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Fine Particles - a Fracture Mechanical Approach

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ABSTRACT

The work is a closer analysis of Kronlöf's earlier work [1994] and thesis [1997]. It is also related to Björn Lagerblad's and Carsten Vogt's work [2004] as well as Vogt's theses [2010], all dealing with the unexplained substantial strengthening in the presence of large amounts of fine quartz. In this analysis the strengthening effect was up to 20 MPa but could be also negative. At the age of 7 days the effect depended on the average distance between particles as well as on the water to binder ratio, while at the age of 91 days it only depended on the average distance, being independent of the water to binder ratio over the wide range from 0.22 to 2.0. It was concluded that in the later case the effect was mechanical. An empirical model was made and fracture mechanical explanation given to describe the strengthening effect.

Key words: fracture mechanics, modelling, filler effect, optimising OPC content, compressive strength, fine particles

1. MATERIALS AND METHODS

The aggregate was 100% well crystallised quartz and its maximum size was 6 mm. The particle size distributions (PSD) did not vary from 0.5 – 6 mm, but varied widely below this range. The specific surface area of the three fine fractions was determined from their PSDs measured with the X-ray sedimentation method and was in the range of OPC: 993, 584 and 306 m^2/kg. The binder comprised 90% of relatively coarse OPC (P40/91 LH SR) and 10 % of silica fume. The aggregate to binder ratio with each of the aggregate mixes varied over a wide range from 1.7 to 22. The water requirement was determined by adding a sufficient amount of water to give a workability flow value of roughly 13 cm by the Haegermann method. All mixes were plasticized. The mixes were tested for compressive strength at the ages of 7 and 91 days. The experimental details are given elsewhere (Kronlöf 1994).

2. MODELLING

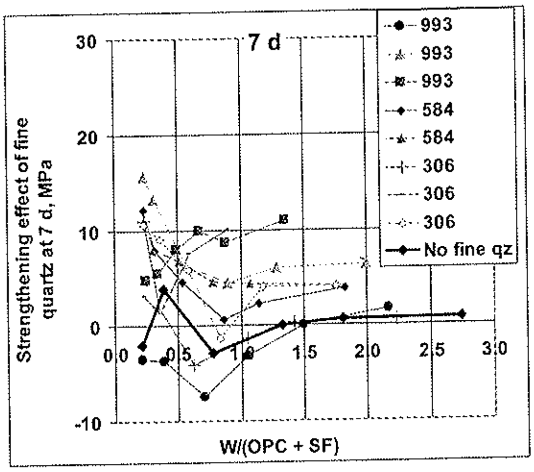
The compressive strength was estimated with a modified rule of mixtures (Equation 1, 2 and 3).

$$f = V_{Paste} \cdot f_{Paste} + f(Aggr) \qquad [1]$$

$$f(Aggr)_{7d} = 6.80 \cdot V_{Aggr} \cdot f_{Paste}^{0.60} \qquad [2]$$

$$f(Aggr)_{91d} = 15.54 \cdot V_{Aggr} \cdot f_{Paste}^{0.48} \qquad [3]$$

Equation 1 provided a good description of the strength of mixes made without fine quartz (R^2 va= 0.994 at 7 d and 0.998 at 91 d), but when fine fractions were introduced to the aggregate the experimental strength was upto 20 MPa higher that the estimation. The difference is shown in Figure 1.



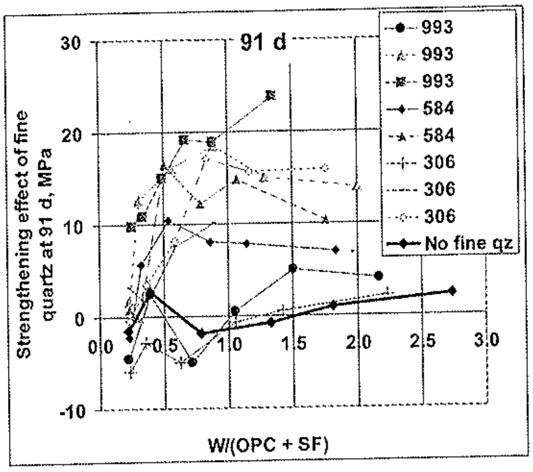
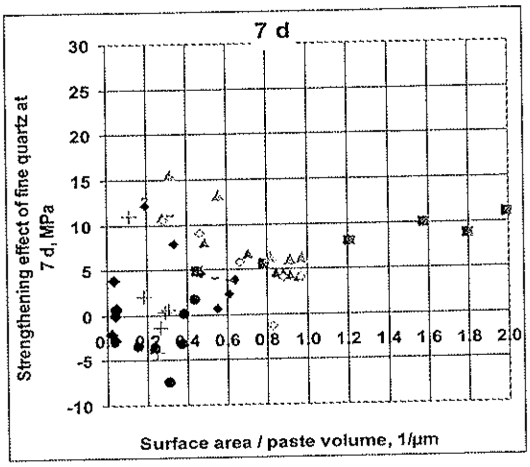


Figure 1a. *Figure 1b.*

The strengthening effect of fine quartz (the difference between experimental results and Equation 1) plotted against the water-to-binder ratio for 7 and 91 days results. The symbols give the SSA of the fine quartz. W denotes water, OPC cement and SF silica fume as weight units.



