

羟基聚合铝晶体研究进展

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摘要 羟基聚合铝的研究在环境化学中具有重要作用。自然条件下存在的无机单核铝本身具有毒性,而多核铝是比单核铝更毒的铝形态,它们很容易进入人体和植物产生毒害作用。因此,水解聚合铝形态研究一直是环境化学、地球化学和材料催化等众多研究领域的前沿热点课题。本文综述了在新环境材料开发中羟基聚合铝晶体研究的进展,对已获得表征的典型羟基聚合铝的结构特点进行了对比与评述,讨论了不同羟基聚合铝晶体的科学意义和应用价值。

关键词 羟基聚合铝晶体;研究进展

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Research progress of hydroxyl polymeric aluminum crystals

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Abstract Speciation of hydroxyl polymeric aluminum is very important in the environmental chemistry due to the uncertain toxicity of hydroxyl polymeric aluminum. It has been reported that natural inorganic monomeric aluminum species are toxic to biological systems. However, polyaluminum might be more toxic than monomeric aluminum, because polyaluminum is more easily penetrating into human body and plant. Therefore, the structural characterizations of hydrolytic polymeric aluminum in solutions become the research focuses in the fields of environmental analysis, geochemistry and material catalysis etc. The progresses for studying a few of typical hydroxyl polymeric aluminum crystals designed and synthesized as new environmental materials are reviewed in this paper. Some comparisons and comments were made on the structural characteristic of some typical hydroxyl polymeric aluminum crystals which of structures were well characterized before. Scientific significance and practical application potentials of the new hydroxyl polymeric aluminum crystals were also discussed.

Keywords hydroxyl polymeric aluminum crystal; research progress

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1 引言

铝在自然界中分布广泛,是地壳中含量最丰的金属元素(8%左右),天然水体和土壤中日益增加的铝浓度对环境生物产生的影响已越来越受到人们的广泛关注^[1-9]。铝通过改变土壤 pH 及其缓冲容量,进而影响一些重要元素如磷、钙和溶解有机碳等的循环;还可以通过影响水体内以及水与颗粒物界面上的系列物理化学反应来决定和改变其他元素的生物地球循环,影响其它污染物的转移。同时,铝水解产生的一系列羟基聚合铝由于具有独特的电荷和结构特征,已在水处理、矿物化学以及材料催化化学等方面得到了广泛应用,并发挥着独特的作用^[10-14]。由于聚合铝结构的复杂性和分析手段的局限性,羟基聚合铝晶体研究的发展一直很缓慢,直到 2000 年,仅有几种典型聚合铝型体得到了合成和表征。近十年来随着分析手段的进步和对聚合铝广泛应用前景的重视,科学家对铝水解化学进行了大量的研究,并在水解羟基聚合铝的研究上取得了重要进展^[15-20]。本文从羟基聚合铝离子类型和晶体特点等方面对羟基聚合铝晶体的研究工作进行了全面综述,并对其未来发展进行了展望。

2 羟基聚合铝晶体的研究进展

2.1 羟基聚合铝离子晶体

到目前为止,小聚合铝只有 Al_2^{4+} 得以报道。由于 Al_2^{4+} 只含两个 AlO_6 八面体,结构较为简单。其余的羟基聚合铝可以分为两大结构系列:第一种是具有 Baker-Figgis-Keggin 结构的异构体和衍生物,它们结构中均含有 AlO_4 四面体,金属羟基聚合物的研究学者都极为熟悉;第二种是含有由共边的 AlO_6 八面体所组成的、结构类似水镁石矿($Mg(OH)_2$)中间特征核结构的羟基聚合铝。

2.1.1 $[AlO_4Al_{12}(OH)_{24}(H_2O)_{12}]^{7+}$ 和 $[(AlO_4)_2Al_{28}(OH)_{56}(H_2O)_{26}]^{18+}$ 聚合铝离子

