

MODIFICATION OF LAYERED DOUBLE HYDROXIDES

The present invention relates to processes for modifying a layered double hydroxides (LDHs), in particular, by dispersing LDHs in solvents with an optional, subsequent step of dissolving polymer material in the LDH dispersion. The invention also relates to stable dispersions of LDHs in solvents and composites of polymer and LDH.

Layered double hydroxides (LDHs) are a class of compounds which comprise two metal cations and have a layered structure. A review of LDHs is provided in *Structure and Bonding*; Vol 119, 2005 *Layered Double Hydroxides* ed. X Duan and D.G. Evans. The hydrotalcites, perhaps the most well-known examples of LDHs, have been studied for many years. LDH's can intercalate anions between the layers of the structure. WO 99/24139 discloses use of LDHs to separate anions including aromatic and aliphatic anions.

LDH materials are generally hydrophilic and it has proven difficult to form LDH composites with generally hydrophobic materials. It would however be greatly advantageous to provide LDH/polymer composites.

It would also be advantageous to provide for stable dispersions of LDHs in relatively non-polar solvents. There have been attempts to modify LDHs to enable stable dispersions or good composites to be formed.

WO-A-2007/065860 relates to processes of preparing nanocomposites of rubber and LDH by chemically linking organic anions through silane groups to the rubber.

EP-A-2174909 relates to LDHs containing generally acidic organic compounds to reduce discolouration of LDH-containing polymers.

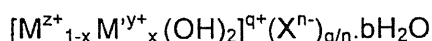
WO-A-2007/065861 relates to LDHs having fatty acid anions intercalated therein to promote compatibility with polymers.

Unfortunately, until now a prerequisite condition for using LDHs as a nanofiller in a polymer/LDH composite was making the LDH platelets compatible with the polymer which required appropriate and expensive treatment of either the polymer or the LDH prior to their incorporation into polymer matrix. Thus, previous attempts to stabilise LDH/relatively non-polar

systems require complicated processing and often do not succeed. Furthermore, the organo-modified LDH materials often decompose at a relatively low temperature.

It is an aim of the present invention to address these problems.

- 5 The present invention accordingly provides in a first aspect, a process for modifying a layered double hydroxide (LDH), the process comprising, (a) providing a material comprising a layered double hydroxide of formula:



- 10 wherein M and M' are metal cations, z is 1 or 2, x is 0.1 to 1, b is 0 to 5, y is 3 or 4, X is an anion, n is 1 to 3 and q is determined by x, y and z, (b) optionally washing the material at least once with a mixture of water and a mixing solvent miscible with water, and (c) washing the material obtained in step a or b at least once with at least one first solvent, the first solvent being miscible
15 with water and preferably having a solvent polarity (P') in the range of 3.8 to 9 to obtain a modified layered double hydroxide.

- Solvent polarity (P') is defined based on experimental solubility data reported by Snyder and Kirkland (Snyder, L. R.; Kirkland, J. J. In *Introduction to modern liquid chromatography*, 2nd ed.; John Wiley and Sons: New York,
20 1979; pp 248-250,) and as described in the table in the Examples section, below.

M may be a single metal cation or a mixture of different metal cations for example Mg, Zn, Fe for a MgFeZn/Al LDH. Preferred M is Mg, Zn, Fe, Ca or a mixture of two or more of these.

- 25 Preferably, z is 2 and M is Ca or Mg or Zn or Fe.

Preferably, M' is Al.

The preferred LDHs are Mg/Al, Ca/Al or Zn/Al.

- Preferably, the particle size of the LDH particles comprised in the material is in the range of 1 nm to 50 microns, preferably 1 nm to 20 microns,
30 more preferably 5 nm to 20 microns and most preferably 10 nm – 20 microns.

Generally any dimension of the LDH particles may be in this range, but, preferably the LDH particles have a thickness (substantially perpendicular to the layers of the particles) in this range or ranges.

Although LDHs particles up to 20 microns can generally be used or
5 dispersed in a nonpolar solvent after being modified using the method of the invention, generally the smaller the particle is, the more stable is the colloid solution and larger effect it has on the polymer composite on a wt% basis. Therefore, LDHs with a particle size of 20 microns or less are preferred.

Preferably, the aspect ratio of the LDH particles will be in the range 30
10 nm to 1500 nm (determined as platelet area/platelet thickness) preferably 80 to 500 nm and more preferably 100 nm to 350 nm.

The anion X in the LDH may be any appropriate anion, organic or inorganic, preferably selected from halide (e.g. chloride), inorganic oxyanions (eg. $Y_mO_n(OH)_p^{q-}$; $m = 1-5$; $n = 2-10$; $p = 0-4$, $q = 1-5$; $Y = B, C, N, S, P$),
15 anionic surfactants (such as sodium dodecyl sulfate, Fatty acid salts or sodium stearate), anionic chromophores, an anionic UV absorbers (for example 4-hydroxy-3-10 methoxybenzoic acid, 2-hydroxy-4 methoxybenzophenone-5-sulfonicacid (HMBA), 4-hydroxy-3-methoxy-cinnamic acid, p aminobenzoicacid and/or urocanic acid), or mixtures thereof.

20 The step of washing with a mixture of water and the mixing solvent results in even further improved results including (if the material is subsequently dispersed) improved dispersion of the LDH in the hydrocarbon solvent. It is preferred if the mixing solvent in mixture with water comprises a relatively polar solvent, more preferably an alcohol and most preferably the
25 mixing solvent is a C_1 to C_3 alcohol, e.g. methanol, ethanol or propanol. The preferred volume ratio of the mixing solvent and water is in the range 1:2 to 2:1.