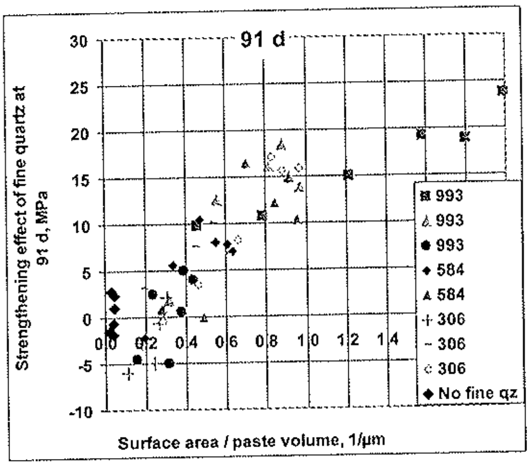


Figure 2a. *Figure 2b.*

The strengthening effect of fine quartz (the difference between experimental results and Equation 1) as a function of the ratio between the total quartz surface area (the area of the interfacial transition zone) and the paste volume (ITZ ratio) for 7 and 91 days results.

Attempts were made to relate the above mechanism to some kind of chemical effect by applying the cement equivalent concept. It showed that the chemically identical quartz particles in the chemically identical environment and rheologically stable conditions could either strengthen or weaken the material. A hypothesis was made that the strengthening/weakening mechanism is not chemical in nature in the sense of binding reaction products but mechanical. According to the hypothesis quartz particles could be either strengthening components or flaws depending on the overall mix composition structure. This was also supported by the fact that quartz is a very inert material. The net strength was given the formulation given in Equation 4.

$$f = V_{Paste} \cdot f_{Paste} + f(Aggr) + f(Fine\,quartz) \qquad [4]$$

In this equation the third term *(f(Fine quartz))* represents the strengthening effect of fine quartz powder. This was examined in terms of mix composition geometry (volume fractions and distributions) of the two phases, paste and quartz. It was found that at the age of 91 days the most dominating quantity was the ratio between the total quartz surface area (the area of the interfacial transition zone) and the paste volume (ITZ ratio). The larger was the ITZ ratio, the larger was the strengthening effect. When the ITZ ratio was lower than 0.25 (1/μm), indicating that the average distance was larger than 8 μm between quartz surfaces, the quartz particles weakened the concrete structure and thus indicating that they behaved as flaws. However, at the age of 7 d the previous tendency was more diverged (Figures 2 and 3). This finding was modelled with Equations 5 and 6.

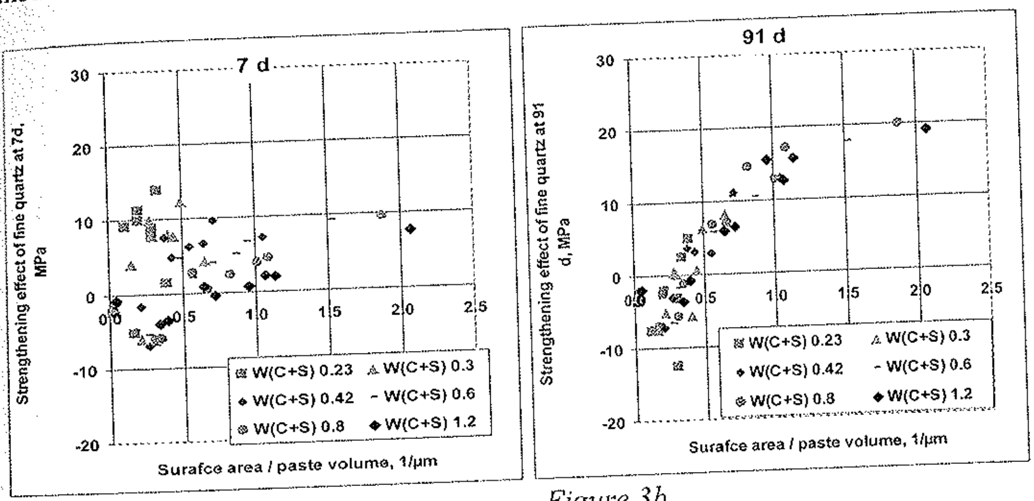
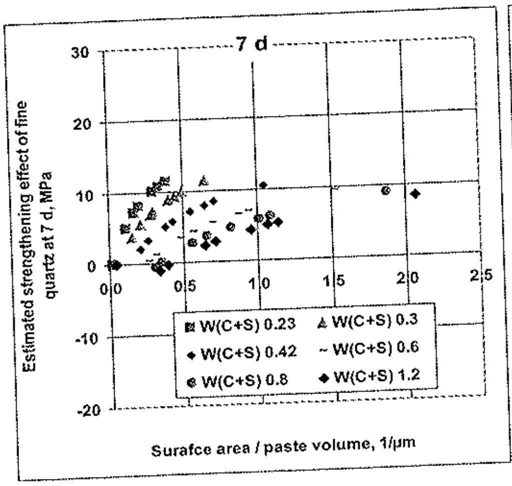