(1) $AlO_4Al_{12}(OH)_{24}(H_2O)_{12}]^{7+}$

Johansson 等^[21]在合成的聚合氯化铝溶液中加入 Na_2SeO_4 或 $(NH_4)_2SO_4$ 溶液,制备出 $Na[Al_{13}O_4(OH)_{24}(H_2O)_{12}](SeO_4)_4 \cdot 13H_2O$ 和 $(NH_4)_7[Al_{13}O_4(OH)_{24}(H_2O)_{12}](SO_4)_7 \cdot xH_2O$ 晶体,用单晶 X 射线衍射仪对晶体进行分析得到了 $[Al_{13}O_4(OH)_{24}(H_2O)_{12}]^{7+}$ 的空间结构,它属于 Keggin 结构系列中的 ϵ 异构体(简称为 $\epsilon-Al_{13}^{7+}$)。Akitt 等^[22]采用 ^{27}Al -NMR 波谱分析方法检测羟基聚合铝的水溶液,

证实溶液中确实存在着 Johansson 所描述的 $\epsilon-Al_{13}^{7+}$ 型体,其化学位移为 62.5 ppm。 $\epsilon-Al_{13}^{7+}$ 的结构中间是一个 AlO_4 正四面体,周围环绕着十二个 AlO_6 八面体(图 1);Keggin 结构的化合物有 α 、 β 、 γ 、 δ 、 ϵ 等五种异构体^[15],目前在实验室里已经合成和分离出 ϵ 和 δ 两种 Keggin- Al_{13}^{7+} 异构体。由于 $\epsilon-Al_{13}^{7+}$ 结构的高度对称性,因此中心铝原子周围的电子云密度梯度近乎等于零,导致弛豫速率慢,用 ^{27}Al -NMR 波谱仪进行测试可得到较窄的共振吸收峰。

(2) $[(AlO_4)_2Al_{28}(OH)_{56}(H_2O)_{26}]^{18+}$

Allouche^[23]和 Nazar^[24]两个研究组分别合成和表征了 $[Al_{30}O_8(OH)_{56}(H_2O)_{26}](SO_4)_9 \cdot xH_2O$ 单晶,其中的羟基聚合铝离子为 $[Al_{30}O_8(OH)_{56}(H_2O)_{26}]^{18+}$ (简称为 Al_{30}^{18+}), ^{27}Al -NMR 波谱分析表明 Al_{30}^{18+} 的化学位移为 70 ppm。 Al_{30}^{18+} 是迄今为止分离出来并得到结构表征的最大的羟基聚合铝阳离子,尺寸约为 2 nm。它是由两个 Keggin 结构的 Al_{13}^{7+} ,加上中间成环连接的四个 AlO_6 八面体形成的(图 2)。Nazar 等在合成 Al_{30}^{18+} 的过程中得到了一个中间产物 $Na-\delta-[Al_{13}O_4(OH)_{24}(H_2O)_{12}][SO_4]_4 \cdot 19H_2O$,单晶 X 射线衍射分析表明,其中羟基聚合铝离子是 $\epsilon-Al_{13}^{7+}$ 的一个异构体: $\delta-Al_{13}^{7+}$ 。这也就证明了 Al_{30}^{18+} 中的两个 Keggin 结构的 Al_{13}^{7+} 是 $\delta-Al_{13}^{7+}$,它是由 $\epsilon-Al_{13}$ 转变而来,将 $\epsilon-Al_{13}$ 顶上的三个 AlO_6 八面体沿着它的 C_3 轴旋转 60° 即可变成 $\delta-Al_{13}^{7+}$ (图 3)。

