WATER PRESSURE IN FRESH AND YOUNG CEMENT PASTE.

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ABSTRACT

Changes in water pressure, due to both gravitation and capillary forces, have been measured in fresh and young cement paste with W/C-ratio in the range 0.25-0.5.
Influence of parameters such as cement type, W/C-ratio, curing conditons, micro silica and superplasticizers is investigated. It is shown that changes in water pressure can describe bleeding, plastic shrinkage and hydration of cement.

1. INTRODUCTION

The aim of this project is to gain basic knowledge about the relationship between pore water pressure distribution and consolidation of the solid particles during the first hours after placing the paste. Consolidation of the granular material involves a water flow through the structure of the cement paste. The three directions of water transport are: "upward" by bleeding, "outward" by evaporation and "inward" by hydration.

1.1 Bleeding of cement paste

Bleeding is a form of sedimentation in which some of the water in the mix tends to rise to the surface of freshly placed cement paste. Settlement of the cement particles reduces the interparticle distance, principally in the vertical direction, and leaves a layer of water over the surface of the paste.

The bleeding process and the bleeding properties of cement paste are described, according to Powers/1/, by the bleeding rate and the bleeding capacity. The rate of bleeding as well as the bleeding capacity can be determined experimentally using the A.S.T.M. Standard C 232 test.

Figure 1 shows a bleeding curve, i.e. the relationship between the subsidence of surface and time, obtained from a sample of cement paste that was in a vessel 4.25 cm deep and 10 cm in diameter. The curve is made up of two sections: a straight line that indicates a period of constant rate of settlement and bleeding, followed by a period of diminishing rate.

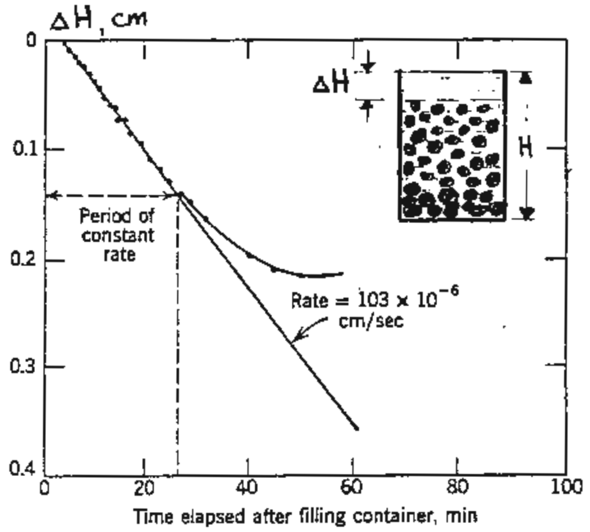


FIG.1 A typical bleeding curve. W/C=0.41. Powers/1/

Several models which describe bleeding during the constant rate period are suggested by Powers/1/. The bleeding process is supposed to be described as one involving the flow of fluid through a permeable structure and controlled by Darcy's law:

$$Q = K \cdot (\Delta h/L) \qquad (1)$$

where Q is the rate of flow; K is the coefficient of permeability; Δh is the drop in hydraulic head across the thickness of the permeable body, L being the thickness. The coefficient of permeability is expressed as a function of water content and physical properties of cement. The dimensionless hydraulic gradient $\Delta h/L$ depends on the weight of the solid material in unit volume of the mixture.

Experimental results show that equation (1) accurately represents a nonflocculent suspension of spheres. Application of equation (1) to the bleeding of cement paste, which is a moderately flocculent suspension, gives rise to several difficulties. The equation of flow has to be altered by empirical constants with uncertain physical meaning. The expression obtained in this way cannot be used to predict the bleeding rate of a given paste from its water content and the specific surface area of the cement.

The models presented by Powers do not take into account the degree of flocculation of cement particles and the fact that the hydraulic gradient is not constant during the bleeding process.

The bleeding process can be studied by measuring the changes in water pressure due to the settlement of cement particles. Immediately after placing the paste the water pressure $p_H(0)$ at a given depth H will be higher than the normal hydrostatic pressure for the respective depth:

$$p_H(0) - \rho_w g H = (\rho_s - \rho_w) V_s(0) g \qquad (2)$$

$p_H(0)$ = water pressure, Pa
ρ_s = density of solid particles, kg/m^3
ρ_w = density of water, kg/m^3
$V_s(0)$ = volume of solid particles supported by water per unit area, m^3/m^2
g = gravitational constant, m/s^2
$\rho_w gH$ = normal hydrostatic pressure, Pa

At the time t=0 the total volume of solid particles $V_s(0)$ is supported entirely by water. At time t a certain amount of particles has already settled and the water pressure $p_H(t)$ will be lower than the initial pressure:

$$p_H(t) - \rho_w gH = (\rho_s - \rho_w)V_s(t)g \tag{3}$$

The difference between the initial pressure and the pressure at time t should depend on the bleeding rate:

