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Mendeleev Commun., 2021, **31**, 412–414

Mendeleev Communications

A facile approach to prepare water-soluble magnetic metal (oxide) frameworks based on Na,Ca alginate and maghemite

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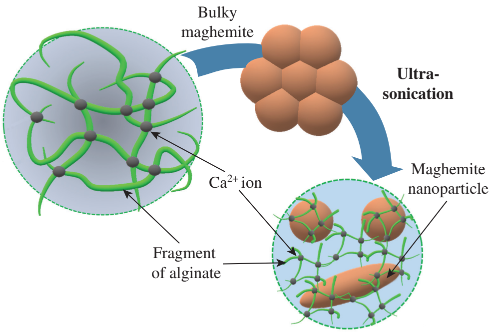
DOI: 10.1016/j.mencom.2021.05.043

A one-step ultrasonication technique for the preparation of magnetic metal (oxide) organic frameworks (MOFs) with a size of >135 nm based on sodium alginate crosslinked with Ca^{2+} ions and maghemite (γ-Fe_2O_3) nanoparticles with sizes from 7 to 20 nm was proposed. The MOFs were characterized by Mössbauer spectroscopy, TEM, magnetometry, and UV-VIS and IR spectroscopy. The grid (crosslinks) preliminarily formed by Ca^{2+} ions plays an important role in the stabilization of maghemite nanoparticles, and the resulting MOFs can be used as magnetic carriers in systems for hyperthermia and drug delivery.



Keywords: alginate, maghemite, ultrasonic dispersion, nanoparticles, metal (oxide) frameworks, magnetic liquid.

Magnetic nanoparticles are widely used in biomedicine for magnetic resonance imaging[1] and as a magnetic component in targeted drug delivery systems[2] and systems for hyperthermia.[3,4] Due to their unique magnetic characteristics and low toxicity, nanoparticles based on iron(III) oxides, maghemite and magnetite, are the most promising.[5] Magnetic nanoparticles used in biomedicine should exhibit high solubility and colloidal stability. However, they are extremely prone to aggregation due to strong hydrophobic, magnetic and surface interactions. Therefore, the stabilization of magnetic nanoparticles against aggregation is significant for the preparation of magnetosensitive nanocarriers for biomedical applications. Natural polymer matrices can prevent the aggregation of nanoparticles and impart them important properties such as hydrophilicity and biocompatibility.[6,7]

The most common natural polymers used for stabilizing magnetic nanoparticles are chitin,[8] chitosan,[9] carboxymethyl cellulose,[10] and alginates.[11] Alginates occupy a special place due to their high solubility, biocompatibility, and biodegradability. On the other hand, a large number of functional (hydroxyl and carboxyl) groups makes these polysaccharides suitable for the stabilization of nanoparticles, including magnetic nanoparticles, from aggregation, in the preparation of magnetic metal (oxide) organic frameworks (MOFs). An essential advantage of the resulting MOF is a combination of magnetic properties, solubility in water, high biocompatibility, and biodegradability. Moreover, a magnetic phase is formed by maghemite, a chemically inert form of iron(III) oxide.

Here, we describe a facile one-step technique for the preparation of water-soluble MOF based on crosslinked Na,Ca alginate and maghemite nanoparticles. Bulky magnetic γ-Fe_2O_3 was used as a precursor of magnetic nanoparticles. The maghemite was dispersed by ultrasonic treatment in the presence of Na,Ca alginate. According to transmission electron microscopy (TEM) data, inorganic nanoparticles were spheres with diameters from 7 to 20 nm. These nanoparticles and Na,Ca alginate formed a MOF greater than 135 nm. Using Mössbauer spectroscopy, we established that maghemite nanoparticles included in a Na,Ca alginate matrix after the ultrasonic treatment retained its initial structure. Magnetic properties of the MOF were detected using a magnetometer. IR sprectroscopy was used to characterize interactions in a Na,Ca alginate matrix. Preliminary steric stabilization was due to the grid structure of used polysaccharide. Further stabilization of maghemite nanoparticles was owing to the electrostatic interactions of carboxylic groups and the coordinating interactions between glycosidic groups as Na,Ca alginate moieties and the surface of maghemite nanoparticles.[†]

[†] Crosslinked Na,Ca alginate (Na 95% and Ca 5%) with molecular weight $M = 2.7\times10^6$ Da (ISP, UK) was extracted by freeze drying. The preparation, purification, and isolation of maghemite was carried out according to a previously published procedure.[12]

Ultrasonic treatment was carried out in a Sapphire-6580 100 W ultrasonic bath (Sapphire, Russia) at an operating frequency of 35 kHz. Aqueous suspensions of maghemite and Na, Ca alginate were exposed in an aqueous immersion liquid at 25 °C for 40 min.