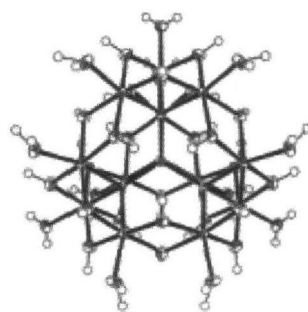


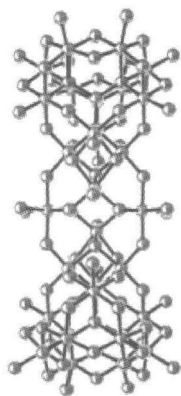
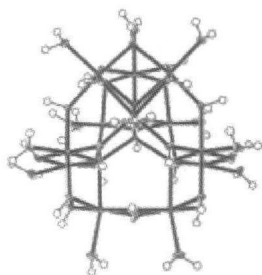
图 1 $\epsilon-Al_{13}^{7+}$ 的球棍结构模型

Fig. 1 The ball-and-stick model of $\epsilon-Al_{13}^{7+}$

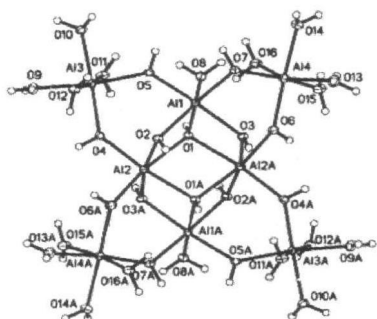
2.1.2 具有中心平面核结构的 Al_8^{10+} 和 Al_{13}^{15+}

(1) Al_8^{10+} 聚合阳离子

Al_8^{10+} 的发现可以认为是一种连续研究中的偶然成果。Casey 等^[25]用单晶 X 射线衍射仪测试放置了 7 年的羟基聚合铝硫酸盐晶体,发现有孪晶形成,通过对分析数据的处理得到了孪晶的表达式:

图 2 Al_{30}^{18+} 的球棍结构模型Fig. 2 The ball-and-stick model of Al_{30}^{18+} 图 3 $\delta\text{-Al}_{13}^{7+}$ 的球棍结构模型Fig. 3 The ball-and-stick model of $\delta\text{-Al}_{13}^{7+}$

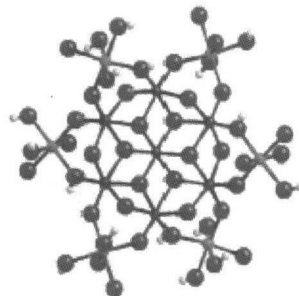
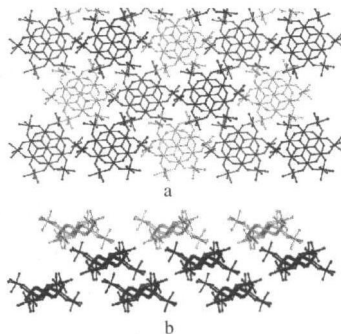
$[\text{Al}_8(\text{OH})_{14}(\text{H}_2\text{O})_{18}](\text{SO}_4)_5 \cdot 16\text{H}_2\text{O}$ 和 $\text{Al}_8(\text{OH})_{14}(\text{H}_2\text{O})_{18}^{10+}$ 的结构(简称为 Al_8^{10+})。 Al_8^{10+} 含有八个 AlO_6 八面体,中间的四个 AlO_6 八面体为共边的连接方式,外围的四个 AlO_6 八面体采取共角的方式与中间的 AlO_6 八面体连接(图 4)。

图 4 Al_8^{10+} 的球棍结构模型Fig. 4 The ball-and-stick model of Al_8^{10+}

(2) Al_{13}^{15+} (Mögel) 聚合阳离子

Seichter 等^[26]合成出一种具有平面中心核的 Al_{13} 晶体 $[\text{Al}_{13}(\text{OH})_{24}(\text{H}_2\text{O})_{24}]\text{Cl}_{15} \cdot 13\text{H}_2\text{O}$ 。它的离子带有高电荷(简称为 Al_{13}^{15+} (Mögel)),其结构与 $\epsilon\text{-Al}_{13}^{7+}$ 完全不同,全部是由 AlO_6 八面体按氢氧镁石的结构连接而成。 Al_{13}^{15+} (Mögel)的中心为一

