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Published in:
Cement and Concrete Research

DOI:
10.1016/0008-8846(76)90029-6

Published: 01/01/1976

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THE ENTHALPIES OF FORMATION AND OF DEHYDRATION
OF SOME AFm PHASES WITH SINGLY CHARGED ANIONS*.

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(Communicated by H. F. W. Taylor)
(Received June 23, 1976)

ABSTRACT

The enthalpies of formation of some AFm phases of the type Ca$_2$Al(OH)$_6$X.xH$_2$O (X = Cl$^-$, Br$^-$, I$^-$, NO$_3^-$, ClO$_4^-$, ClO$_3^-$, BrO$_3^-$ and IO$_3^-$) were determined by measuring the heats of solution in hydrochloric or perchloric acid. From the differences between the heats of solution of the compounds and their dehydration products, the enthalpies of dehydration were established. They increase with increasing enthalpies of hydration of the individual anions X in aqueous solution. However, this relationship is not the same for halide ions as for oxy-anions.

Die Bildungsenthalpien einiger AFm Phasen Ca$_2$Al(OH)$_6$X.xH$_2$O (X = Cl$^-$, Br$^-$, I$^-$, NO$_3^-$, ClO$_4^-$, ClO$_3^-$, BrO$_3^-$ und IO$_3^-$) wurden bestimmt durch Messung der Lösungswärme dieser Verbindungen in HCl oder HClO$_4$. Mittels der Differenzen zwischen den Lösungswärmen der hydratisierten und dehydratisierten Verbindungen wurden die Dehydrationsenthalpien festgestellt. Diese nehmen zu mit steigender Hydrationsenthalpie der individuellen Anionen X in wässriger Lösung; aber die Relation ist verschieden für Halogenionen und für Oxy-anionen.

Introduction

A number of data concerning the enthalpies of formation of calcium aluminates and silicates have been published (1-13). These values are based partly on calculated, partly on experimentally determined quantities. Thus Babushkin and Mchedlov-Petrosyan (1) calculated the enthalpy of formation of $\text{C}_4\text{AH}_{13}$ (-1983 kcal) making use of the contributions to this quantity from $\text{Ca(OH)}_2$, $\text{Al(OH)}_3$ and the lattice water. The contributions from $\text{Ca(OH)}_2$ and $\text{Al(OH)}_3$ to the enthalpy of formation were calculated from that of $\text{C}_3\text{AH}_6$ (-1317.6 kcal), on the supposition that this compound consists of $3\text{Ca(OH)}_2.2\text{Al(OH)}_3$, and from the enthalpy of formation of $\text{C}_2\text{AH}_5$ ($2\text{Ca(OH)}_2.2\text{Al(OH)}_3$), -1078 kcal (11). Such calculations may be justified in some cases, but in others they lead to large errors. Thus the enthalpy of formation of $\text{C}_3\text{AH}_6$ calculated from that of $\text{C}_3\text{A}$ (8) using an approximate general relationship for the enthalpy of hydration of anhydrous compounds (14, 15) is -1283.5 kcal, but the experimental value is -1326 kcal (8). Clearly there is a need for experimental data.

The AFm compounds of general formula $\text{Ca}_2\text{Al(OH)}_6X.x\text{H}_2\text{O}$ have almost identical crystal structures, which are essentially unaffected by removal of the interlayer water (16-18). Dehydration causes mainly a decrease of the layer thickness $c$ and is reversible as long as the dehydration conditions are not too severe. The question is whether any relationship exists between the enthalpies of dehydration of these compounds and the enthalpies of hydration of the individual anions $X$. For the clay minerals such as montmorillonite and vermiculite, the cations located in the interlayers have an important effect on the ability to accommodate interlayer water (19-21); the enthalpies of dehydration of these clay minerals depend on the enthalpies of hydration of the cations in aqueous solution. In the AFm phases anions might play a similar role.

