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THE INFLUENCE OF Na₂O ON THE HYDRATION OF C₃A.
II. SUSPENSION HYDRATION.

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ABSTRACT

The influence of Na₂O on the hydration of C₃A was studied in suspensions from the start of the reaction onwards. The heat evolution rate in very early stages of the hydration, measured at varying NaOH concentrations, and SEM, indicate that at NaOH concentrations larger than 0.1 M the reaction mechanism differs from that in water. In these solutions the hydration is thought to be controlled at first by a more or less amorphous Ca(OH)₂ layer.

Der Einfluss von Na₂O auf die Hydration des C₃A wurde untersucht vom Anfang der Reaktion an. Die Wärmeentwicklungsgeschwindigkeit in den ersten Hydrationsstadien, gemessen bei verschiedenen NaOH-Konzentrationen, und SEM-Aufnahmen deuten auf einen anderen Reaktionsmechanismus bei NaOH-Konzentrationen größer als 0.1 M. In diesen Lösungen ist die Hydratation im Anfang beherrscht durch eine mehr oder weniger amorfe Ca(OH)₂-Schicht.
Introduction

In a previous paper (1) the influence of Na₂O on the hydration of C₃A in pastes was reported. To elucidate some of the aspects of the hydration mechanism, especially during the first minutes of hydration, C₃A hydration in suspension (w/s = 100) was studied from the start of the hydration onwards using isoperibolic calorimetry.

Experimental

Methods for SEM, X-ray analyses and the arresting of hydration were as described previously (1). Conductivity measurements were performed as described by de Jong, Stein and Stevels (2).

The heat evolution rates in the suspensions were measured using a precision calorimeter LKB 8700-1. The principles of these measurements have been described by Wadsø (3). An isoperibolic calorimeter consists in principle of a nearly adiabatic reaction vessel in an environment of constant temperature. The total heat Q(t₁) developed after a certain hydration time t₁ can be calculated from the following equation (4):

\[ Q(t_1) = \alpha \Delta T(t_1) + \beta \int_0^{t_1} \Delta T(t) \, dt, \]

where

- \( \alpha \) = heat capacity of reaction vessel + contents,
- \( \Delta T(t) \) = temperature difference between environment and reaction vessel after time t (presumably),
- \( \beta \int_0^{t_1} \Delta T(t) \, dt \) = total heat leak during t₁ seconds.

\( \Delta T(t) \) was calculated by measuring the change in resistance of a thermistor \( \Delta R \) with a Wheatstone bridge. The heat leak from the reaction vessel to the environment was found to be proportional to \( \Delta T(t) \).

The experiments were conducted with an environment temperature of 25°C ± 0.01°C and the maximum temperature rise in any experiment was 0.7°C.

The materials used and methods for determining sodium and calcium were those described previously (1). Aluminium was determined as described by Pribil and Vesely (5).

Hydration of C₃A in NaOH Solutions in Suspensions

Results

Fig. 1 shows the cumulative heat evolution for C₃A hydrated in suspension in water and NaOH solutions (w/s = 100). Fig. 2 shows the heat evolution rate obtained by differentiating the curves in Fig. 1. In all cases the heat evolution rate is high during the first seconds and decreases rapidly as hydration proceeds. At higher pH (>0.1M NaOH) a second peak in the heat evolution rate appears which is accelerated by increasing NaOH concentrations.

In Fig. 3 the initial heat evolution rate is plotted against
FIG. 1
Cumulative heat evolution from C₃A hydrated in water and NaOH solutions

FIG. 2
Heat evolution rates of C₃A hydrated in water and NaOH solutions
the NaOH concentration. This "initial" heat evolution rate is the maximum rate of increase of the thermistor temperature, which is reached a few seconds after the first contact between the reactants. A time lag arises because of the delay in the response of the thermistor.

At low NaOH concentration (<0.1M) the initial heat evolution rate decreases rapidly with increasing NaOH concentration while higher NaOH concentrations effect only a minor additional decrease. X-ray analyses of the hydration products are shown in Table I.

Fig. 4 shows SEM's of the hydration products on the surfaces of particles after 10 seconds and 10 minutes hydration. In water without NaOH addition the plate-like hydrates are, in many cases, orientated more or less perpendicularly to the surface of a particle instead of the predominantly parallel orientation in paste hydration (1).