个 AlO_6 八面体,围绕着中心排列着六个 AlO_6 八面体,这六个 AlO_6 八面体之间以及与中心的 AlO_6 八面体之间均采用共边的连接方式。最外围的六个 AlO_6 八面体与内圈的 AlO_6 八面体以共角的方式连接。也可以这样来看 Al_{13}^{15+} (Mögel)的结构:它的中间由七个 AlO_6 八面体构成了平面六边形的核 $\{\text{Al}_7(\text{OH})_{12}^{9+}\}$,外围的六个 AlO_6 八面体在此平面上上下交错排列(图 5)。带有 Mögel 结构的羟基聚合物基本上是按照以下方式形成晶体——羟基聚合物横向复制形成面,面与面之间根据羟基聚合物的位置进行错层堆叠形成立体结构^[27](图 6)。

图 5 Al_{13}^{15+} (Mögel) 的球棍结构模型Fig. 5 The ball-and-stick model of Al_{13}^{15+} 图 6 Al_{13}^{15+} (Mögel) 的晶体结构模型Fig. 6 The crystal structural model of Al_{13}^{15+}

2.2 杂化羟基聚合铝离子晶体

Parker 等^[28-30]合成并表征了 $\text{Na}[\text{GaO}_4\text{Al}_{12}(\text{OH})_{24}(\text{H}_2\text{O})_{12}](\text{SeO}_4)_4 \cdot 10\text{H}_2\text{O}$ 晶体,Casey 等^[31]合成并表征了 $[\text{GeO}_4\text{Al}_{12}(\text{OH})_{24}(\text{H}_2\text{O})_{12}](\text{SeO}_4)_4 \cdot 14\text{H}_2\text{O}$ 晶体。它们的聚阳离子分别为: $\text{GaAl}_{12}^{7+}(\text{OH})_{24}(\text{H}_2\text{O})_{12}^{7+}$ (简称为 GaAl_{12}^{7+}) 和 $\text{GeAl}_{12}^{8+}(\text{OH})_{24}(\text{H}_2\text{O})_{12}^{8+}$ (简称为 GeAl_{12}^{8+})。 GaAl_{12}^{7+} 溶液的 ^{71}Ga -NMR 波谱分析可观察到 138 ppm 处 GaO_4 正四面体的特征共振吸收峰^[32]。比较 GeAl_{12}^{8+} 、 GaAl_{12}^{7+} 与 $\epsilon\text{-Al}_{13}^{7+}$ 硒酸盐的固体 MAS ^{27}Al -NMR 波谱信号, $\epsilon\text{-Al}_{13}^{7+}$ 在 +61 ppm 处有特

征共振峰,而 GeAl_{12}^{8+} 与 GaAl_{12}^{7+} 在此处的信号都非常小,说明在它们的晶体中基本不存在 $\epsilon\text{-Al}_{13}^{7+}$ 。 GeAl_{12}^{8+} 硒酸盐在 -110 ppm 和 -140 ppm 处有两个独特的共振吸收峰^[31]。单晶 X 射线衍射分析表明 GaAl_{12}^{7+} 和 GeAl_{12}^{8+} 的结构与 $\epsilon\text{-Al}_{13}^{7+}$ 相同,只是中间 AlO_4 正四面体被 GaO_4 或 GeO_4 所取代,其中 GeAl_{12}^{8+} 的结构略微有些变形,这两个化合物都属于杂化的羟基聚合铝。

2.3 杂多酸羟基聚合铝晶体

Son 等^[33-36] 采用羟基聚合铝阳离子 $\epsilon\text{-Al}_{13}^{7+}$ 、 Al_{30}^{18+} 和 GaAl_{12}^{7+} 为构晶材料,分别与杂多酸聚合阴离子: $\text{H}_2\text{W}_{12}\text{O}_{40}^{6-}$ 、 $\text{CoW}_{12}\text{O}_{40}^{6-}$ 、 $\text{Mo}_7\text{O}_{24}^{6-}$ 和 $\text{V}_2\text{W}_4\text{O}_{19}^{4-}$ 反应,形成了一些多孔渗水型结构的晶体,它们的化学式分别为:

- $[\text{AlO}_4\text{Al}_{12}(\text{OH})_{12}(\text{H}_2\text{O})_{24}][\text{Al}(\text{OH})_6\text{Mo}_6\text{O}_{18}]_2(\text{OH})\cdot 29.5\text{H}_2\text{O}$; (简式: $\text{Al}_{13}\text{AlMo}_6$)
- $[\delta\text{-Al}_{13}\text{O}_4(\text{OH})_{24}(\text{H}_2\text{O})_{12}][\text{H}_2\text{W}_{12}\text{O}_{40}](\text{OH})\cdot 22\text{H}_2\text{O}$; (简式: $\delta\text{-Al}_{13}\text{H}_2\text{W}_{12}$)
- $[\delta\text{-Al}_{13}\text{O}_4(\text{OH})_{24}(\text{H}_2\text{O})_{12}][\text{CoW}_{12}\text{O}_{40}](\text{OH})\cdot 19\text{H}_2\text{O}$; (简式: $\delta\text{-Al}_{13}\text{CoW}_{12}$)
- $[\text{W}_2\text{Al}_{28}\text{O}_{18}(\text{OH})_{48}(\text{H}_2\text{O})_{24}][\text{H}_2\text{W}_{12}\text{O}_{40}]_2\cdot 55\text{H}_2\text{O}$; (简式: $\text{W}_2\text{Al}_{28}\text{H}_2\text{W}_{12}$)
- $[\epsilon\text{-Al}_{13}\text{O}_4(\text{OH})_{24}(\text{H}_2\text{O})_{12}]_2[\text{V}_2\text{W}_4\text{O}_{19}]_3(\text{OH})_2\cdot 27\text{H}_2\text{O}$ (简式: $\epsilon\text{-Al}_{13}\text{V}_2\text{W}_4$)

f. $[\text{GaO}_4\text{Al}_{12}(\text{OH})_{12}(\text{H}_2\text{O})_{24}][\text{Al}(\text{OH})_6\text{Mo}_6\text{O}_{18}]_2(\text{OH})\cdot 30\text{H}_2\text{O}$; (简式: $\text{GaAl}_{12}\text{AlMo}_6$)

$\text{Al}_{13}\text{AlMo}_6$ 与 $\epsilon\text{-Al}_{13}\text{V}_2\text{W}_4$ 两晶体是 $\epsilon\text{-Al}_{13}^{7+}$ 与相应的杂多酸聚阴离子结合生成的产物,而 $\delta\text{-Al}_{13}\text{H}_2\text{W}_{12}$ 、 $\delta\text{-Al}_{13}\text{CoW}_{12}$ 和 $\text{W}_2\text{Al}_{28}\text{H}_2\text{W}_{12}$ 晶体却是用 Al_{30}^{18+} 与相应的杂多酸聚阴离子反应得到的产物,它们最大的特点是在晶体中都有着许多孔洞型结构。其中 Al_{30}^{18+} 在形成晶体之前首先分解成了 $\delta\text{-Al}_{13}^{7+}$, 分解出来的 $\delta\text{-Al}_{13}^{7+}$ 并没有变成 $\epsilon\text{-Al}_{13}^{7+}$, 而是与杂多酸聚阴离子结合形成了新的晶体,并且倾向于生成二聚体,有其它杂原子存在的情况下,很可能生成杂化羟基聚合铝,其中 $\text{W}_2\text{Al}_{28}^{12+}$ 即是按照这种机理生成的(图 7)。 $\text{W}_2\text{Al}_{28}^{12+}$ 的结构与 Al_{30}^{18+} 相同,只是中间的四个 AlO_6 八面体有两个被 WO_6 所取代。晶体制备实验证明 $\delta\text{-Al}_{13}^{7+}$ 不仅存在于 Al_{30}^{18+} 中,也可能存在于其它的晶体之中。Nazar 等在推测 Al_{30}^{18+} 的生成机理时曾认为 64.5 ppm 吸收峰是 $\delta\text{-Al}_{13}^{7+}$ 型体的核磁共振信号,这一不太确定的判断,通过对 $\delta\text{-Al}_{13}\text{H}_2\text{W}_{12}$ 和 $\delta\text{-Al}_{13}\text{CoW}_{12}$ 晶体样品的 MAS ^{27}Al -NMR 波谱分析得到了进一步的确认,它们的波谱图中均有 64.7 ppm 的共振吸收峰。