Preparation and Characterization

Samples were prepared by the following methods:

a. To a suspension of $\text{C}_3\text{A}$ (2.7 g) in 2-propanol (50 ml), prepared as described by De Jong (22), was added a solution of 50 to 100 mmoles $\text{CaX}_2.z\text{H}_2\text{O}$ in CO$_2$-free water (500 ml). The 2-propanol was used to prevent a too rapid hydration of $\text{C}_3\text{A}$. The reaction mixture was magnetically stirred for at least five days at room temperature. The precipitate was filtered off, washed with a methanol-water mixture followed by a methanol-acetone mixture, and dried over saturated CaCl$_2.6\text{H}_2\text{O}$ (37% relative humidity) in a vacuum desiccator.

b. $\text{C}_3\text{AH}_6$ was prepared by heating $\text{C}_3\text{A}$ (2.7 g) in water (250 ml) at 175°C in an autoclave for 120 hours, as described by Thorvaldson (2).

c. "$\text{C}_4\text{AH}_{13}$" was prepared at 0°C by adding a solution of sodium aluminate to a saturated solution of calcium hydroxide in such a way that the Ca/Al ratio in the solution was always greater than two. This method is analogous to that employed by Buser (23).

d. Samples of $\text{Ca}_2\text{Al(OH)}_6\text{NO}_3.x\text{H}_2\text{O}$ were prepared by a method analogous to method a, but about 175°C in an autoclave, resulting in larger crystals.

e. The iodate compound was prepared as described by Le Bel and Grasland (18).
In all preparations precautions were taken against carbonation. The water used was distilled twice at reduced pressure. Filtration was performed in a CO$_2$-free glove box. All samples were analysed chemically. Table I gives the compositions of the samples and their dehydration products; despite the precautions taken some carbonation usually occurred. The samples and dehydration products were also characterized by X-ray diffraction, care being taken to exclude CO$_2$ and H$_2$O by covering the samples with "Mylar" foil. For the hydrated phases no differences were found between X-ray diffraction patterns made with and without such a foil, except for C$_4$AH$_{13}$. The hemicarbonate phase with layer thickness 8.2 Å was absent, but the 7.9 Å reflection had a shoulder on the low-angle side and chemical analysis (Table I) showed that CO$_2$ was present. In general the layer thicknesses found for the AFm phases and their dehydration products agreed with those in the literature (17, 18). Results of interest were for the hydrated chlorate compound, 9.30 Å; for the dehydrated nitrate, 7.28 Å; and for the dehydrated bromate, 8.36 Å. All molar quantities used in this paper relate to formulae of the type Ca$_2$Al(OH)$_6$X.xH$_2$O.

**Heat of Solution Measurements**

The heats of solution of the AFm phases were determined in HCl (1N or 2N) or in perchloric acid (1N) at 25oC with a precision calorimeter, LKB 8700-1 (24). The heats of solution were calculated using the graphical extrapolation method of Dickinson (25, 26). The calorimeter was calibrated electrically and chemically by measuring the heat of solution of CaO, prepared by burning CaCO$_3$ (Merck p.a.) at 1100°C for several hours. \( \Delta H_{\text{soln}} \) was found to be $-46.7 \pm 0.3$ kcal mole$^{-1}$, which implies \( \Delta H_{\text{soln}} \) of CaO, \( \Delta H_{\text{soln}} \) = $-151.9 \pm 0.3$ kcal mole$^{-1}$, in agreement with literature data (10). For accurate determinations the heat of dilution caused by the disappearance of the acid and the formation of water on dissolution of the samples must be taken into account. It can, however, be proved that, if the amount of sample (0.2 mmole) is small compared with the amounts of acid (80 mmoles) and of water (4.5 mole), the heat of dilution is negligible. The enthalpy of dehydration i.e. the change of enthalpy involved in the hypothetical reaction:

\[
\text{Ca}_2\text{Al(OH)}_6\text{X}.\text{xH}_2\text{O}(c) \rightarrow \text{Ca}_2\text{Al(OH)}_6\text{X}(c) + \text{xH}_2\text{O}(l) \quad (1)
\]

was determined as the difference between the heats of solution of the dehydrated and the hydrated compounds. This procedure is justified because, if equimolar amounts of the hydrated compounds are dissolved, the final states of the resulting solutions are nearly the same.