**TABLE I**

X-ray Data for hydration of C₃A in NaOH solutions

<table>
<thead>
<tr>
<th>NaOH (M)</th>
<th>Hydration time (min)</th>
<th>C₂AH₈</th>
<th>C₄AH₁₃</th>
<th>C₃AH₆</th>
<th>C₃A</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>w</td>
<td>-</td>
<td>w</td>
<td>vs</td>
</tr>
<tr>
<td>0.04</td>
<td>10</td>
<td>-</td>
<td>vw</td>
<td>vw</td>
<td>vs</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>-</td>
<td>w</td>
<td>vvw</td>
<td>vs</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>-</td>
<td>-</td>
<td>s</td>
<td>s</td>
</tr>
</tbody>
</table>

Fig. 5 shows the change in conductivity of C₃A suspensions during the hydration in H₂O and dilute NaOH solutions

**Discussion**

The decrease in conductivity (Fig. 5) after a certain hydration time (5.7 h for a suspension of C₃A in water) indicates the point during the hydration at which the conversion of hexagonal hydrates into C₃AH₆ becomes important enough to cause the solution to leave the metastable point of coexistence of C₂AH₈, C₄AH₁₃ and aqueous solution (9). Both the conductivity experiments and the behaviour of the second heat evolution peak shows that this conversion is accelerated when the NaOH
FIG. 4
SEM's of C₃A hydrated in suspension (w/s = 100) for
a 10 sec in H₂O
b 10 sec in 0.1M NaOH
c 10 sec in 2M NaOH
d 10 min in H₂O
e 10 min in 0.1M NaOH
f 10 min in 2M NaOH
In the early hydration stages, the heat evolution rate in pastes is about equal to that in suspensions after the same time. This is remarkable in view of the different orientation of the platey crystals in the hydrate layer in the two cases, and rules out a direct screening action of the hydrates.

The SEM results show that a hydrate layer exists on the C₃A surface. Because of misfit between the latter and the hydrates, some space will exist between them. Three possible explanations of retardation of C₃A hydration will be considered.

1) This space is filled by an aqueous solution saturated towards the anhydrous C₃A, the hydration rate of the C₃A then being determined either by the diffusion of ions out of the space concerned and of water into it, or by the growth of the hexagonal hydrates in the layer.

2) Feldman and Ramachandran (10) proposed that the hydration of C₃A is impeded, not by hydrates, but by the blocking of movements of surface dislocations by adsorption of ions, such as OH⁻. In this case, the second peak would be caused by the
recrystallization of hexagonal hydrates because the latter is accompanied by some changes in the concentrations of these ions.

3) An aqueous solution occurs in the space between the C₃A and the hexagonal hydrates, in which conditions differ from those in the outside solution; this leads to the formation in this space of an amorphous solid that can match the C₃A surface on an atomic scale more closely than can a hexagonal hydrate (11). The role of the hexagonal hydrates is then an isolating one, and the rate determining step is the transport between the crystals of the hexagonal hydrates of ions, which tend to attack the retarding agent.

Regarding these three reaction mechanisms the following remarks can be made:

According to the "saturated solution" mechanism the heat evolution rate at t = 0 corresponds to a situation in which the dissolution of C₃A is not hindered by hydrates, and follows the equation

\[
\text{C}_3\text{A} + 6\text{H}_2\text{O} \rightarrow 3\text{Ca}^{2+}(\text{aq}) + 2\text{Al(OH)}_4^{-}(\text{aq}) + 4\text{OH}^{-}(\text{aq})
\]

However, the dependence of the heat evolution rate at t = 0 on the NaOH concentration is too weak, especially at higher concentrations, to be compatible with the mechanism, at least if equal volumes of liquid are assumed to be saturated per unit of time in all cases. This mechanism could account for the facts only if with increasing NaOH concentration either a larger volume would be accessible to saturation by C₃A, or increasing contributions of hydrate precipitation to the heat evolved at t = 0 are assumed. Both alternatives are improbable; the former because large NaOH concentrations promote precipitation of Ca(OH)₂, the latter because this precipitation is an endothermic process.

According to the mechanism postulated by Feldman and Ramachandran (10), the influence of increasing NaOH concentrations at t = 0 is caused by increasing difficulty in movement of dislocations; the levelling off with higher NaOH concentrations is due to all surface sites being occupied by OH⁻ ions, the decrease of the heat evolution rate is due to gradual exhaustion of surface dislocations, and the second peak can be ascribed to a decrease in OH⁻ concentration, as has indeed been observed in suspensions at that particular stage of reaction by de Jong, Stein and Stevels (9). However, this effect is small (the pH changes from 12.2 to 12.1), especially when compared with the OH⁻ concentrations present, for instance, in 4M NaOH where the second peak remains quite remarkable (Fig. 2). Thus, the data do not support a surface dislocation movement inhibition by absorbed OH⁻ ions.

The following mechanism appears to be compatible with the results: In NaOH solutions of high concentration the amount of Ca²⁺ going into solution as a result of hydration of the C₃A must be small. Aluminate ions may go into solution but Ca²⁺ ions stay behind, their charge being compensated by OH⁻ ions. Rearrangement into crystalline Ca(OH)₂ is prevented by the adjacent C₃A. The resulting primary layer thus formed prevents contact between C₃A and the solution, and can follow the C₃A
surface closely because of its in situ formation. Figs. 4a-c show that after 10 seconds hydration in water a structure consisting of plates reminiscent of the hexagonal hydrates is formed, while in 2M NaOH a dense layer is formed which might be capable of preventing contact between the C₃A and the solution. Some H₂O and OH⁻ will penetrate through this layer and react with aluminate ions from the C₃A to form Al(OH)₄⁻. These aluminate ions replace part of the OH⁻ ions in the layer, and at some distance from the C₃A rearrangement into hexagonal hydrates may occur, as is shown by X-ray analyses (Table I) and SEM (Fig. 4d-f).