Figure 3a. *Figure 3b.*
Interpolated fine quartz strengthening effect as a function of ITZ ratio for 7 and 91 days results. The interpolated values are the values of the previous figures interpolated and calculated to show the water-to-binder ratio effect in the range from 0.23 to 1.2. The legends denote the water-to-binder ratios.

A fracture mechanical explanation of the found behaviour can be given as follows: The compressive strength of concrete is controlled by the initiation and subsequent coalescence of a large number of individual cracks. If the number of quartz particles is small, i.e. the distance between particles is larger than some effective grain size of concrete, the particles only enhance the probability of crack initiation. The resulting crack sizes and coalescence are here controlled by the paste properties. The quartz particles have in this case a detrimental effect on concrete strength. Besides acting as crack initiators, the particles may also act as microcrack arresters in the paste. With an increasing number of particles, the interparticle spacing decreases and at some point begins to control the coalescence process. The crack driving force is roughly controlled by the square root of the crack size and in this case the crack size will be a function of the interparticle spacing. The end-result will be the behaviour described by Equations [5] and [6] (Figure 4).

$$f(Fine\,quartz)_{7d} = 5.24 \cdot \ln(A_{Aggr} / V_{Paste}) + 0.19 \cdot f_{Paste} + 4.27 \qquad [5]$$

$$f(Fine\,quartz)_{91d} = 10.68 \cdot \ln(A_{Aggr} / V_{Paste}) + 14.80 \qquad [6]$$



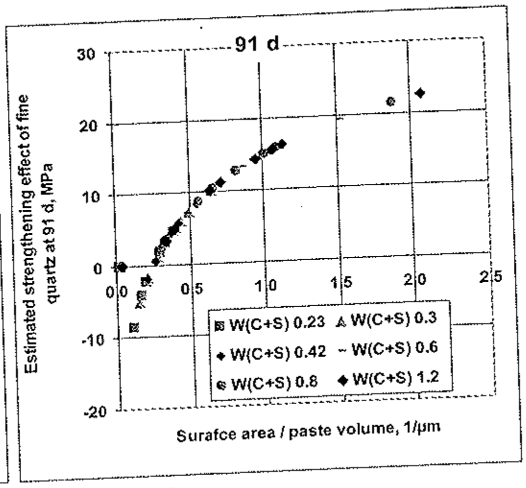


Figure 4a. *Figure 4b.*

Estimated fine quartz strengthening effect for 7 and 91 days results by Equations 5 and 6.

3. SUMMARY AND CONCLUSIONS

The binding effect of substituting materials in OPC is often explained by their chemical activity such as pozzolanic reaction or surface nucleation of CSH while their mechanical effect is overlooked. This study examined strengthening effect which was mainly mechanical. The experimental result showed that powder was detrimental to strength if used in small quantities and if it was coarser that cement. However, if the powder was very fine and its potential for improving particle packing was utilized as reduced paste content, the positive strengthening effect was up to 20 MPa. At the age of 91 days the positive effect was not dependent on the water to binder ratio. It depended only on the ratio between the total aggregate surface area which is the area of the interfacial transition zone and the paste volume (ITZ ratio). This ratio is inversely proportional to the distance between the quartz particles. At the age of 7 days the strengthening effect depended also on the water to binder ratio. Also when reactive powders are used the mechanical effect is a part of the under-laying mechanism whenever a part the particle remains un-reacted. This is the case also with pure OPC in high strength mixes. In addition to the geometry addressed here, the significance of the particle surface bond to the surrounding paste as well as the options to modify it should be further studied.

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