**Enthalpies of Formation**

The enthalpies of formation of the AFm phases were determined from heats of solution in HCl using the following reaction scheme:

\[
\begin{align*}
\text{Ca}_2\text{Al(OH)}_6\cdot \text{yX} & \cdot 0.5(1-y)\text{CO}_3 \cdot \text{xH}_2\text{O} + n_1\text{HCl} + n_2\text{H}_2\text{O} + \\
2\text{Ca}^{2+} + \text{Al}^{3+} + \text{yX}^- + (7-y)\text{Cl}^- + 0.5(1-y)\text{CO}_2(\text{aq}) + \\
n_3(= n_1 - 7 + y)\text{HCl} + n_4(= n_2 + 6.5 - 0.5y + x)\text{H}_2\text{O}
\end{align*}
\]
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The enthalpy of formation is then:

\[
\Delta H_f^{O} \text{Ca}_2\text{Al(OH)}_6. \, yX. \, 0.5(1-y)\text{CO}_3. \, x\text{H}_2\text{O} = 2 \Delta H_f^{O}\text{CaCl}_2, \, n_4/2\text{H}_2\text{O} + \\
\Delta H_f^{O}[\text{AlCl}_3, \, n_4\text{H}_2\text{O}, \, n_3\text{HCl}] + y \Delta H_f^{O}X, \, n_4/y\text{H}_2\text{O} - y\Delta H_f^{O}\text{HCl}, \, n_4/y\text{H}_2\text{O} + \\
0.5(1-y)\Delta H_f^{O}\text{CO}_2(aq) - n_2\tilde{\text{H}}_1(\text{H}_2\text{O}) - n_1\tilde{\text{H}}_1(\text{HCl}) + n_4\tilde{\text{H}}_2(\text{H}_2\text{O}) + n_3\tilde{\text{H}}_2(\text{HCl}) - \Delta H_{\text{soln}}. \tag{2}
\]

\(\Delta H_f^{O}[\text{CaCl}_2, \, n_4/2\text{H}_2\text{O}]\) is the enthalpy of formation of one mole \(\text{CaCl}_2\) in \(n_4/2\) mole \(\text{H}_2\text{O}\). \(\tilde{\text{H}}_1(\text{H}_2\text{O})\) and \(\tilde{\text{H}}_2(\text{H}_2\text{O})\) are the partial molar enthalpies of water in solutions of one mole \(\text{H}_2\text{O}\) with \(n_1/n_2\) mole \(\text{HCl}\) or \(n_3/n_4\) mole \(\text{HCl}\), respectively. \(\tilde{\text{H}}_1(\text{HCl})\) and \(\tilde{\text{H}}_2(\text{HCl})\) are the partial molar enthalpies of \(\text{HCl}\) in solutions of one mole \(\text{HCl}\) with \(n_2/n_1\) and \(n_3/n_4\) mole \(\text{H}_2\text{O}\) respectively. The enthalpy of formation of \(\text{AlCl}_3\) in aqueous solution depends strongly on the water and \(\text{HCl}\) concentrations (12). This enthalpy was found by interpolation of literature data (12) \(\Delta H_f^{O}[\text{AlCl}_3, \, 200\text{HCl}, \, 11000\text{H}_2\text{O}] = -245.7\ \text{kcal mole}^{-1}\). The other data were taken from literature (8,12,13). In the calculations, thermochemical data for \(\text{CO}_2\) dissolved in water have been used (12). This may be questionable in view of the small solubility of \(\text{CO}_2\) in \(1\text{N HCl}\). However, the difference between the enthalpies of formation of \(\text{CO}_2\) in aqueous solution and in the gas phase is too small to have any noticeable influence on the calculations.