It is preferred if the first solvent is neutral or alkaline. Although some relatively weak acid solvents may be used, if the pH is too low then this can
30 adversely affect the properties of the LDH and a very low pH can result in dissolution of the LDH with reduction in the efficiency of the overall process.

Preferably, therefore, the first solvent, when used in the process, has a pH of 7 or higher.

Generally, any suitable first solvent may be used but the preferred first solvent is selected from one or more of acetone, acetonitrile, dimethylformamide, dimethyl sulfoxide, dioxane, ethanol, methanol, n-propanol, iso-propanol, 2-propanol or tetrahydrofuran.

Preferably, the process further comprises a step d of dispersing the washed material obtained in step c in a second, hydrocarbon solvent to form a hydrocarbon-dispersed layered double hydroxide.

10 This process is greatly advantageous because despite being such a simple process it, surprisingly, results in good dispersion of the material comprising the LDH in the hydrocarbon solvent despite the fact that hydrocarbon solvents are non-polar. The resulting hydrocarbon-dispersed layered double hydroxide is advantageously used in various applications and
15 may be used for further processing. By preparing a stable dispersion of the LDH in an appropriate solvent no pretreatment of the LDH (e.g. intercalation with a fatty acid) or functionalisation of the polymer chains is required.

Another great advantage of the invention is that the dispersion is generally stable and also optically transparent.

20 Preferably, the second, hydrocarbon solvent comprises an aromatic compound.

The second, hydrocarbon solvent is preferably selected from one or more of benzene, toluene, xylene, mesitylene, benzyl alcohol, chlorobenzene, o-dichlorobenzene, or trichlorobenzene.

25 The material (or dispersion if the material is dispersed in a hydrocarbon solvent) obtained in the first aspect of the invention may be used in subsequent processing steps, preferably, the inventive process is further comprising mixing the material with a polymer to form a LDH/polymer composite or in the inventive process is further comprising dissolving a
30 polymer material in the hydrocarbon-dispersed layered double hydroxide to form a polymer loaded hydrocarbon dispersion.

Preferably, the polymer material is dissolved in the hydrocarbon-dispersed layered double hydroxide by heating to a predetermined temperature for a predetermined period. The predetermined temperature and period will depend upon the nature of the second, hydrocarbon solvent used to make the dispersion. However, generally the predetermined temperature will be in the range 25 °C to 250 °C. The predetermined period will usually be that required for the dissolution of the polymer in the hydrocarbon-dispersion and will usually be less than 4 hours.

Processing of the polymer material dissolved in the hydrocarbon-dispersion is preferably further comprising precipitating a composite material (usually a nanocomposite i.e. an intimately mixed composite with interaction of the phases of the material on the nanometer scale) from the polymer loaded hydrocarbon dispersion. Such precipitation may be, for example, by rapidly cooling the polymer loaded hydrocarbon dispersion or by adding a fourth solvent to the polymer loaded hydrocarbon dispersion. Suitable fourth solvents include solvents such as water or an alkane, for example hexane.

Generally, the polymer that can be suitably used in this method is any polymer known in the art and, if it is to be dispersed, that is soluble in an aromatic solvent that disperses the LDHs.

Polymers as discussed in this specification are organic substances of at least two building blocks (i.e. monomers), including oligomers, copolymers, and polymeric resins. Suitable polymers for use in the invention are polyadducts and/or polycondensates. The polymers may be homopolymers and/or copolymers.

Preferably, the polymer material comprises at least one polymer selected from a polyolefin, vinyl polymers, saturated esters or mixtures thereof.

Even preferred, the polyolefin comprises polyethylene and/or polypropylene.

Examples of suitable polymers are polyolefins, such as polyethylene or polypropylene, vinyl polymers, such as polystyrene, polymethyl methacrylate, polyvinyl chloride, polyvinylidene chloride, saturated polyesters, such as

polyethylene terephthalate.

Particularly preferred are polymers or copolymers obtainable by polymerization of at least one ethylenically unsaturated monomer. Examples of such polymers are polyolefins and vinyl polymers. The polyolefin or vinyl
5 polymer can be a homopolymer or a copolymer. Suitable examples of such polymers are polyethylene, polypropylene, polybutylene, polystyrene, polyvinyl chloride, polyvinylidene chloride, and ethylene-propylene rubber, propylene-butene copolymer, ethylene-vinyl chloride copolymer, ethylene-vinyl acetate copolymer, acrylonitrile-butadiene-styrene copolymer (ABS),
10 acrylonitrile-acrylate-styrene copolymer (AAS), methyl methacrylate-butadiene-styrene copolymer (MBS), chlorinated polyethylene, chlorinated polypropylene, ethylene-acrylate copolymer, vinyl chloride-propylene copolymer, and mixtures thereof. Even more preferred polymers are polyethylene, polypropylene, polystyrene, and polyvinyl chloride.

15 Specific examples of polyethylene are high-density polyethylene, low-density polyethylene, straight chain low-density polyethylene, ultra-low-density polyethylene, and ultra-high-molecular weight polyethylene. Examples of ethylene-based copolymers are ethylene-vinyl acetate copolymer (EVA), ethylene-ethyl acrylate copolymer (EEA), ethylene-methyl acrylate copolymer
20 (EMA), and ethylene-acrylic acid copolymer (EAA). A specific example of a polypropylene is a so-called thermoplastic polyolefin (TPO), which include blends or reactor grades of polypropylene and EPR rubber.

One of the great advantages of the present invention is that the LDH dispersion can function as a multifunctional additive to the polymer. For
25 example, ZnAl-LDHs have good UV absorption enhancing the UV stability of the polymer and LDH can acts as a radical scavenger to improve UV stability of PVC.