The decrease in the heat evolution rate with time (Fig. 2) is ascribed to the layer becoming thicker, and the second peak to recrystallization of the hydrates into C₃AH₆, which affects the concentration gradients in the vicinity of the C₃A sufficiently to destabilize the primary layer. This hypothesis would explain the absence of X-ray reflections due to crystalline Ca(OH)₂ and the presence of only weak lines due to the hexagonal hydrates (Table I).

It appears from the conductivity curve that, after the formation of the layer seen in Fig. 4b, some hydrate nucleates in the surrounding liquid. This is shown by the conductivity maximum found after about 1 minute (Fig. 5; the SEM shown in Fig. 4b was taken after 10 sec., which is before the conductivity maximum). This supports the existence of two hydrates: one at the C₃A surface, a second one somewhat further away from it. The second one is the one seen in Figs. 4e-f, and is thought to be a disordered form of one of the hexagonal hydrates playing an isolating rather than a retarding role.

The mechanism described is not necessarily the mechanism operative in H₂O or in Ca(OH)₂ solutions. On the contrary, the shape of the heat evolution rate at t = 0 versus the NaOH concentration graph (Fig. 3) suggests that a different mechanism becomes operative when the NaOH concentration exceeds 0.1M.

Hydration of 0.25Na₂O.2.75CaO.Al₂O₃ in Suspensions

Results

The total heat developed up to a certain hydration time and the heat evolution rate at the time concerned are both shown in Fig. 6. The total heat liberated after a certain hydration time and the heat liberation rate during the N₀.25C₂.75A hydration are somewhat lower than for C₃A (Figs. 1 and 2).

In Fig. 7 the conductivity of a suspension of N₀.25C₂.75A is plotted against time. At certain times designated by A, B, C and D the hydration was arrested and X-ray analyses of the solid phases and chemical analyses of the liquid phase were performed. Table II shows the results of these analyses.

Discussion

When N₀.25C₂.75A is hydrated in suspensions with w/s = 100 no second peak in the heat evolution rate curve appears (Fig. 7). The total heat developed up to a certain hydration time is only slightly less than the total heat developed during the hydration
FIG. 6
Cumulative heat evolution and heat evolution rate during the hydration in suspension (w/s = 100) of $\text{N}_0.25\text{C}_2.75\text{A}$ in $\text{H}_2\text{O}$

FIG. 7
Specific conductivity of a suspension (w/s = 100) of $\text{N}_0.25\text{C}_2.75\text{A}$ in $\text{H}_2\text{O}$

TABLE II
X-ray and chemical analyses data for hydration of $\text{N}_0.25\text{C}_2.75\text{A}$ in $\text{H}_2\text{O}$

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>$\alpha_2\text{AH}_8$</th>
<th>$\alpha_4\text{AH}_{19}$</th>
<th>$\alpha_3\text{AH}_6$</th>
<th>$\text{N}_0.25\text{C}_2.75\text{A}$</th>
<th>$\text{Ca}^{2+}$</th>
<th>$\text{Al}^3\text{(OH)}_4^-$</th>
<th>$\text{Na}^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3 vw</td>
<td>-</td>
<td>-</td>
<td>vs</td>
<td>1.54</td>
<td>1.47</td>
<td>0.58</td>
</tr>
<tr>
<td>B</td>
<td>32 w</td>
<td>-</td>
<td>vw</td>
<td>s</td>
<td>0.62</td>
<td>0.75</td>
<td>1.22</td>
</tr>
<tr>
<td>C</td>
<td>200 s</td>
<td>m</td>
<td>m</td>
<td>w</td>
<td>0.06</td>
<td>0.91</td>
<td>1.86</td>
</tr>
<tr>
<td>D</td>
<td>410 s</td>
<td>-</td>
<td>vs</td>
<td>vw</td>
<td>0.42</td>
<td>1.96</td>
<td>2.40</td>
</tr>
</tbody>
</table>

of $\text{C}_3\text{A}$. Thus the hydration characteristics of $\text{N}_0.25\text{C}_2.75\text{A}$ in suspensions are almost similar to those of $\text{C}_3\text{A}$, while in pastes there exists a significant difference (1). The similarity between the hydration in suspension of $\text{C}_3\text{A}$ and $\text{N}_0.25\text{C}_2.75\text{A}$ is to
be expected in view of the small NaOH concentrations effected by
the former (Fig. 2). Again it appears (see ref. 1) that the NaOH
concentration in the solution is more important than changes in
solid state properties.

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