If the heat of solution in perchloric acid was measured, the enthalpy of formation was established as follows:

\[
\Delta H_f^{O} \text{Ca}_2\text{Al(OH)}_6. \, yX. \, 0.5(1-y)\text{CO}_3. \, x\text{H}_2\text{O} = -\Delta H_{\text{soln}}. + \\
2\Delta H_f^{O}[\text{Ca}^{2+}, \, n_4/2\text{H}_2\text{O}] + \Delta H_f^{O}\text{Al}^{3+}, \, n_4\text{H}_2\text{O}] + y\Delta H_f^{O}X, \, n_4/y\text{H}_2\text{O} + \\
0.5(1-y)\Delta H_f^{O}\text{CO}_2(aq) + (n_4-n_2)\Delta H_f^{O}[\text{H}_2\text{O}, \, n_3/n_4\text{HClO}_4] \tag{3}
\]

\[
\Delta H_f^{O}[\text{Ca}^{2+}, \, n_4/2\text{H}_2\text{O}] = \Delta H_f^{O}[\text{CaCl}_2, \, n_4/2\text{H}_2\text{O}] - 2\Delta H_f^{O}[\text{HCl}, \, n_4/4\text{H}_2\text{O}] \tag{4}
\]

\[
\Delta H_f^{O}\text{Al}^{3+}, \, n_4\text{H}_2\text{O}] = \Delta H_f^{O}[\text{AlCl}_3, \, n_4\text{H}_2\text{O}] - 3\Delta H_f^{O}[\text{HCl}, \, n_4/3\text{H}_2\text{O}] \tag{5}
\]

Discussion

A. The Heats of Solution and the Enthalpies of Formation

The heats of solution of the \(\text{Ca}_2\text{Al(OH)}_6X.\, x\text{H}_2\text{O}\) compounds are nearly independent of \(X\), if \(x = 2\) and \(X = \text{Cl}^-, \text{Br}^-, \text{I}^-, \text{NO}_3\, , \text{ClO}_4^-\) or \(\text{ClO}_3^-\) (Table I). If \(x > 2\) (\(X = \text{BrO}_3\, , \text{IO}_3\)) the heats of solution decrease with increasing amount of interlayer water. With increasing carbonation the heat of solution increases, since the heat of solution of \(\text{Ca}_2\text{Al(OH)}_6.0.5\text{CO}_3.2.39\text{H}_2\text{O}\) is \(-63.7\ \text{kcal}\) which is relatively large. The heat of solution of the iodide compound containing 0.03 mole % \(\text{CO}_2\) differs about 1 kcal from that of the almost \(\text{CO}_2\)-free compound (Table I). The heat of solution of \(\text{Ca}_2\text{Al(OH)}_6.0.92\text{H}_2\text{O}, \, 0.04\text{CO}_3.3\text{H}_2\text{O}\ (-76.9\ \text{kcal})\) differs considerably from those of the other \(\text{AFm}\) phases. The heat of solution of pure \(\text{Ca}_2\text{Al(OH)}_6\text{OH}.3\text{H}_2\text{O}\ (-78\ \text{kcal})\) was established by
extrapolation, assuming a linear relation between the heats of solution of Ca$_2$Al(OH)$_6$.0.920H.0.04CO$_3$.3H$_2$O and of Ca$_2$Al(OH)$_6$.0.5CO$_3$.2.39H$_2$O. The heats of solution of the dehydration products can be correlated with the interaction energies between the anions X and the Ca$_2$Al(OH)$_6$-layers (27).

We can conclude from equation 2 that, if $x = 2$, the enthalpies of formation of Ca$_2$Al(OH)$_6$.X.xH$_2$O (X = Cl$^-$, Br$^-$, J$^-$, NO$_3^-$, ClO$_4^-$ and ClO$_3^-$) can be expressed by the equation:

$$\Delta H^0_{f} \text{Ca}_2\text{Al(OH)}_6^{+}.2\text{H}_2\text{O} = -874(\pm 1) + \Delta H^0_{f}[\text{X}, 10.000\text{H}_2\text{O}]$$

This means that the lattice enthalpies of these AFm phases depend linearly on the enthalpies of hydration of the anions X concerned.