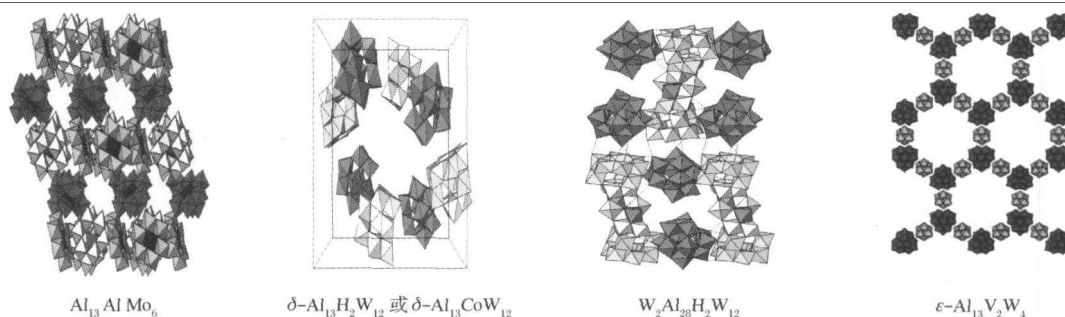


图 7 羟基聚合铝聚阴离子晶体结构模型

Fig. 7 The crystal structural model of polyanion and polycation of hydroxyl polymeric aluminum

通过对晶体结构的观察, Son 等^[36] 发现晶体中多面体的聚阳离子和聚阴离子之间的排列方式符合这样一些基本规律: 首先, 静电相互作用发生在交替排列的聚阴离子之间, 以使体系处于稳定状态; 其次, 除了静电相互作用之外, 在聚阴离子之间还存在着数目众多的氢键; 第三, 多面体的聚阴离子采取面对面的接触方式, 面与面尽可能保持平行状态以便使彼此之间有最大的接触面积。在这种最佳状态条件下, 聚阴离子之间有最大的静电吸引力与

氢键相互作用力。

2.4 有机配体羟基聚合铝晶体

(1) $[\text{Al}_{13}(\mu_3\text{-OH})_6(\mu_2\text{-OH})_{12}(\text{heidi})_6(\text{H}_2\text{O})_6]^{3+}$

有机羟基聚合铝的合成与表征为在水溶液中寻找新的羟基聚合铝型体提供了参照。Sarah 等^[37] 制备了含有羟基聚合铝的有机化合物硝酸盐晶体, 其阳离子为: $[\text{Al}_{13}(\mu_3\text{-OH})_6(\mu_2\text{-OH})_{12}(\text{heidi})_6(\text{H}_2\text{O})_6]^{3+}$, 其中 $\text{H}_2\text{heidi} = \text{N}(\text{CH}_2\text{CO}_2\text{H})_2(\text{CH}_2\text{CH}_2\text{OH})$, 阳离子符号可简写为: $\text{Al}_{13}(\text{heidi})$

$^{3+}$ (图 8)。 ^{27}Al -NMR 波谱分析表明在 25 ppm 处有尖锐的强信号峰。比较 $\text{Al}_{13}(\text{heidi})^{3+}$ 与 Al_{13}^{15+} (Mögel) 的结构可以发现它们都具有相同的核。