The anion used in the LDH can add additional properties to the dispersion. Thus, the anions may comprise for example one or more of the
30 following: oxyanions (e.g. phosphate or carbonate) for improved thermal properties), anionic borates (for fire retardancy, smoke suppression), organic

/inorganic anion chromophores (for colour), anionic UV absorbers (for UV stability).

Examples of specific anions that may be used include organic UV absorbers (such as 4-hydroxy-3-methoxybenzoic acid, 2-hydroxy-4
5 methoxybenzophenone-5-sulfonic acid (HMBA), 4-hydroxy-3-methoxy-
cinnamic acid, p aminobenzoic acid and/or urocanic acid). Borate anions
(such as $\text{B}(\text{OH})_4^-$, $\text{B}_2\text{O}_4^{2-}$, $\text{B}_4\text{O}_5(\text{OH})_4^{2-}$, $\text{B}_5\text{O}_6(\text{OH})_4^-$) give good fire
retardancy and smoke suppression to polymers such as PVC, anionic dyes
(such as acid red 1(AR)— $\text{C}_{18}\text{H}_{33}\text{N}_3\text{Na}_2\text{O}_8\text{S}_2$, acid yellow 3(AY)—
10 $\text{C}_{18}\text{H}_9\text{NNa}_2\text{O}_8\text{S}_2$, acid green 25(AG)— $\text{C}_{28}\text{H}_{20}\text{N}_2\text{Na}_2\text{O}_8\text{S}_2$, acid blue 45(AB)—
 $\text{C}_{14}\text{H}_8\text{N}_2\text{Na}_2\text{O}_{10}\text{S}_2$, AB 80(AB2)— $\text{C}_{32}\text{H}_{20}\text{N}_2\text{Na}_2\text{O}_8\text{S}_2$), give improved colour
stability especially to bleaching by UV.

Homogeneously dispersed LDH(s) using this invention in a polymer
matrix can dramatically improve any or all the following aspects of the
15 polymer: mechanical properties, rheological properties, thermal properties,
gas barrier properties, UV stability, IR absorbance, heat retention, colour
stability, reduced flammability and smoke index. Combination of two or more
LDH materials enables these properties to be further improved or tuned by
adding mixtures of suitable LDHs.

20 Preferably, the LDH is present in a range of 0.01 to 85 wt%, preferably
0.1 to 50 wt%, even more preferably 0.5-50 wt% or 0.5 to 25 wt% and most
preferably 0.5 to 15 wt%, based on the weight of polymer.

In a preferred embodiment of the invention, there is provided a
composite material (preferably a nano-composite material), wherein the
25 polymeric matrix is selected from polyolefins, vinyl polymers, polyesters,
polycarbonates, polyamides, polyurethanes and/or polyepoxides.

The (nano)composite materials according to the invention are
particularly suitable to be used for a large variety of applications. The
materials are eminently processable and can be shaped in conventional
30 shaping steps, such as injection molding and extrusion processes. Shaped
articles of a variety of natures can be manufactured from the present
nanocomposite material. Examples comprise any application for which the

material of the polymeric matrix is suited. Preferred applications may include fibers, packaging materials and construction materials.

In a second aspect, the present invention provides a modified layered double hydroxide obtainable by the inventive process.

5 In a third aspect, the present invention provides a stable dispersion of the inventive modified layered double hydroxide of formula: $[M^{z+}_{1-x} M'^{y+}_x (OH)_2]^{q+} (X^{n-})_{q/n} \cdot bH_2O$ in a hydrocarbon solvent, wherein M and M' are metal cations, z is 1 or 2, x is 0.1 to 1, b is 0 to 5, y is 3 or 4, X is an anion, n is 1 to 3 and q is determined by x, y and z.

10 In a fourth aspect the present invention provides a composite comprising a layered double hydroxide of formula: $[M^{z+}_{1-x} M'^{y+}_x (OH)_2]^{q+} (X^{n-})_{q/n} \cdot bH_2O$ and a polymer material, wherein M and M' are metal cations, z is 1 or 2, x is 0.1 to 1, b is 0 to 5, y is 3 or 4, X is an anion, n is 1 to 3 and q is determined by x, y and z.

15 In a fifth aspect, the invention provides a process according to the first aspect but with the additional step of providing a material comprising two or more different layered double hydroxides of the formula specified above.

The great benefit of the fifth aspect of the invention is that adding two or more different LDHs into the polymer may markedly improve a number of properties such as its thermal stability and melting point, mechanical properties and/or UV stability. For example, addition of $Mg_3Al_1-CO_3$, $Mg_3Al_1-SO_4$, and $Ca_3Al_1-NO_3$ into a polymer, results in LDHs absorbing heat by different decompositions over the whole temperature range of 240-540°C as illustrated by the thermogravimetric analysis (in relation to a mixture of LDHs without polymer) in Figure 1.

The preferred and optional features of the second, third, fourth and fifth aspects of the invention are as discussed in relation to the first aspect and as specified in the claims.

The invention is illustrated by the Figures in which:

30 **Figure 1.** is a graph of the thermogravimetric analysis (TGA) of $Mg_3Al_1-CO_3$, $Mg_3Al_1-SO_4$, and $Ca_3Al_1-NO_3$.

Figure 2. is a series of photographs of $\text{Mg}_3\text{Al}_1\text{-CO}_3$ LDHs with water wash, LDH synthesised at pH12 (left), H_2O /ethanol and acetone wash (x 2) LDHs synthesised at pH10 (middle) and pH12 (right) dispersed in xylene solution.

