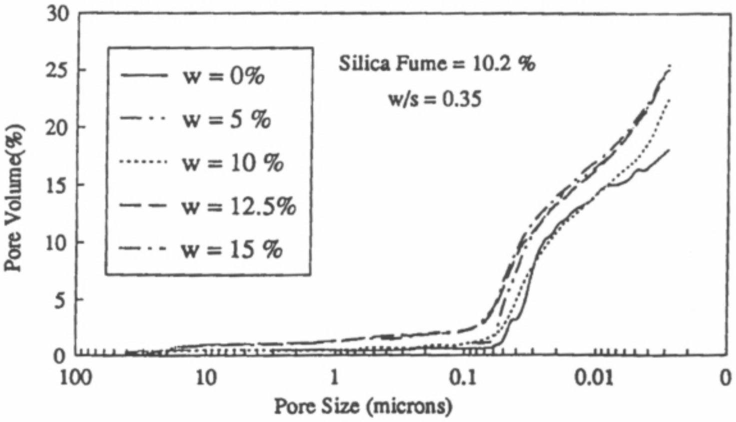

Figure 8. Pore size distribution in the cement-silica fume-wollastonite composite mixtures containing 10.2% silica fume.

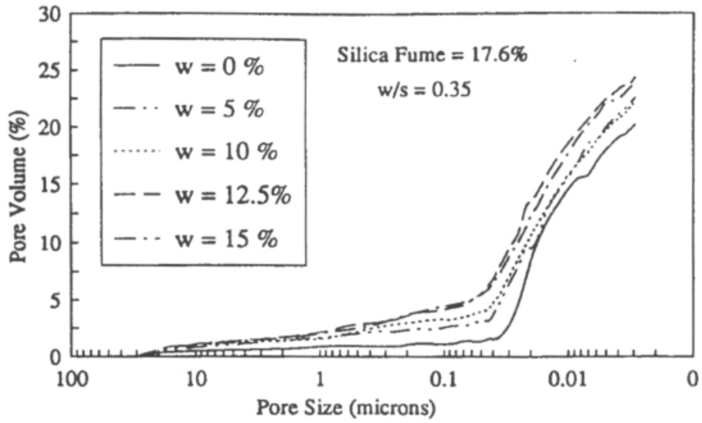

Figure 9. Pore size distribution in the cement-silica fume-wollastonite composite mixtures containing 17.6% silica fume.

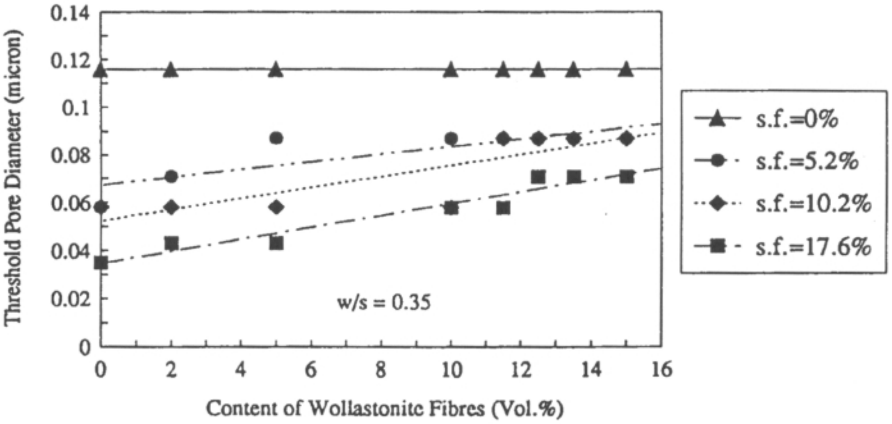

Figure 10. Threshold pore diameters of cement-wollastonite and cement-silica fume-wollastonite composite systems containing different amount of silica fume in mixtures.

Conclusions

The experimental results obtained in this investigation appear to support the following conclusions.

1. The flexural strength characteristics of hydrated cement and cement-silica fume matrices can be maximized by incorporating an optimum amount of natural wollastonite micro-fibres and silica fume in the composite mixture. A maximum flexural strength in excess of 28 MPa (4080 psi) can be attained when a composite mixture consisting of 11.5% by volume of wollastonite micro-fibres and 5.2% silica fume is prepared with a water/cement+silica fume ratio of 0.35 and 1% superplasticizer solution and hydrated in calcium hydroxide solution for a period of 28 days.

2. Improvement of the pre-peak and the post-peak load-deflection response by the incorporation of wollastonite micro-fibres was observed in composite systems with and without the presence of silica fume. This resulted in higher flexural strength and better ductility characteristics.

3. The microstructure of the cement-based composite systems is significantly modified by the incorporation of wollastonite micro-fibres and silica fume. The characteristics change depending on the composition of the mixture.

4. Very different total porosity, pore size distribution and threshold pore diameter characteristics are observed in hydrated cement-wollastonite and cement-silica fume-wollastonite composite systems.

5. Total porosity in the hydrated phases determined by mercury intrusion porosimetry is generally greater than that determined by the helium gas pycnometry.

6. Total porosity in the hydrated phases determined by isopropyl alcohol saturation method is also greater than that determined by the helium gas pycnometry; the values are close to those determined by the mercury intrusion porosimetry method.

7. Addition of wollastonite micro-fibres and silica fume appears to promote pore discontinuity in cement systems. This suggests that permeability may be significantly reduced and durability increased.

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