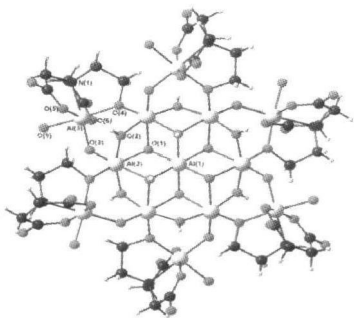
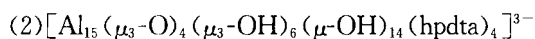


图 8 $\text{Al}_{13}(\text{heidi})^{3+}$ 的球棍结构模型

Fig. 8 The ball-and-stick model of $\text{Al}_{13}(\text{heidi})^{3+}$



Schmitt 等^[38] 合成了含有 Mögel 结构的 Al_{15} 的有机化合物, 离子表达式为 $[\text{Al}_{15}(\mu_3\text{-O})_4(\mu_3\text{-OH})_6(\mu\text{-OH})_{14}(\text{hpdt})_4]^{3-}$, ($\text{H}_5\text{hpdt} = \text{HOCH}_2[\text{CH}_2\text{N}(\text{CH}_2\text{COOH})_2]_2$), 简称为 $\text{Al}_{15}(\text{hpdt})^{3-}$ (图 9), 结晶分子式为 $(\text{pipzH}_2)(\text{H}_3\text{O})[\text{Al}_{15}(\mu_3\text{-O})_4(\mu_3\text{-OH})_6(\mu\text{-OH})_{14}(\text{hpdt})_4] \cdot \text{pipz} \cdot 41\text{H}_2\text{O}$, (pipz 为哌嗪), 简称为 $\text{pipzH}_2\text{-H}_3\text{O Al}_{15}(\text{hpdt})_4$ 。 $\text{Al}_{13}(\text{heidi})^{3+}$ 和 $\text{Al}_{15}(\text{hpdt})^{3-}$ 与纯无机 Al_{13}^{15+} (Mögel) 的结构相似, 有着相同的核, 只是外层结构随着有机物的差异而发生变化。 $\text{pipz H}_2\text{Al}_{15}(\text{hpdt})$ 晶体中的 $\text{Al}_{15}(\text{hpdt})^{3-}$ 按沸石结构外貌特征进行复制和堆叠形成了超分子排列, 晶体结构类似于多孔型的沸石或分子筛 (图 10)。

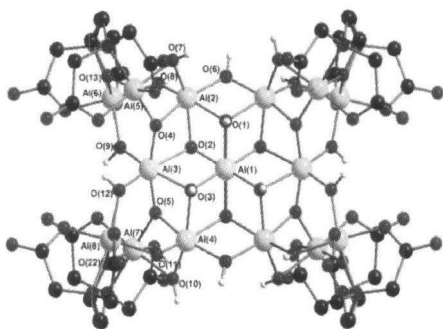


图 9 $\text{Al}_{15}(\text{hpdt})^{3-}$ 的球棍结构模型

Fig. 9 The ball-and-stick model of $\text{Al}_{15}(\text{hpdt})^{3-}$

(3) 一种自组装机理形成的有机化合物—— $\text{Al}_{13}(\text{crown})$

Drljaca 等^[39] 在碱中和法合成的 $\epsilon\text{-Al}_{13}^{7+}$ 羟基聚合铝溶液中, 加入 18-冠醚-6、杯状[4]芳烃四磺酸钠水溶液, 通过混合物自发选择性成键的自组装过

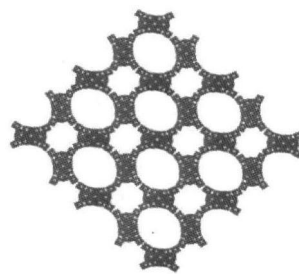


图 10 $\text{pipz H}_2\text{Al}_{15}(\text{hpdt})$ 的晶体结构模型

Fig. 10 The crystal structural model of $\text{pipz H}_2\text{Al}_{15}(\text{hpdt})$