$$p_H(0) - p_H(t) = f(\text{bleeding rate}) \tag{4}$$

1.2 Plastic and chemical shrinkage

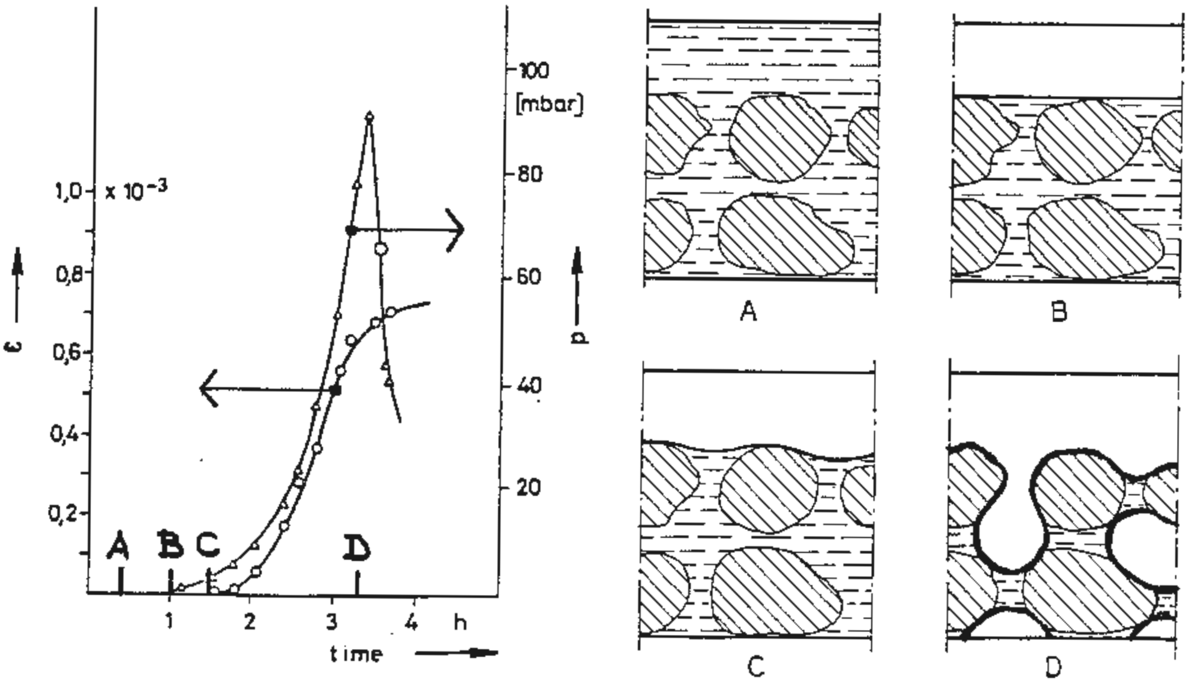
Plastic shrinkage is the contraction of fresh concrete that may occur within the first few hours after placing the mix.

A great number of papers on plastic shrinkage and plastic shrinkage induced cracks have been published during the last three decades with rather contradictory observations and explanations of the phenomenon. The fact that plastic shrinkage induced cracks are created as soon as the surface of the fresh concrete becomes dry is, however, a common observation.

The surface of evaporation may become dry if the rate of evaporation exceeds the rate of bleeding, or if the total amount of bleeding is very low. In such cases the water between the particles near the surface forms a complicated system of menisci. Capillary forces due to the surface tension of water decrease the pressure in the mixing water and the mean distance between the particles tends to be reduced.

Wittmann/2/ has simultaneously measured capillary pressure and plastic shrinkage in fresh concrete. An example is shown in Figure 2.a. The process is represented schematically in Figure 2.b:

A. A period of evaporation of the bleeding water
B. The surface of concrete becomes dry. The time required depends on the climate conditions and the bleeding properties of concrete
C. The evaporation continues and causes the formation of a system of water menisci on the surface. The water pressure decreases.
D. The capillary water becomes discontinuous = breakthrough pressure



a.   b.

FIG. 2.a Plastic shrinkage and capillary pressure of concrete as a function of time. Wittmann/2/
b Schematic representation of the process

According to Wittmann chemical shrinkage does not contribute to plastic shrinkage, mainly because the degree of hydration is very low during the first two-three hours.

The concrete mass' volume change is a function of the magnitude of the negative pressure and the mobility of individual particles in relation to each other (consolidation capacity).

For cement paste, as well as for concrete, the negative water pressure induced by capillary forces depends on climate conditions, bleeding properties and consolidation capacity of the paste. Consolidation capacity is a function of both W/C-ratio and the degree of hydration.

2. EXPERIMENTAL

The experimental program consists of measurements of small, positive changes in water pressure during the bleeding process and negative pressure due to capillary forces. The tests were carried out during the first 24 hours after placing the paste.

2.1 Raw materials

Two types of cement were used:

1) Skövde Standard Portland cement (Std-P)
Time of setting: 150 min
Specific surface area: 360 m^2/kg

2) Degerhamns cement, low alkali, sulphate resistent cement (D)
Time of setting: 150 min
Specific surface area: 300 m^2/kg

Condensed silica fume (MS) of Norwegian origin had a specific surface area of approx. 15000 m^2/kg and density 2200 kg/m^3. SiO content was 87-89%.

Superplasticizer "Flyttillsats V" (FM): a melamin based solution manufactured in Sweden.