The iron content was deternined by UV-VIS spectrophotometry as described elsewhere.[13]

The shape and size of maghemite nanoparticles and Na,Ca alginate–maghemite MOF were determined by TEM on a JEM-100B instrument (JEOL, Japan).

Magnetic properties of MOF based on Na,Ca alginate–γ-Fe_2O_3 were studied on a Lakeshore 7400 vibrating sample magnetometer (Lake Shore Cryotronics, USA) at room temperature in a range from –800 to +800 kA m^{-1}.

The ^{57}Fe Mössbauer spectra of the MOF were recorded on an MS-1104m spectrometer (Russia) at 78 K using ^{57}Co (Rh) sources.

The IR spectra were recorded at room temperature in a KBr matrix on a Specord M-80 (Carl Zeiss, Germany) in a range of 4000–500 cm^{-1}.

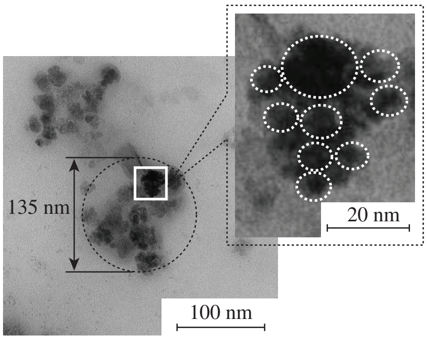


Figure 1 TEM images of iron-containing Na,Ca alginate.

We used polyanions consisting of sodium mannuronate and guluronate macromolecules randomly crosslinked with Ca^{2+} ions. The Na,Ca alginate–maghemite MOF was prepared by the ultrasonic nanodispersion of bulky maghemite (1–10 mg) in 2.5 ml of a 2% solution of Na,Ca alginate. The maghemite sediment after the formation of MOF was separated from supernatant by magnetic separation. The resulting solutions were purified using freeze drying.

The iron(III) content of the resulting nanocomposite was determined spectrophotometrically.[13] MOF with a maximum iron(III) content of 5.2 wt% was used in further experiments.

The presence of nanoparticles coated by a Na,Ca alginate matrix was detected by TEM (Figure 1).

Dark contrasting spherical isotropic nanoparticles, which correspond to inorganic iron(oxide)-containing phase, can be observed in the TEM images. The size of inorganic nanoparticles varied in a range from 7 to 20 nm. These inorganic nanoparticles formed ensembles with a diameter of 135 nm with Na,Ca alginate as a stabilizing component.

Mössbauer spectroscopy was used to characterize the inorganic nanoparticles included in the MOF formed after ultrasonication (Figure 2).

A comparison of the positions of peaks corresponding to the composite with the peaks characterizing pure bulky maghemite[12] indicated that the structure of the magnetic phase remained unchanged in the process of ultrasonic treatment of bulky maghemite in the presence of Na,Ca alginate.

The found magnetostatic characteristics such as saturation magnetization, residual magnetization, coercive force, and squareness coefficient were 0.93 Emu g^{-1}, 0.12 Emu g^{-1}, 104 Oe, and 0.1, respectively. Moreover, the MOF dissolved in water (concentration, 2 wt%) behaved as an aggregatively stable dispersion, which responded to an external magnetic field and exhibited the properties of a magnetic liquid.

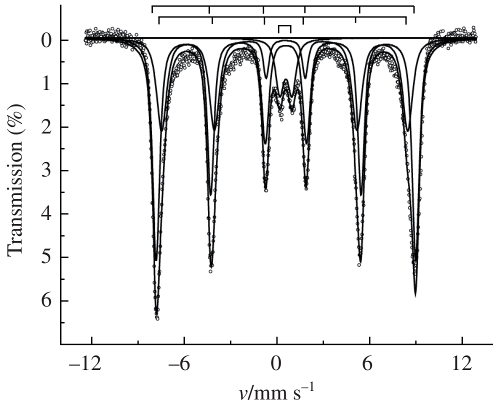


Figure 2 ^{57}Fe Mössbauer spectrum of iron(oxide)-containing Na,Ca alginate at 78 K.