程, 形成了复杂大分子化合物的晶体 (简写成 $\text{Al}_{13}(\text{crown})$): $[\text{Al}_{13}\text{O}_4(\text{OH})_{24}(\text{H}_2\text{O})_{12}][\text{Na}(18\text{-crown-6})(\text{H}_2\text{O})_2\text{L}_2(\text{H}^+)_w]_{0.5}^{x-}[\{\text{L}(\text{H}^+)_y\}]^{z-} \cdot 29\text{H}_2\text{O}$, $\text{L} = p\text{-sulfonatocalix[4]arene}$, $x + z = 7$ 。在 $\text{Al}_{13}(\text{crown})$ 晶体中, 18-冠醚-6、杯状[4]芳烃四磺酸钠相互连接形成了多条相互平行的长链, 在它的垂直方向上, 多个 $\epsilon\text{-Al}_{13}^{7+}$ 相互连接也形成了多条相互平行的长链, 两种链交替垂直排列组成晶体 (图 11)。

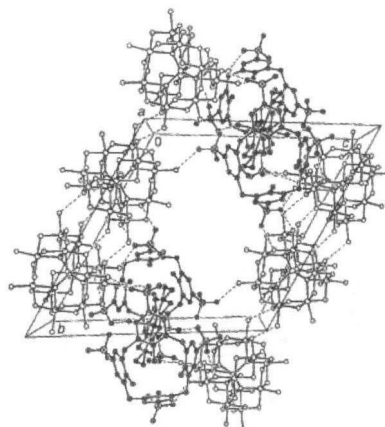


图 11 $[\text{Al}_{13}\text{O}_4(\text{OH})_{24}(\text{H}_2\text{O})_{12}]$

$[\text{Na}(18\text{-crown-6})(\text{H}_2\text{O})_2\text{L}_2(\text{H}^+)_w]_{0.5}^{x-}$

$[\{\text{L}(\text{H}^+)_y\}]^{z-} \cdot 29\text{H}_2\text{O}$ 中 Keggin

离子和超阴离子相互作用

Fig. 11 Interplay of Keggin ions and superanions within

$[\text{Al}_{13}\text{O}_4(\text{OH})_{24}(\text{H}_2\text{O})_{12}]$

$[\text{Na}(18\text{-crown-6})(\text{H}_2\text{O})_2\text{L}_2(\text{H}^+)_w]_{0.5}^{x-}$

$[\{\text{L}(\text{H}^+)_y\}]^{z-} \cdot 29\text{H}_2\text{O}$, $x + z = 7$

3 结论与展望

近十年来, 羟基聚合铝晶体的研究已经逐步深入到理论计算领域, 并开始对聚合铝晶体结构进行详细的解析, 通过寻找构晶物质之间的内在关系, 延

伸到对水溶液中各种单核铝和聚合铝形态的水解聚合机理的揭示^[12-13,41-52],这些探讨无论是在理论上还是在实践上无疑都对新型聚合铝型体的研究具有重要的意义。还有许多其它高极化度的金属离子也会像铝离子一样发生水解聚合反应生成羟基聚合物,因此铝离子羟基聚合物及其晶体的研究所得到的经验和所形成的理论将会为其它金属离子水解聚合反应机制的相关研究提供借鉴和帮助。同时,由羟基聚合铝形成的晶体(包括 Al_{13}^{7+} 的硫酸盐和 Al_{30}^{18+} 的硫酸盐等)都还有这样一些特点:(1)构晶物质表面带有羟基和结构水等活性基团,根据位置的不同这些基团的活性存在着差异^[40];(2)晶体中都含有孔洞结构,孔洞的体积占有很大的比例;(3)孔洞中都填充着结晶水、溶剂分子和用于电荷平衡的 H_3O^+ 、 OH^- 离子;(4)在空气中晶体很容易失去水和溶剂分子,说明水和溶剂分子可以在孔洞中自由运动。羟基聚合铝离子晶体的这些结构特点和性质有望使它们成为具有特殊用途的功能性材料。随着研究的不断进展,相信还将会有更多的结构新奇与性能独特的羟基聚合铝晶体被发现并成功应用于环境新材料科学领域。

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