2.2 Sample preparation

The mixing procedure was as follows:

1) Superplasticizer and micro silica were added to water before cement

2) Cement was added to the total amount of water in 4 or 5 portions, mixed each time for about 3 minutes

3) Period of rest of approx. 2 minutes

4) Final mixing period of approx. 3 minutes

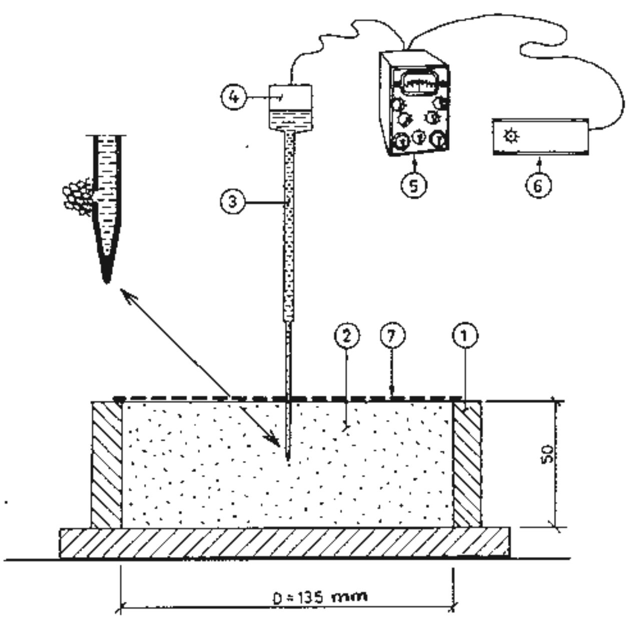
Total mixing time for the lower W/C-ratios was approx. 20 minutes.

2.3 Method of testing

A test method for continuous measuring of the water pressure has been developed. The test equipment is shown schematically in Figure 3.

The connecting tubing is filled with fresh deaerated water and the equipment is calibrated before each measurement.
Water pressure is measured simultaneously at three depths, 10,25 and 40 mm, using three sensors. Before inserting in cement paste each sensor is set to zero for respective depth by using a similar sample container as in Figure 3 filled with water. In this way the end of the settlement can be noticed much easier on the instruments.

Different curing conditions can be simulated by varying the boundary conditions at the surface of the cement paste.



1. Sample container
2. Cement paste

Pressure sensor:
3. Connecting tubing
4. Pressure transducer; semiconductor strain gages measure the deflection of the diaphragm in its center.

5. Amplifier
6. Datalogger

7. Boundary conditions (curing conditions):
   a. Free evaporation:
      temperature=20°C
      relative humidity=50%
      Wind speed approx 0.5m/s
   b. Sealed curing: approx. 3 mm liquid paraffin
   c. Water curing: approx. 5 mm water

FIG. 3 Equipment for measurement of water pressure

3. RESULTS

3.1 <u>Changes in pressure due to gravitation; bleeding</u>

The diagram in Figure 4 shows changes in pressure in cement paste with W/C-ratio 0.4. Only the differences between effective pressure and hydrostatic pressure are plotted. The initial pressure p_{iH} at a given depth is a function of the density of the paste:

$$p_{iH}(0) = (\rho_p - \rho_w)H \qquad \text{[mm water]} \qquad (5)$$

ρ_p = density of paste, kg/m^3
ρ_w = density of water, kg/m^3
H = depth, m

In this case the density of the paste was 1950 kg/m^3. As can be seen in Figure 4 the initial pressures at all three depths are represented accurately by equation (5).

The curves in Figure 4 have several interesting characteristics:

1. only the pressure at 40 mm depth shows a period of constant rate.

2. the pressure gradient between 25 and 40 mm depth decreases faster than between 10 and 25 mm
3. after approx. 25 minutes the pressure gradient in the lower part of the sample becomes zero
4. the pressure gradients are not constant during the bleeding process

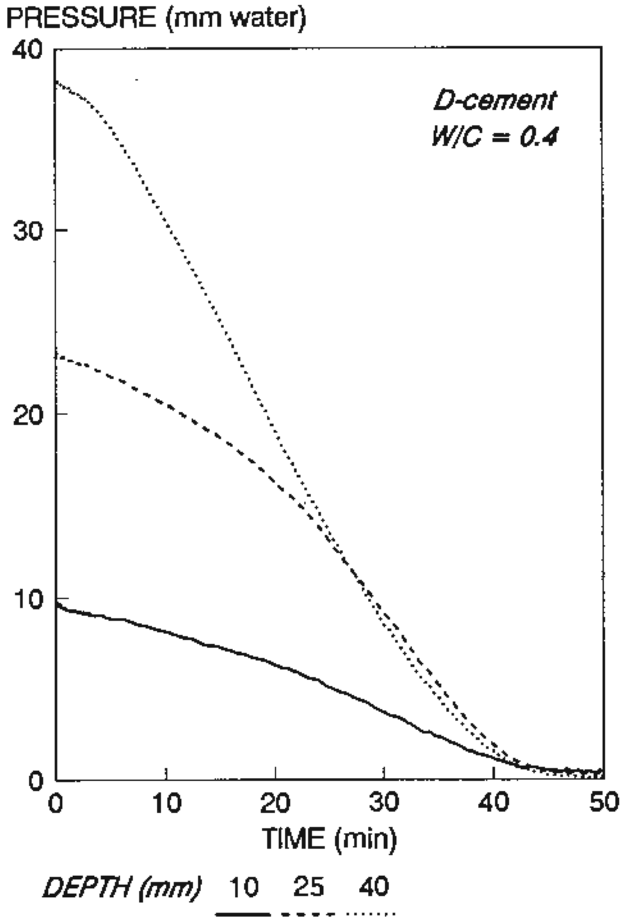


FIG. 4 Changes in pressure in cement paste. W/C=0.4.

3.1.1 Effect of water content and specific surface area

Figure 5 shows changes in pressure at 40 mm depth obtained from different cement pastes. All curves show a period of constant rate. The bleeding time for Std-P cement is approx. 40 minutes longer than for D cement for both 0.35 and 0.5 W/C-ratio; which correspond to the higher specific surface area of Std-P. Both bleeding rate and the total amount of bleeding, that was measured separately, seem to be a function of the specific surface area.