For: $\Delta H_{\text{lattice}} = \Delta H^O_{f}[\text{Ca}_2\text{Al(OH)}_6^{+}, g] + \Delta H^O_{f}[\text{X}, g] + 2\Delta H^O_{f}[\text{H}_2\text{O}, g] - \Delta H^O_{f} \text{Ca}_2\text{Al(OH)}_6^{+}.2\text{H}_2\text{O}$

$$\Delta H_{\text{lat.}} = C_1 + \Delta H^O_{f}(\text{X}^-, g) - \Delta H^O_{f}(\text{X}^-, \text{aq}) = C_1 - \Delta H_{\text{hydr.}}(\text{X}^-, g)$$

since

$$\Delta H_{\text{hydr.}}(\text{X}^-, g) = \Delta H^O_{f}(\text{X}^-, \text{aq}) - \Delta H^O_{f}(\text{X}^-, g)$$

The enthalpy of formation of pure C$_4$AH$_3$, calculated from the heat of solution, -156 kcal mole$^{-1}$ and the enthalpies of formation of the reactants is -1988 kcal. Babushkin calculated -1983 kcal; the agreement is in this case very satisfactory. But if we calculate the enthalpy of formation of e.g. Ca$_2$Al(OH)$_6$Cl.2H$_2$O by the method of Babushkin, supposing that the hydrate consists of 1.5 Ca(OH)$_2$, Al(OH)$_3$ and 0.5 CaCl$_2$.4H$_2$O we get -899 kcal. The experimental value is -914 kcal. This difference occurs because the surroundings of the ions in the AFm phases differ from those in Ca(OH)$_2$, Al(OH)$_3$ and CaCl$_2$.4H$_2$O, to extents that apparently cannot be neglected.

B. The Enthalpies of Dehydration

In Fig.1 the enthalpies of dehydration of the AFm phases are given together with the absolute enthalpies of hydration of the anions X. For the halide ions, the hydration enthalpies were calculated from the enthalpies of formation in the gas state and the "absolute" enthalpies of formation in aqueous solution. The "absolute" enthalpies of formation are related to the conventional enthalpies of formation (tabulated in the literature) by the equation:

$$\Delta H^O_{f}(\text{X}, \text{aq})_{\text{abs.}} = \Delta H^O_{f}(\text{X}, \text{aq})_{\text{conv.}} - \Delta H^O_{f}(\text{H}^+, \text{aq})_{\text{abs.}}$$

where $\Delta H^O_{f}(\text{H}^+, \text{aq})_{\text{abs.}} = 95.6$ kcal mole$^{-1}$ (ref. 30).

The enthalpies of dehydration of the AFm phases are linearly related to the enthalpies of hydration of the anions X (Fig.1).

For the oxy-anions, the hydration enthalpies are not known precisely, because the enthalpies of formation of the gaseous
TABLE I