5 **Figure 3.** is a series of photographs of a dispersion of $\text{Mg}_3\text{Al}_1\text{-CO}_3$ pH 12 in xylene, at 1.25g/L, 2.5g/L, 5g/L, and 10g/L loading.

Figure 4. is a series of photographs of synthesized PP/ $\text{Mg}_3\text{Al}_1\text{-CO}_3$ LDH nanocomposite with different loadings.

10 **Figure 5** shows X-ray diffractograms (XRD) of PP (polypropylene) and PP/ $\text{Mg}_3\text{Al}_1\text{-CO}_3$ LDH nanocomposite (6 wt%), ($\blacktriangledown$) $\text{Mg}_3\text{Al}_1\text{-CO}_3$.

Figure 6 shows TGA analysis of PP/LDHs nanocomposite tested in air.

Figure 7 shows TGA analysis of pure PP and PP nanocomposites with $\text{Mg}_3\text{Al}_1\text{-CO}_3$, $\text{Mg}_3\text{Al}_1\text{-SO}_4$, $\text{Mg}_3\text{Al}_1\text{-Cl}$, $\text{Mg}_3\text{Al}_1\text{-NO}_3$.

15 **Figure 8** shows TGA analysis of pure PP and PP nanocomposites with $\text{Mg}_3\text{Al}_1\text{-CO}_3$ and $\text{Ca}_3\text{Al}_1\text{-NO}_3$.

Figure 9 shows a transmission electron micrograph (TEM) images of $\text{Mg}_3\text{Al}_1\text{-CO}_3$ LDH dispersed in H_2O .

Figure 10 shows TEM image of $\text{Mg}_3\text{Al}_1\text{-CO}_3$ LDH dispersed in xylene.

20 **Figure 11** shows TGA analysis of pure HDPE (high density polyethylene) and HDPE/ $\text{Mg}_3\text{Al}_1\text{-CO}_3$ (9wt%).

Figure 12. Effect of the LDH loadings on the crystallisation temperature of PP/LDH nanocomposites.

Figure 13. Effect of the interlayer anions on the crystallisation temperature of PP/LDH nanocomposites.

25 **Figure 14.** Effect of the LDH loadings on the crystallisation temperature of HDPE/LDH nanocomposites.

Figure 15. Flow diagram of the synthesis of PP/ $\text{Mg}_3\text{Al}_1\text{-CO}_3$ nanocomposite.

30 **Figure 16.** Transmission UV-Visible spectrometric data for $\text{Mg}_3\text{Al}_1\text{-CO}_3$ suspensions in xylene solvent (path length 4mm) with different w% loadings in xylene.

Figure 17. Heat release rate for PP/Zn₂Al-borate nanocomposites with different LDH loadings (6, 15, and 30 wt%).

Figure 18. Photographs of residual char for (a) pure PP, (b) 6 wt% PP/Zn₂Al-borate, (c) 15 wt%PP/Zn₂Al-borate, and (d) 30 wt%PP/Zn₂Al-borate.

5 **Figure 19.** UV-visible spectrometry analysis of PP/Mg₃Al-tartrazine nanocomposites.

The invention is further illustrated by the following Examples.

Examples

10

LDHs dispersions in hydrocarbons

LDHs were dispersed by modifying the LDH by washing with specific solvents. Inorgano-LDHs were successfully dispersed into hydrocarbon solvents such as xylene, enabling, for example, synthesis of
15 polyolefin/inorgano-LDHs directly and simply.

Characterisation Methods

Elemental analysis was carried out using a quantitative combustion technique. Powder X-ray diffraction (XRD) data were collected on a PAN
20 Analytical X'Pert Pro diffractometer in reflection mode at 40 kV and 40 mA using Cu K α radiation ($\alpha_1 = 1.54057 \text{ \AA}$, $\alpha_2 = 1.54433 \text{ \AA}$, weighted average = $1.54178 \text{ \AA}$). Samples were mounted on stainless steel sample holders. A TA Instruments Q200 differential scanning calorimeter (DSC) was used to obtain DSC thermograms. Experiments were run on samples of about 10 mg. Each
25 sample was first heated from room temperature to 220 °C with a heating rate of 10 °C/min to remove thermal history, followed by cooling down to 40 °C at a rate of 10 °C/min to record re-crystallization temperature, and then reheated to 220 °C at a rate of 10 °C/min to determine the melt temperature. The experiments were carried out under an argon purge (50mL/min). TEM images
30 were obtained from a JEOL JEM-2100 transmission electron microscope. The

LDHs particles were dispersed in H₂O or xylene and then loaded on to a Cu grid covered with a very thin carbon film.

Synthesis of LDH

5 LDH may be synthesized by a number of methods, e.g. coprecipitation method.

One example of the synthesis of Mg₃Al₁-CO₃ by coprecipitation method is as follows:

In brief, a salt solution A (100 ml) containing a mixture of 0.075 mol
10 Mg(NO₃)₂·6H₂O and 0.025 mol Al(NO₃)₃·9H₂O was added drop-wise to a basic solution B (100 ml) containing 0.05 mol Na₂CO₃. The pH value of solution B was kept constant (10–14) by addition of a solution C (50 ml) containing 0.17 mol NaOH. The resulting mixture D was aged at room temperature for 24 h with continuous stirring. The aged mixture was filtered
15 and washed with deionized water until pH = 7.