The curves in Figure 5 confirm Powers' assumptions and results according to which, the bleeding properties of cement paste are dependent on the concentration of solid particles and the specific surface area of cement.

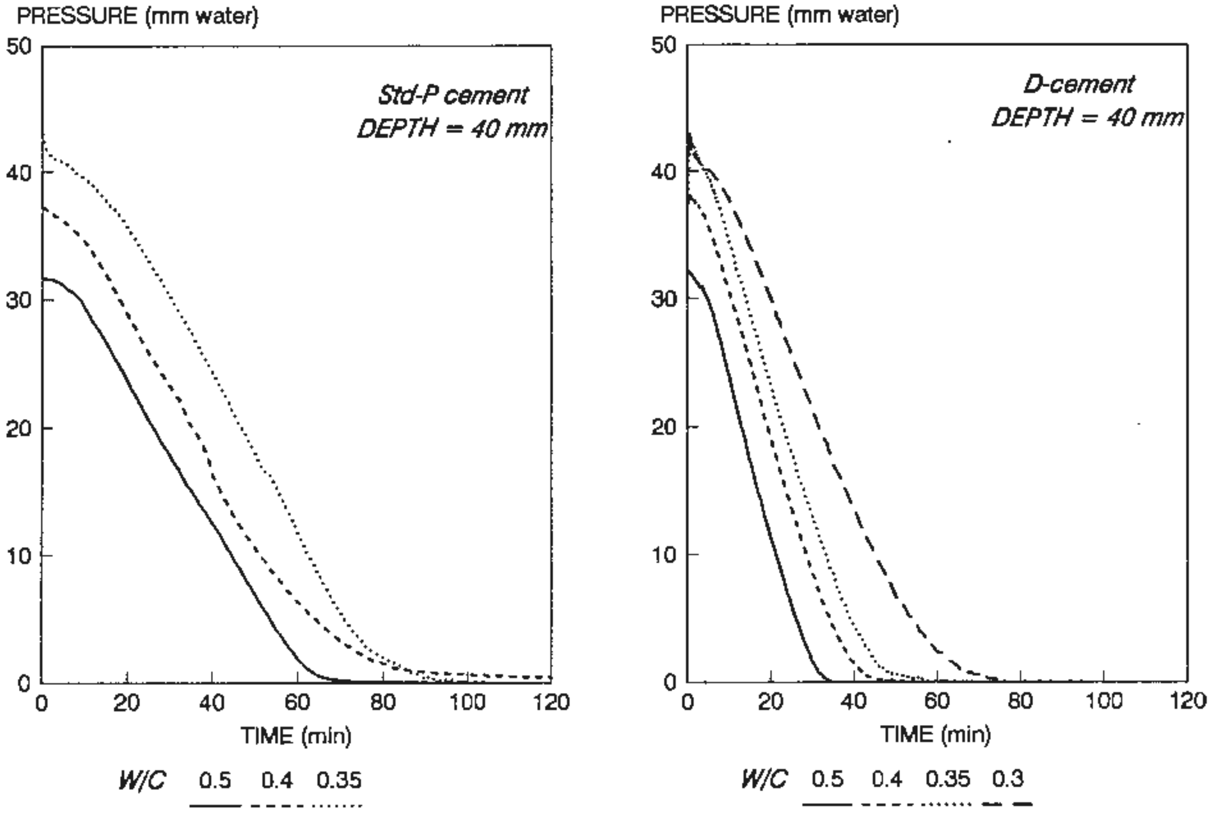


FIG. 5 The effect of W/C-ratio and specific surface area

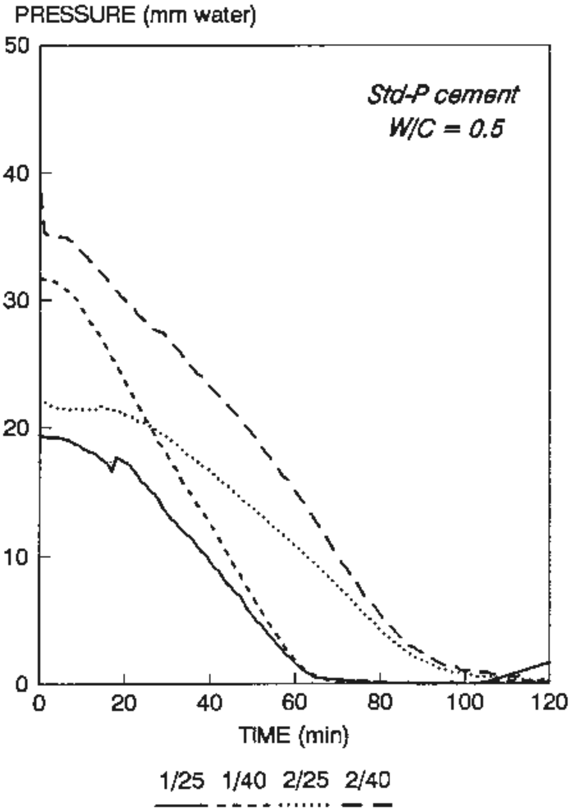


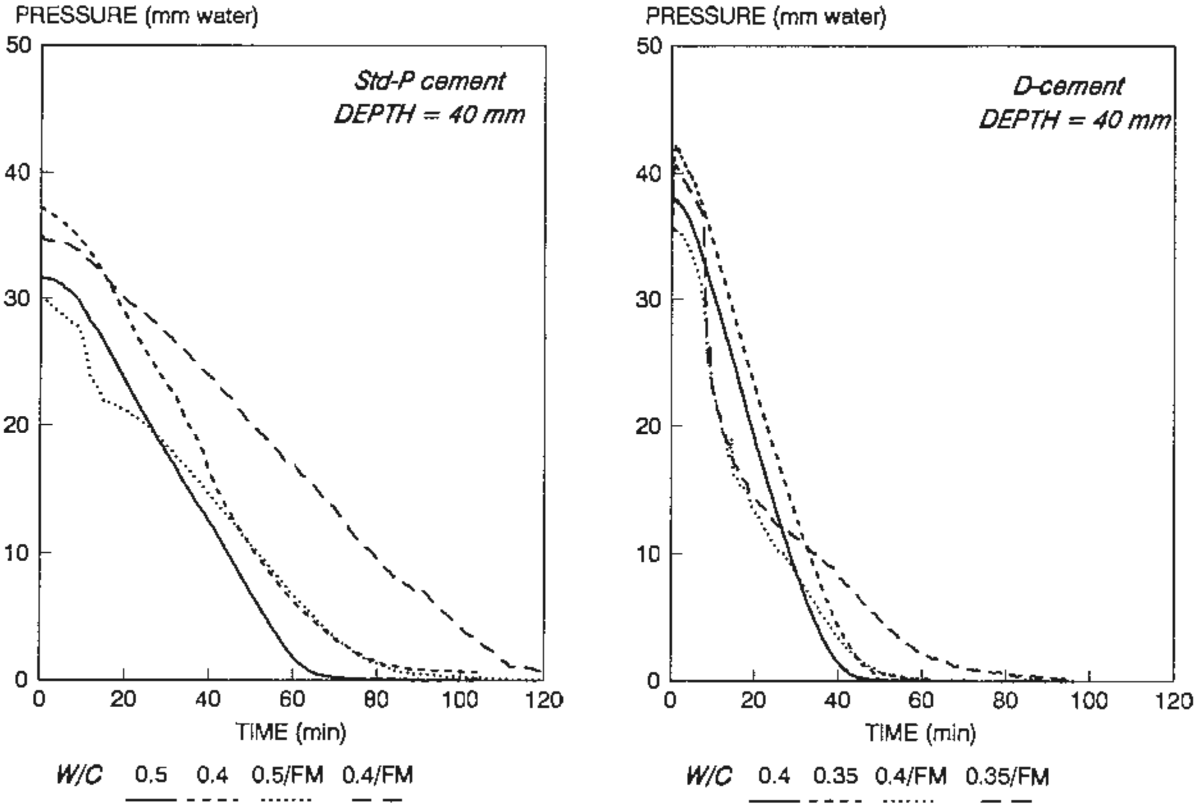
FIG. 6 The effect of the mixing procedure

3.1.2 Effect of mixing procedure

Figure 6 shows the influence of the mixing procedure on bleeding rate. Firstly paste was mixed as described in section 2.2. Secondly paste was mixed by adding small amounts of water, during a period of approx 10 minutes, to the total amount of cement. Paste 2 had a slightly higher density than paste 1 which does not justify a 30 minutes longer bleeding time. The two mixing procedures seem to have different dispersion effects.

3.1.3 Effect of superplasticizers

Figure 7.a shows the effect of superplasticizer (FM) on Std-P cement paste with W/C-ratio 0.4 and 0.5. Addition of superplasticizer had a greater effect on the paste with lower W/C-ratio. The same superplasticizer had a completely different effect on cement pastes with D cement; Figure 7.b. After approx 10 minutes from placing the paste a short period of very high pressure rate begins; it looks like a collapse of the system. Afterwards a period of "normal" rate follows. It is impossible at this stage to explain such behaviour. It can be the mixing procedure as well as the mixing time or the particular effect of this plasticizer on this type of cement.