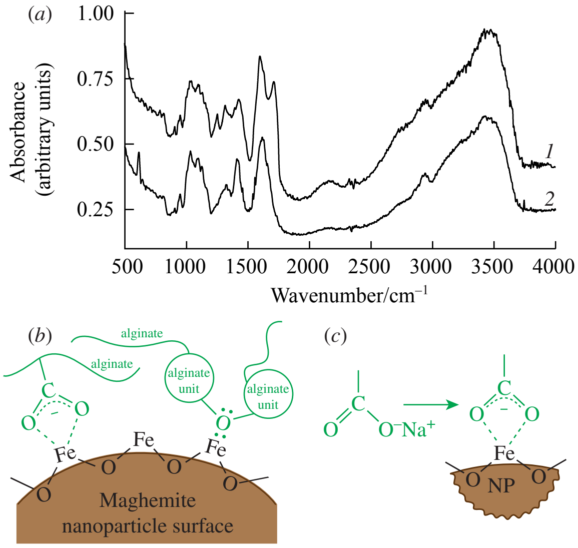


Figure 3 (*a*) IR spectra of (*1*) initial Na,Ca alginate and (*2*) Na,Ca alginate–maghemite MOF; (*b*) stabilization of maghemite nanoparticles; and (*c*) the carboxylic group of Na,Ca alginate and its resonance form.

The interactions between maghemite nanoparticles and polysaccharide macromolecules were studied by IR spectroscopy.

The IR spectrum of initial Na,Ca alginate [Figure 3(*a*), curve *1*] contains a characteristic broad band at 3500 cm^{-1} due to stretching vibrations of OH groups, bands at 1710, 1600, and 1417 cm^{-1} due to carboxyl groups, and bands corresponding to stretching and bending vibrations of glycosidic bonds (C–O–C) at 1250 and 1058 cm^{-1}, respectively. The IR spectrum of the Na,Ca alginate–maghemite MOF [Figure 3(*a*), curve *2*] had no band at 1710 cm^{-1}, which determines the vibrations of carboxyl groups. This effect can be associated with electrostatic interactions between Fe^{3+} ions on the surface of maghemite nanoparticles and carboxyl groups of Na,Ca alginate. The band due to the vibrations of C–O–C glycosidic bonds around 1250 cm^{-1} also disappeared. This fact can be explained by coordinating interactions of the oxygen atoms of glycoside bonds with the surface of maghemite nanoparticles. At the same time, the band due to bending vibrations of C–O–C groups at 1058 cm^{-1} was present in both of the spectra. Note that the IR spectrum of the Na,Ca alginate–maghemite MOF had a peak at 610 cm^{-1} due to the bending vibrations of the Fe–O bonds of a magnetic inorganic phase.[10,12]

Figure 3(*b*) illustrates the electrostatic and coordinating interactions between the carboxyl and glycoside functional groups of Na,Ca alginate and Fe^{3+} ions on the nanoparticle surface, and Figure 3(*c*) shows changes in the resonance forms of the carboxyl group of Na,Ca alginate during the stabilization of nanoparticles.

The IR spectrum of the product obtained by ultrasonic dispersion of maghemite in the presence of linear sodium alginate macromolecules almost completely coincided with that of the initial linear sodium alginate. Thus, the macromolecules of linear sodium alginate are not able to stabilize reliably the maghemite nanoparticles obtained under the ultrasonic treatment. The important role of a polymer network is in the preliminary steric stabilization of nanoparticles.[14]

In conclusion, magnetic water-soluble metal organic frameworks based on sodium alginate preliminary crosslinked with Ca^{2+} ions and maghemite (γ-Fe_2O_3) nanoparticles were synthesized. Ultrasonic treatment led to the formation of spherical maghemite nanoparticles with diameters of 7 to 20 nm. The magnetic nanoparticles were stabilized by Na,Ca alginate due to the steric factor and electrostatic and coordinating interactions between polysaccharide functional groups and nanoparticle surfaces. As a result, a magnetic MOF with a size of about 135 nm was formed.

This MOF with biocompatible and magnetic moieties is promising for biomedical applications.

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (project no. 13.1902.21.0017).

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Received: 15th December 2020; Com. 20/6398