Similarly, Mg₃Al₁-X with different inorganic anions including NO₃⁻, SO₄²⁻, Cl⁻, etc can be synthesized. Briefly, Mg₃Al₁-NO₃ and Mg₃Al₁-SO₄ were prepared by adding an aqueous solution (100 ml) containing 0.075 mol Mg(NO₃)₂·6H₂O and 0.025 mol Al(NO₃)₃·9H₂O drop-wise to a solution (100)
20 containing 0.05 mol NaNO₃ or Na₂SO₄. The pH was controlled at 10 during the whole preparation process using NaOH (3.4 M). Mg₃Al₁-Cl was synthesized by adding an aqueous solution (100 ml) containing 0.075 mol MgCl₂ and 0.025 mol AlCl₃·xH₂O drop-wise into a solution (100 ml) containing 0.05 mol NaCl, with the pH controlled at ~10 using a NaOH solution (4 M).

25 Other syntheses of LDH materials are as follows:

Coprecipitation and intercalation reactions were carried out in round-bottomed flasks or finger ampoules appropriate to the scale of the reaction, containing a suitable solvent and a magnetic follower with a pivot ring. The contents of the flask were stirred for the requisite time at a suitable
30 temperature. The mixture was allowed to cool and filtered using a sintered glass frit. If the filtrate was required, it was collected in a Büchner flask and removed before washing the solid residue with deionised water and acetone.

The powder was left to dry in air before characterisation by XRD.

Synthesis of $[\text{Mg}_2\text{Al}(\text{OH})_6]\text{NO}_3 \cdot n\text{H}_2\text{O}$ and $[\text{Ca}_2\text{Al}(\text{OH})_6]\text{Cl} \cdot n\text{H}_2\text{O}$

$[\text{Mg}_2\text{Al}(\text{OH})_6]\text{NO}_3 \cdot n\text{H}_2\text{O}$ was synthesised by coprecipitation. A mixed
5 metal nitrate solution was prepared by dissolving 21.4 g of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$
and 10.5 g of $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ in 100 ml of water. This was added dropwise to a
solution of 6 g of NaOH and 9.5 g of NaNO_3 in 100ml of water over a period of
about 30 minutes. The mixture, which was thoroughly purged with nitrogen
gas at all stages, was stirred vigorously for 24 hours at 80°C. The product
10 formed as a white powder which was collected.

$[\text{Ca}_2\text{Al}(\text{OH})_6]\text{Cl} \cdot n\text{H}_2\text{O}$ was produced by the same method, in which
 CaCl_2 and AlCl_3 were added dropwise to a solution of NaOH and NaCl.

Synthesis of $[\text{Ca}_2\text{Al}(\text{OH})_6]\text{NO}_3 \cdot n\text{H}_2\text{O}$

15 $[\text{Ca}_2\text{Al}(\text{OH})_6]\text{NO}_3 \cdot n\text{H}_2\text{O}$ was synthesised by a salt-oxide method. 2.48 g
of CaO was added to 100 ml of water and stirred until fully suspended. Then,
to this suspension, 4.72 g of $\text{Al}(\text{NO}_3)_3$ was added and stirred until dissolved.
The mixture, which was thoroughly purged with nitrogen at all stages, was
stirred vigorously for 12 hours at 90°C. The solid product was collected. The
20 product formed as a white powder.

Suitable modification of these methods enables particular LDH
materials to be prepared.

Modification of LDHs

25 $\text{Mg}_3\text{Al}_2(\text{OH})_6\text{CO}_3$ was synthesised at pH 12 and washed with water. No clear
dispersion in xylene was observed as shown in Figure 2, left. In contrast,
when $\text{Mg}_3\text{Al}_2(\text{OH})_6\text{CO}_3$ was washed with ethanol+ H_2O (1:1) once and then with
acetone twice, LDHs synthesized at pH =10 and pH = 12 were highly
dispersed in xylene solution (Figure 2, middle and right respectively). Then
30 different amount of LDHs (1.25g/L to 10g/L) were dispersed in xylene to give

a stable, optically transparent dispersion. All LDHs were highly dispersed, as shown in Figure 3.

Synthesis of Zn_2Al -borate LDH

Zn_2Al -borate LDH was prepared by adding 100 ml $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (0.075 mol) and $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (0.0375 mol) solution drop-wise into a 100 ml H_3BO_3 (0.187 mol) solution. The pH of the precipitation solution was controlled at ca. 8.3 using a NaOH (1 M) solution. During the whole synthesis, the system was protected with N_2 gas to prevent the contamination by atmosphere CO_2 . The sample was washed with deionised (DI) water till pH close to 7. The water washed wet cake was further thoroughly washed with acetone (at least 3 times). And the acetone washed wet cake was directly used for the preparation of polymer nanocomposites (as described previously) without being dried.

Synthesis of Mg_3Al -tartrazine LDH

First, $\text{Mg}_3\text{Al-NO}_3$ was synthesized by coprecipitation method. Metal precursor solution containing 9.6 g $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and 4.7 g $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ in 50 ml H_2O was added drop-wise into the anion solution containing 2.125 g NaNO_3 in 50 ml H_2O , in the meantime, the pH was kept constant using NaOH (4 M). The mixture was aged at room temperature for 12 h, followed by filtration and washing with water until pH close to 7. The obtained water washed "wet cake" was directly used for the synthesis of Mg_3Al -tartrazine via anion exchange method. Then Mg_3Al -tartrazine LDH was synthesized by anion exchange method. The above obtained $\text{Mg}_3\text{Al-NO}_3$ LDH "wet cake" was re-dispersed in 130 ml aqueous solution containing 20.04 g tartrazine. The pH of the solution was adjusted to 10 using NaOH (4M), followed by aging at 70 °C for 12 h. The sample was washed with DI water till pH close to 7. The water washed wet cake was further thoroughly washed with acetone (at least 3 times). And the acetone washed wet cake was directly used for the preparation of polymer nanocomposites without being dried.