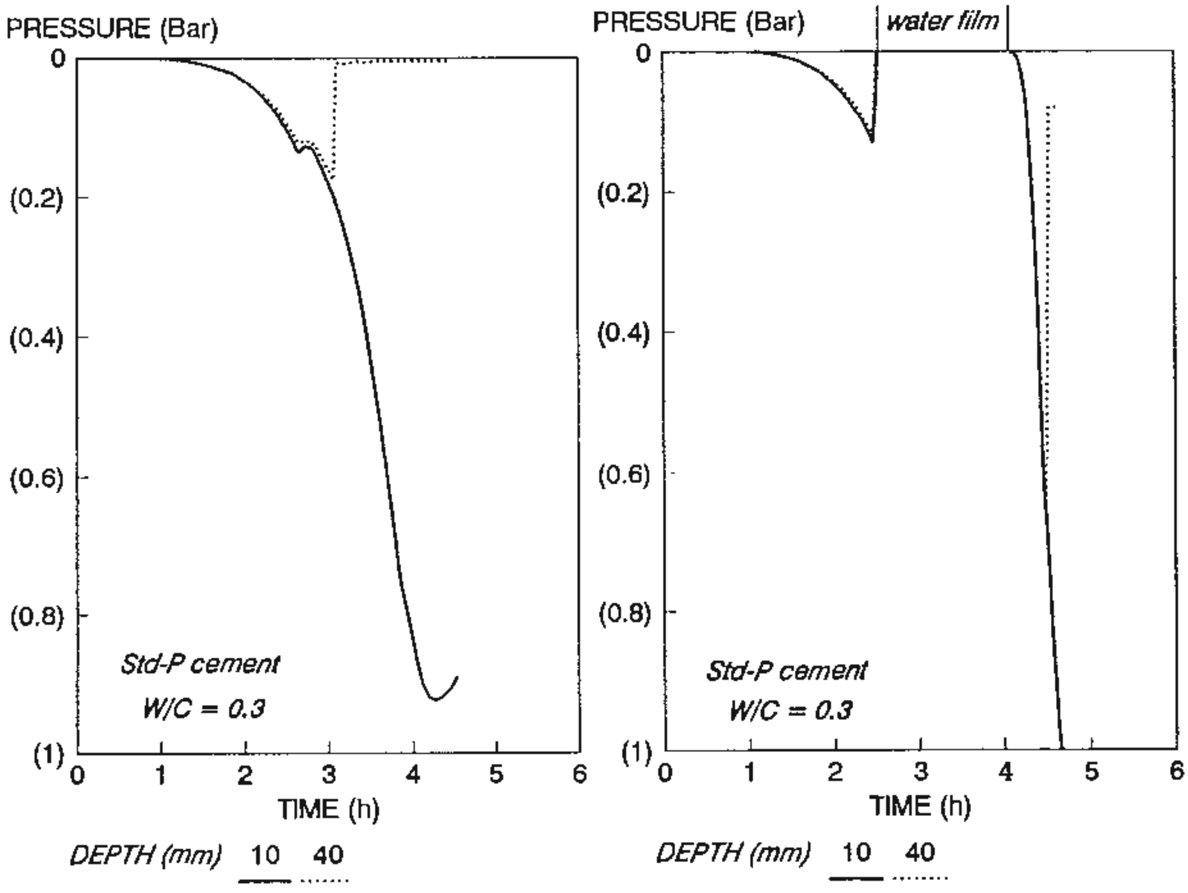


a. b.

FIG. 7 The effect of superplasticizer

3.2 Changes in pressure due to capillary forces

Changes in water pressure due to capillary forces have been measured in a great number of cement pastes with different W/C-ratios. Typical curves are shown in Figure 8.a. The pressure was measured simultaneously at two points: 10 and 40 mm below the surface. The surface of this paste, exposed to the climate conditions described in Section 2.3, became dry after 1 h from placing it in the mould. At this time the water pressure began to decrease at a relatively low rate. After approximately 3 h the pressure at 40 mm depth suddenly became zero (break-through pressure) while the pressure at 10 mm depth continued to decrease. The measurement was interrupted after 4.5 h. To demonstrate that water menisci are the source of the negative pressure, the surface of the paste, represented by the curves in Figure 8.b, was rewetted when the pressure at both points reached approx -0.15 Bar. The pressure became zero after some minutes. When the surface dried again the water pressure decreased at a higher rate. This change in the pressure rate depends on a lower consolidation capacity of the paste resulting from further hydration of cement.



a. b.

FIG. 8 Negative pressure due to capillary forces

3.2.1 Effect of specific surface area

In Figure 9 two cement pastes with W/C-ratio 0.3 are compared. The water pressure in the paste with D-cement begins to decrease approx 3 h later than in the paste with Std-P cement. This can be explained by the difference in bleeding properties of the two cement pastes. The surface of D paste dries later because both the bleeding rate and the total amount of bleeding are higher in D paste than in Std-P paste.

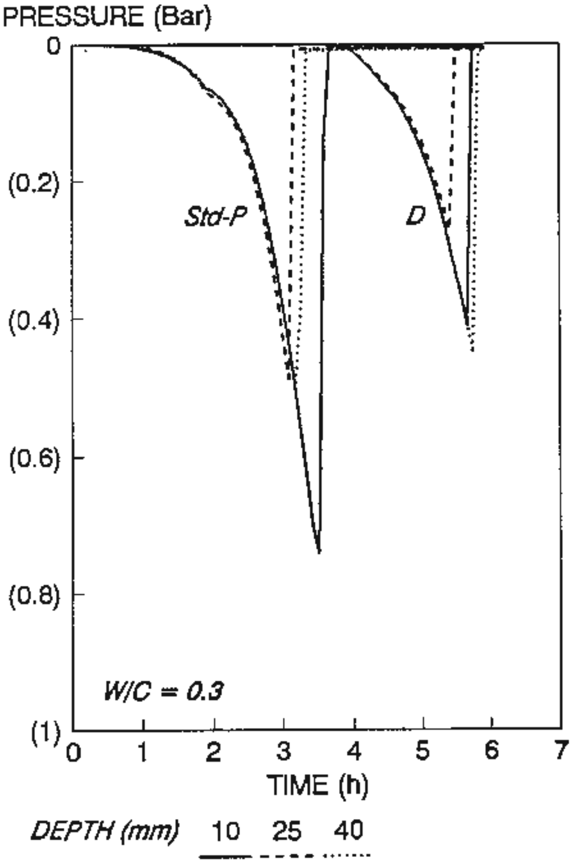


FIG. 9 The effect of specific surface area

3.2.2 Effect of curing conditions

In Figure 10 three equivalent cement pastes are compared. The curves represent the water pressure at 40 mm depth. The surface of each paste was exposed to different curing conditions: free evaporation (solid line), sealed curing (dashed line) and water curing (dotted line).

In the first case (solid line) the pressure begins to decrease after 1 h. The second paste (dashed line), where the surface was sealed with liquid paraffin, shows an unexpected result: after approx 3 h the pressure begins to decrease though the evaporation was prevented. The weight of the sample was determined continuously during 15 h and no loss of water was observed. On the surface of the third paste (dotted line) a water layer of approx. 5 mm was manitained throughout the experiment. The pressure begins to decrease at the same time as for the

sealed sample, but at a much lower rate.
For lower W/C-ratios the negative pressure seems to be caused by both capillary forces and the hydration of the cement. The pressure development in the water cured sample should be a function of the degree of hydration and permeability of the paste.