Analytical and thermochemical results

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>prep.</th>
<th>mmoles</th>
<th>( \Delta H_{\text{soln.}} ) kcal</th>
<th>( \Delta H_f^\circ ) kcal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.92OH. 0.04CO(_3). 3.0H(_2)O</td>
<td>c</td>
<td>0.3924</td>
<td>76.9</td>
<td>993</td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.96NO(_3). 0.02CO(_3). 2.0H(_2)O</td>
<td>d</td>
<td>0.4238</td>
<td>61.0</td>
<td>992</td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.96NO(_3). 0.02CO(_3).</td>
<td>f</td>
<td>0.3982</td>
<td>67.7</td>
<td></td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.98ClO(_4). 0.01CO(_3). 2.1H(_2)O</td>
<td>a</td>
<td>0.4416</td>
<td>60.9</td>
<td>910</td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.98ClO(_4). 0.01CO(_3).</td>
<td>f</td>
<td>0.3841</td>
<td>66.2</td>
<td></td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 1.00Cl. 2.1H(_2)O</td>
<td>a</td>
<td>0.4092</td>
<td>62.0</td>
<td>917</td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 1.00Cl</td>
<td>f</td>
<td>0.4171</td>
<td>72.0</td>
<td></td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.96Br. 0.02CO(_3). 2.1H(_2)O</td>
<td>a</td>
<td>0.4074</td>
<td>60.9</td>
<td>913</td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.96Br. 0.02CO(_3).</td>
<td>f</td>
<td>0.4084</td>
<td>70.5</td>
<td></td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.94I. 0.03CO(_3). 2.1H(_2)O</td>
<td>a</td>
<td>0.3585</td>
<td>61.6</td>
<td>894</td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.94I. 0.03CO(_3).</td>
<td>f</td>
<td>0.3801</td>
<td>69.2</td>
<td></td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 1.00I. 2.0H(_2)O</td>
<td>a</td>
<td>0.4038</td>
<td>60.5</td>
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</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 1.00I</td>
<td>f</td>
<td>0.4131</td>
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<td></td>
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<tr>
<td>Ca(_2)Al(OH)(_6) 0.98ClO(_3). 0.01CO(_3). 2.1H(_2)O</td>
<td>a</td>
<td>0.4139</td>
<td>60.9*</td>
<td>904</td>
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<tr>
<td>Ca(_2)Al(OH)(_6) 0.98ClO(_3). 0.01CO(_3).</td>
<td>f</td>
<td>0.4113</td>
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<tr>
<td>Ca(_2)Al(OH)(_6) 0.98BrO(_3). 0.01CO(_3). 2.8H(_2)O</td>
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<td>0.3916</td>
<td>58.6*</td>
<td>950</td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 0.98BrO(_3). 0.01CO(_3).</td>
<td>f</td>
<td>0.3909</td>
<td>70.0*</td>
<td></td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 1.00IO(_3). 4.1H(_2)O</td>
<td>e</td>
<td>0.3395</td>
<td>53.4*</td>
<td>1074</td>
</tr>
<tr>
<td>Ca(_2)Al(OH)(_6) 1.00IO(_3)</td>
<td>f</td>
<td>0.3389</td>
<td>72.3*</td>
<td></td>
</tr>
<tr>
<td>C(_3)AH(_6)</td>
<td>b</td>
<td>0.2311</td>
<td>139.1</td>
<td>1326</td>
</tr>
</tbody>
</table>

*For measuring the heats of solution of AFm phases with oxy-anions incorporated, HClO\(_4\) (1N) was used. f = dehydration product.

FIG. 1

The enthalpies of dehydration of some compounds of general formula Ca\(_2\)Al(OH)\(_6\)X.<XH\(_2\)O plotted against the "absolute" hydration enthalpies of the individual anions X in aqueous solution. Numerical values of the quantities are given on the right.

TABLE II

<table>
<thead>
<tr>
<th>X^-</th>
<th>( \Delta H_{\text{hydr.}} ) kcal/mole</th>
<th>( \Delta H_{\text{hydr.}}^\circ ) kcal/mole</th>
</tr>
</thead>
<tbody>
<tr>
<td>IO_3^-</td>
<td>18.9</td>
<td>97.6</td>
</tr>
<tr>
<td>BrO_3^-</td>
<td>11.4</td>
<td>79.3</td>
</tr>
<tr>
<td>Cl^-</td>
<td>10.0</td>
<td>76.7</td>
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<tr>
<td>ClO_3^-</td>
<td>7.8</td>
<td>72.9</td>
</tr>
<tr>
<td>Br^-</td>
<td>9.6</td>
<td>68.7</td>
</tr>
<tr>
<td>NO_3^-</td>
<td>6.7</td>
<td>67.1</td>
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<tr>
<td>ClO_4^-</td>
<td>5.3</td>
<td>65.9</td>
</tr>
<tr>
<td>I^-</td>
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<td>61.8</td>
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</tbody>
</table>
ions cannot be determined experimentally. The most reliable way of estimating them seems to be that first proposed by Morris (28), which is based on the hypotheses that the salting-out of lyophilic colloids by electrolytes is determined by the hydration enthalpies of the ions present (29). The salting-out properties of an anion, expressed as a "lyotropic number", can be measured for both halides and oxy-anions; assuming that the same relation between enthalpy of hydration and lyotropic number applies for halides and oxy-anions, the hydration enthalpies of the oxy-anions are known. Hydration enthalpies thus obtained are shown in Fig.1. As for the halides a linear relationship is found, but the points for the oxy-anions do not lie in the same curve as those for the halides. This is ascribed to differences in the sizes and chemical characteristics of the two kinds of ion.

Acknowledge

The authors wish to thank Mr. C.L.M. Holten and Mr. F.E.A.M.B. Lemmerling for their contributions to this investigation.

References