Synthesis of Polypropylene (PP)/LDHs nanocomposite

The nanocomposite is synthesized as follows:

- a) Disperse a pre-determined amount of LDHs (0-12 wt%)

corresponding to PP) into 100 ml xylene solution, then add 5 g PP.

b) Heat the mixture to $\sim 140^{\circ}\text{C}$ and keep at this temperature for 2 h to dissolve PP completely.

5 c) Pour the mixture into 100 ml hexane (or water) and then filter and dry at 80°C in a vacuum oven. The product is the nanocomposite.

A specific preparation of a (nano)composite is illustrated in Figure 15

Figure 4 shows the synthesized PP/Mg₃Al₁-CO₃ nanocomposites at
10 different loadings. Figure 5 shows the XRD patterns of pure PP and PP/Mg₃Al₁-CO₃ 6 wt%. The characteristic peak of Mg₃Al₁-CO₃ was noticed at 11.43° at for the nanocomposite sample, indicating the successful introduction of LDHs into PP.

This HDPE/Mg₃Al₁-CO₃ 9 wt% nanocomposite was synthesized with
15 the same method as PP/LDHs. The detailed synthesis is as follows:

- (1) Synthesize Mg₃Al₁-CO₃ LDH at pH 10 and room temperature.
- (2) Wash the LDH with water to pH = 7 first, then wash again with ethanol/H₂O once, acetone twice.
- (3) Disperse the LDH gel into xylene (100 ml) at room temperature.
- 20 (4) Put 5 g HDPE to the xylene solution, and heat the mixture to 140°C , hold at that temperature for 2 h to completely dissolve HDPE and mix with LDH.
- (5) Pour the mixture into 150 ml Hexane to quickly cool and precipitate it
- 25 (6) Filter and dry in a vacuum oven at 80°C .

Figure 11 shows that although HDPE is much more thermal stable than PP, adding LDHs can still increase its thermal stability.

Synthesis of Polypropylene (PP)/LDHs nanocomposite

30 The nanocomposite is synthesized as follows:

- a) Disperse a pre-determined amount of LDHs (0-12 wt% corresponding to PP) into 100 ml xylene solution, then add 5 g PP.

b) Heat the mixture to $\sim 140^{\circ}\text{C}$ and keep at this temperature for 2 h to dissolve PP completely.

c) Pour the mixture into 100 ml hexane (or water) and then filter and dry at 80°C in a vacuum oven. The product is the nanocomposite.

5 A specific preparation of a (nano)composite is illustrated in Figure 15.

Flame retardant performance

The flame retardant performance of PP/ Zn_2Al -borate nanocomposites was investigated using cone calorimetry. Figure 1 shows the peak heat
10 release rate (PHRR), which is the key metric for assessing polymer nanocomposite performance under real fire conditions. Adding Zn_2Al -borate LDHs significantly decreased the PHRR compared with pure PP. With 15 wt% of LDH, the PHRR was decreased from 1588 kW/m^2 for pure PP to 643 kW/m^2 , and it can be further decreased to 517 kW/m^2 with 30 wt% LDH.

15 After cone calorimetry test, the formation of a residual char was observed for all samples except pure PP (see Figure 2). According to the barrier fire retardant mechanism, the char can act as a barrier to both heat and mass transfer which makes it more difficult for degrading material to escape to the vapor phase and also prevents heat transfer back to the
20 polymer. It is apparent that as increasing the LDH loading, the amount of char residue was increased.

Thermal stability of PP/ $\text{Mg}_3\text{Al}_1\text{-CO}_3$ pH 10 nanocomposite.

The thermal stability of PP/ $\text{Mg}_3\text{Al}_1\text{-CO}_3$ was tested by TGA, as shown
25 in Figure 6. The optimal LDH loading is found to be ca. 9wt%. The result indicates that the thermal stability of PP is highly enhanced. With 9wt% LDH, the $T_{0.1}$ and $T_{0.5}$ was increased 25°C and 44°C respectively. We believe that some other properties could also be improved, e.g. the mechanical, rheological, and flame retardant properties.

30 Differential scanning calorimetry (DSC) was used to analyse the melting and crystallization behavior of the neat polypropylene (PP) and PP/LDHs nanocomposites.

Experiments were run on samples of about 10 mg. Each sample was first heated from room temperature to 220 °C with a heating rate of 10 °C/min to remove thermal history, followed by cooling down to 40 °C at a rate of 10 °C/min to record the re-crystallization temperature, and then reheated to 220 °C at a rate of 10 °C/min to determine the melt temperature. The experiments were carried out under an argon purge (50mL/min).

a) **Effect of LDH loading for PP/LDH nanocomposites.**

From the DSC analysis, we noticed that both the crystallization temperature (T_c) and the melting temperature (T_m) were increased with $Mg_3Al_1-CO_3$ LDH as additive (See Table 1 and Figure 12). It is obvious that the peak temperature increases with increasing LDH content. Particularly the T_c was increased by 14.6 °C with 12 wt% LDH loading. This phenomenon may be due (without wishing to be bound) by the heterogeneous nucleation effect of $Mg_3Al_1-CO_3$ LDH nanoparticles on PP macromolecular segments which can be easily attached to the surface of the $Mg_3Al_1-CO_3$ LDH, which leads to the crystallization of PP to occur at a higher crystallization temperature.

Table 1. DSC results of PP/ $Mg_3Al_1-CO_3$ with different LDH loadings.