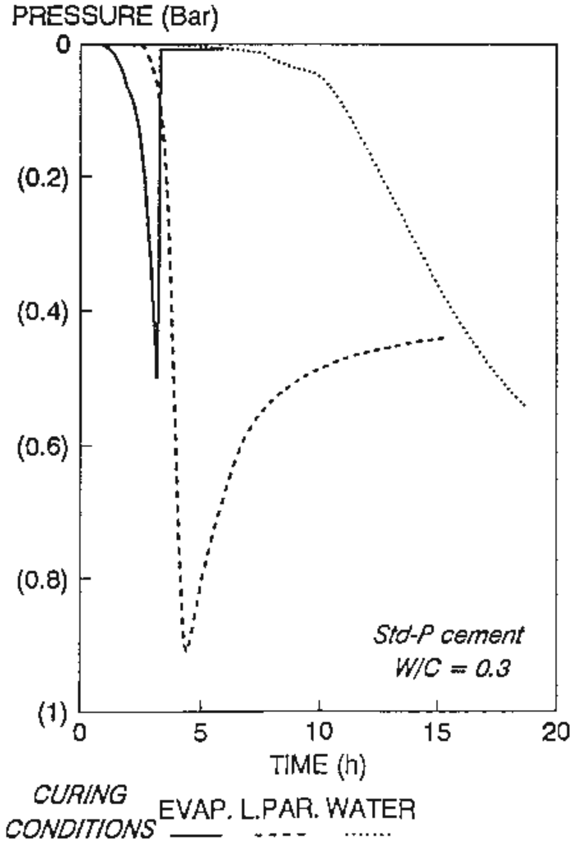


FIG. 10 The effect of curing conditions

3.2.3 Effect of W/C-ratio

The diagrams in Figure 11 show the pressure development in cement pastes with W/C-ratio in the range 0.25-0.5. Only measurements at 40 mm depth are plotted. The time at which the surface becomes dry and the pressure begins to decrease is affected by the bleeding properties of each cement paste. Higher W/C-ratio implies both higher bleeding rate and total amount of bleeding. The rate at which the water pressure decreases depends on W/C-ratio and the degree of hydration.

3.2.4 Effect of superplasticizer

The diagram in Figure 12 shows the effect of superplasticizer (FM) on the negative pressure in cement paste with W/C-ratio 0.25. The dotted curve, that represents the cement paste with superplasticizer, is displaced approx 1 h, but almost parallel to the solid curve. It is difficult to say at this stage if this displacement is caused by the retarding effect of the superplasticizer or by a slight change in the bleeding properties of the paste.