Nanocomposites	$T_c/^\circ C$	$\Delta H_c / J g^{-1}$	$T_m/^\circ C$	$\Delta H_m / J g^{-1}$
Pure PP	108.31	85.61	153.65	85.70
PP/ $Mg_3Al_1-CO_3$ 1 wt%	116.52	91.85	156.19	90.28
PP/ $Mg_3Al_1-CO_3$ 3 wt%	118.10	94.84	157.89	93.75
PP/ $Mg_3Al_1-CO_3$ 6 wt%	120.81	81.76	158.34	86.67
PP/ $Mg_3Al_1-CO_3$ 9 wt%	121.27	87.94	157.98	89.37
PP/ $Mg_3Al_1-CO_3$ 12 wt%	122.90	86.51	158.56	92.79

$T_c/^\circ C$ = Crystallisation temperature

$\Delta H_c / J g^{-1}$ = Enthalpy of crystallisation

$T_m/^\circ C$ = Melting point

$\Delta H_m / J g^{-1}$ = Enthalpy of melting.

b) **Effect of intercalated anions on PP/LDH nanocomposites.**

The influence of the interlayer anions on the melting and crystallization temperatures of PP/Mg₃Al₁-X (X = SO₄²⁻, CO₃²⁻, NO₃⁻, and Cl⁻) was investigated, see Table 2 and Figure 13. All the LDHs studied increase the melting and crystallization temperatures of the nanocomposite, the promoting effect varies with different anions. The highest T_c was observed with Mg₃Al₁-CO₃ LDH as the additive.

Table 2. DSC results of PP/Mg₃Al₁-CO₃ with different interlayer anions at 9 wt% loading.

Nanocomposites	T _c /°C	ΔH _c /J g ⁻¹	T _m /°C	ΔH _m /J g ⁻¹
Pure PP	108.31	85.61	153.65	85.70
PP-Mg ₃ Al ₁ -SO ₄ ,	119.43	81.38	158.33	85.54
PP-Mg ₃ Al ₁ -CO ₃ ,	121.27	87.94	157.98	89.37
PP-Mg ₃ Al ₁ -NO ₃ ,	118.17	89.09	156.56	93.74
PP-Mg ₃ Al ₁ -Cl,	119.22	89.89	156.66	87.09

c) **High Density Polyethylene (HDPE)/LDH nanocomposites.**

We also studied the effect of adding Mg₃Al₁-CO₃ LDH on the melting and crystallization temperature of High Density Polyethylene (HDPE). After adding 9 wt% of LDH, T_m kept unchanged and T_c was slightly increased by 2 °C, see Table 3 and Figure 14.

Table 3. DSC results of HDPE and HDPE/Mg₃Al₁-CO₃ (at 9 wt% loading).

Nanocomposites	T _c /°C	ΔH _c /J g ⁻¹	T _m /°C	ΔH _m /J g ⁻¹
Pure HDPE	116.73	178.2	129.19	172.3
HDPE-Mg ₃ Al ₁ -CO ₃	118.82	166.9	129.09	161.0

Solvents for washing the LDHs

The following organic solvents have been studied, have good miscibility with water and can be used to wash the LDHs paste.

Solvents	Boiling point (°C)	Viscosity (cPoise)	P'	Solubility in water (%w/w)
Acetone	56	0.32	5.1	100
Acetonitrile	82	0.37	5.8	100
Dimethylformamide	155	0.92	6.4	100
Dimethyl Sulfoxide	189	2	7.2	100
Dioxane	101	1.54	4.8	100
Ethanol	78	1.2	4.3	100
Methanol	65	0.6	5.1	100
n-propanol	97	2.27	4.0	100
Iso-propanol (2-propanol)	82	2.3	3.9	100
Tetrahydrofuran	65	0.55	4.0	100

5 Table 4.

Solvents for dispersing LDHs

Many different solvents were tested as dispersing solvents, and it seems aromatic solvents give good dispersion. "Good" dispersion means that an optically clear, transparent stable dispersion was formed. "Not good" means the dispersion was not complete and some precipitate was apparent.

(1) Alkanes

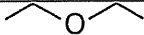
Solvents	Formula	Boiling point (°C)	P'	Dispersion
Hexane	C ₆ H ₁₄	69	0.1	Not good
trimethylpentane	C ₈ H ₁₈	99.3	0.1	Not good
Decane	C ₁₀ H ₂₂	174	0.3	Not good

Dodecane	C ₁₂ H ₂₆	216		Not good
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(2) Alcohols

Solvents	Formula	P'	Dispersion
Methanol	CH ₃ OH	5.1	Not good
Ethanol	C ₂ H ₅ OH	4.3	Not good
1-Butanol	C ₄ H ₉ OH	3.9	Not good

(3) Ethers

Solvents	Formula	Structure	P'	Dispersion
Dioxane	C ₄ H ₈ O ₂		4.8	Not good
Tetrahydrofuran (THF)	C ₄ H ₈ O		4.0	Not good
Diethyl ether	C ₄ H ₁₀ O		2.8	Not good

5

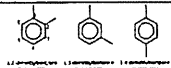
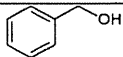
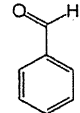
(4) Ketone

Solvents	Formula	Structure	P'	Dispersion
Acetone	C ₃ H ₆ O		5.1	Not good

10

(5) Aromatic solvents

Solvents	Formula	Structure	P'	dispersion
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benzene	C_6H_6		2.7	good
toluene	$C_6H_5-CH_3$		2.4	good
xylene	$C_6H_4(CH_3)_2$		2.5	good
mesitylene	$C_6H_3(CH_3)_3$			good
benzyl alcohol	$C_6H_5CH_2OH$			good
Chlorobenzene	C_6H_5Cl		2.7	good
o-Dichlorobenzene	$C_6H_4Cl_2$		2.7	good
Trichlorobenzene	$C_6H_3Cl_3$			good
Benzenesulfonyl chloride	$C_6H_5SO_2Cl$			Not good
Benzoyl chloride	C_6H_5COCl			Not good
Benzaldehyde	C_6H_5CHO			Not good

Polarity (P') as defined in Snyder and Kirkland (Snyder, L. R.; Kirkland, J. J. In Introduction to modern liquid chromatography, 2nd ed.; John Wiley and Sons: New York, 1979; pp 248-250,)

- 5 Figures 9 and 10 show TEM images of one example of $Mg_3-Al-CO_3$ LDH dispersed in H_2O and xylene. From these two images it is apparent that after

washing with acetone, and re-dispersing into xylene, the particle size and shape remain generally unchanged.

UV-Visible spectrometry data

5 Evidence of the clarity, transparency and stability of the LDH suspensions in xylene was demonstrated by transmission UV-Visible spectrometry. The results are shown in Figure 16.

10 The example is an $\text{Mg}_3\text{Al-CO}_3$ suspension in xylene, the $\text{Mg}_3\text{Al-CO}_3$ particles are well dispersed and negligible light scattering is observed even with a loading as high as 10 g/L. A transmission factor of 99.8% and 96.8% was achieved with 5 g/L and 10 g/L suspension, respectively at 500 nm. When the LDH loading was increased to 20 g/L, the transmission decreased to ca. 60 % at 500 nm.

15

No change in the UV/Vis spectra are observed after 24 hours standing

This result indicates that the LDH suspension in xylene is optically transparent and stable.

20

Colored polymer and UV absorption

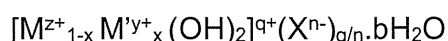
Tartrazine is a good organic UV absorber, therefore, the UV absorbance of PP/ Mg_3Al -tartrazine nanocomposites was evaluated (see Figure 19). Even with 1 wt% of Mg_3Al -tartrazine LDH, 82% of UV absorbance was achieved at 25 350 nm. This result suggests that adding Mg_3Al -tartrazine LDH can significantly increase the thermal stability and the UV absorption. In the meantime, colored polymers can be obtained.

30 The features disclosed in the foregoing description, in the claims and/or in the accompanying drawings may, both separately and in any combination thereof be material for realizing the invention in diverse forms thereof.

CLAIMS

1. A process for modifying a layered double hydroxide (LDH), the process comprising,

- 5 a. providing a material comprising a layered double hydroxide of formula:



- 10 wherein M and M' are metal cations, z is 1 or 2, x is 0.1 to 1, b is 0 to 5, y is 3 or 4, X is an anion, n is 1 to 3 and q is determined by x, y and z,

- 15 b. optionally washing the material at least once with a mixture of water and a mixing solvent miscible with water, and

- c. washing the material obtained in step a or b at least once with at least one first solvent, the first solvent being miscible with water and having a solvent polarity P' in the range of 3.8 to 9 to obtain a modified layered double hydroxide, and
- 20

- d. dispersing the modified layered double hydroxide obtained in step c in a second, hydrocarbon solvent to form a hydrocarbon-dispersed layered double hydroxide.
- 25

2. The process as claimed in claim 1, wherein z is 2 and M is Ca, Mg, Zn, Fe or mixtures thereof.

3. The process as claimed in any one of the claims 1 or 2, wherein M' is Al.
- 30

4. The process as claimed in any one of the preceding claims wherein the particle size of the LDH particles comprised in the material is in the range of 1 nm to 50 micron.

5. The process as claimed in any one of the preceding claims, wherein X is an anion selected from halide, inorganic oxyanion, anionic surfactants, anionic chromophores, an anionic UV absorbers or mixtures thereof.
6. The process as claimed in any one of the preceding claims wherein the mixing solvent is a C₁ to C₃ alcohol.
7. The process as claimed in any one of the preceding claims, wherein the at least one first solvent is neutral or alkaline.
8. The process as claimed in any one of the preceding claims, wherein the first solvent is selected from one or more of acetone, acetonitrile, dimethylformamide, dimethyl sulfoxide, dioxane, ethanol, methanol, n-propanol, 2-propanol, or tetrahydrofuran.
9. The process as claimed in any of the preceding claims, wherein the second hydrocarbon solvent comprises an aromatic compound.
10. The process as claimed in any of the preceding claims, wherein the second, hydrocarbon solvent is selected from one or more of benzene, toluene, xylene, mesitylene, benzyl alcohol, chlorobenzene, o-dichlorobenzene, or trichlorobenzene.
11. The process as claimed in any one of preceding claims, further comprising dissolving a polymer material in the hydrocarbon-dispersed layered double hydroxide to form a polymer loaded hydrocarbon dispersion.

12. The process as claimed in claim 11, wherein the polymer material is dissolved in the hydrocarbon-dispersed layered double hydroxide by heating to a pre-determined temperature for a pre-determined period.
- 5 13. The process as claimed in claim 11 or 12, further comprising a step of precipitating a composite material from the polymer loaded hydrocarbon dispersion.
- 10 14. The process as claimed in any one of claims 1 to 8, further comprising mixing the modified layered double hydroxide with a polymer material to form a LDH/polymer composite.
- 15 15. The process as claimed in any one of claims 11 to 14, wherein the polymer material comprises at least one polymer selected from a polyolefin, vinyl polymers, saturated esters or mixtures thereof.
16. The process as claimed in claim 15, wherein the polyolefin comprises polyethylene and/or polypropylene.
- 20 17. The process as claimed in any one of claims 11 to 16 wherein the LDH is present in a range of 0.01 to 85 wt%, preferably 0.1 to 50 wt % based on the weight of polymer.
- 25 18. A stable dispersion of the modified layered double hydroxide in a hydrocarbon solvent according to any preceding claims.