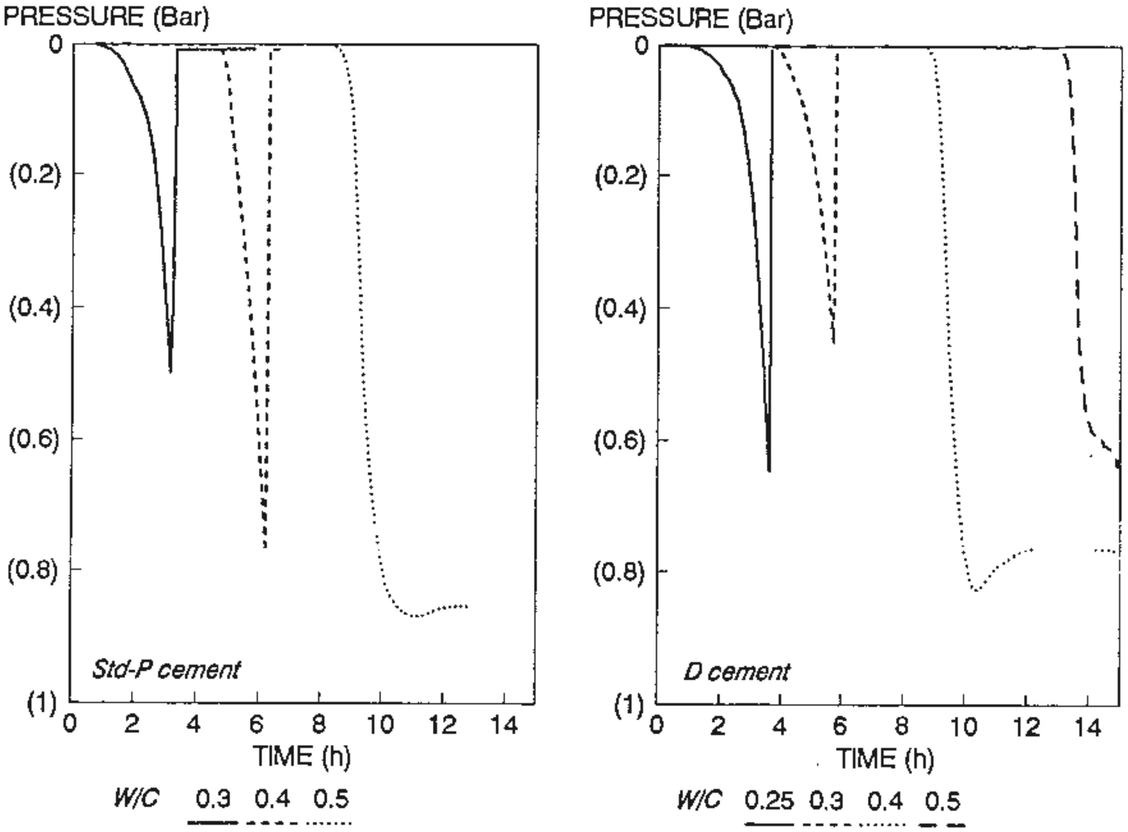


FIG. 11 The effect of W/C-ratio and type of cement

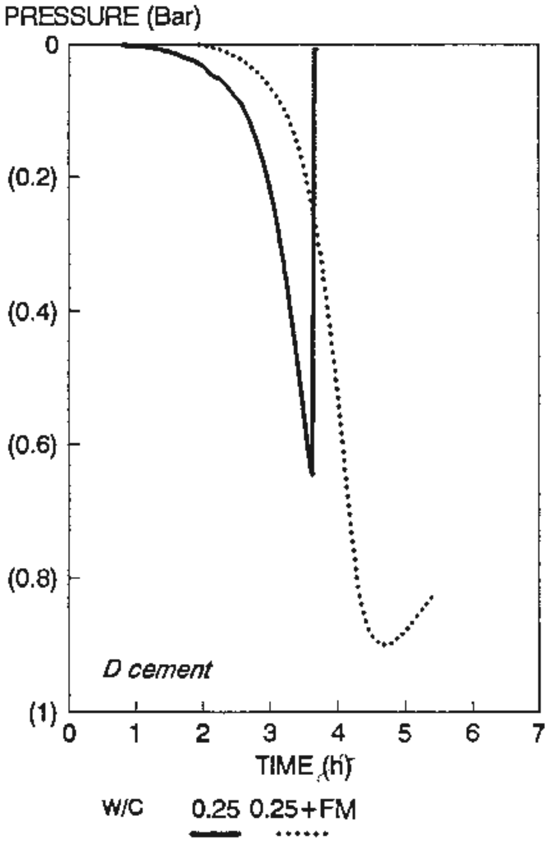


FIG. 12 The effect of superplasticizer. 40 mm depth.

3.2.5 Effect of micro silica

Two cement pastes are compared in Figure 13. In one of the pastes 20% of the volume of the cement was replaced with micro silica so that the water to solid content ratio is the same for both cement pastes. By replacing 20% cement with micro silica the bleeding properties have changed and the surface dries approx 4 h earlier. The rate at which the water pressure decreases is also different. A higher degree of hydration implies a lower consolidation capacity.

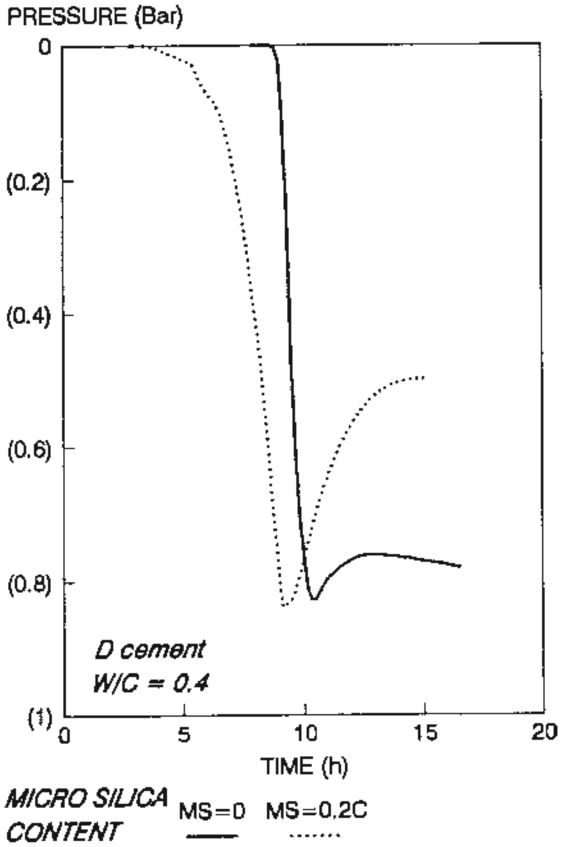


FIG. 13 The effect of micro silica

4. DISCUSSION

To find out the limitations and the reliability of the method of testing, a great number of mixtures of water with cement, fly ash or micro silica have been examined.

Measurements of changes in pressure during settlement, in mixtures with a low concentration of solid particles, show that the method can be used for the estimation of the particle size distribution. Application of equation (3) on the settlement of flyash particles, assuming that the settling velocity is directly proportional to second power of particle diameter (Stokes's law), gave promising results.

In higher concentrations the particles interfere with one another while settling and the settling velocity is affected by interparticle forces. Results presented in this paper show that the interparticle forces depend not only on the type of cement and W/C-ratio but also on the mixing procedure and admixtures. These results led us to believe that measurements of water pressure during settlement can describe the degree of flocculation of the solid particles.

There are several problems of practical importance that could be investigated by measurements of water pressure during settlement of cement particles. The rheological properties of fresh concrete and the effect of superplasticizers on the degree of flocculation of cement particles are examples of such problems.

Concerning plastic shrinkage the results of this study show that negative pressure is a combined effect, at least for lower W/C-ratios, of both water menisci and hydration of cement. It is rather obvious that there is a relationship between the negative pressure in the mixing water and the contraction of the cement paste, but the volume change can never exceed the volume of evaporated water.

Changes in water pressure under different curing conditions can demonstrate the efficiency of water curing especially for lower W/C-ratios.

A more profound examination of the consolidation capacity of the cement paste should bring us closer to understanding the properties of fresh concrete.

7. ACKNOWLEDGEMENT

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