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Process for the production of gel-based composite materials

15 The present invention relates to a process for the production of gel-based composite materials, the materials obtained by this process as well as the use thereof in several applications.

20 A composite material is basically a combination of two or more materials, each of which retains its own distinctive properties. The resulting material has characteristics that are not characteristic of the components in isolation. Most commonly, composite materials have a bulk phase, which is continuous, called the matrix; and a dispersed, non-continuous, phase called the reinforcement. Some other examples of basic composites include concrete (cement mixed with sand and aggregate), reinforced
25 concrete (steel rebar in concrete), and fibreglass (glass strands in a resin matrix).

The following are some of the reasons why composites are selected for certain applications:

- 30
- High strength to weight ratio (low density high tensile strength)
 - High creep resistance
 - High tensile strength at elevated temperatures
 - High toughness

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Typically, reinforcing materials are strong, while the matrix is usually a ductile, or tough, material. If the composite is designed and fabricated correctly, it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material.

- 5 For example: polymer/ceramic composites have a greater modulus than the polymer component, but aren't as brittle as ceramics.

Since the reinforcement material is of primary importance in the strengthening mechanism of a composite, it is convenient to classify composites according to the characteristics of the reinforcement. The following three categories are commonly used:

- 10 a) "fibre reinforced", wherein the fibre is the primary load-bearing component.
b) "particle reinforced", wherein the load is shared by the matrix and the particles.
15 c) "dispersion strengthened", wherein the matrix is the major load-bearing component.
d) "structural composites", wherein the properties depend on the constituents, and the geometrical design.

20 Generally, the strength of the composite depends primarily on the amount, arrangement and type of fibre (or particle) reinforcement in the resin. In addition, the composite is often formulated with fillers and additives that change processing or performance parameters.

25 Advanced composites utilize a combination of resins and fibres, customarily carbon/graphite, kevlar, or fibreglass with an epoxy resin. The fibres provide the high stiffness, while the surrounding polymer resin matrix holds the structure together. The fundamental design concept of composites is that the bulk phase accepts the load over a large surface area, and transfers it to the reinforcement material, which can
30 carry a greater load. These materials were first developed for use in the aerospace

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industry because for certain application they have a higher stiffness to weight or strength-to-weight ratio than metals. This means metal parts can be replaced with lighter weight parts manufactured from advanced composites.

5 Thus, in the prior art it is well-known to implement polymers and the like in composites, which however are relatively expensive and environmentally unfriendly. Furthermore, the addition of fillers as mentioned generally requires surface treatment, implying high processing costs.

10 Thus, there is still a need for the provision of cost-efficient and environmentally friendly composite materials.

Looking for a solution of this object, several materials were investigated, inter alia, cellulose and calcium carbonate.

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Cellulose is the structural component of the primary cell wall of green plants and is the most common organic compound on Earth. It is of high interest in many applications and industries.

20 Cellulose pulp as a raw material is processed out of wood or stems of plants such as hemp, linen and manila. Pulp fibres are built up mainly from cellulose and other organic components (hemicellulose and lignin). The cellulose macromolecules (composed of 1-4 glycosidic linked β -D-Glucose molecules) are linked together by hydrogen bonds to form a so called primary fibril (micelle) which has crystalline and
25 amorphous domains. Several primary fibrils (around 55) form a so called microfibril. Around 250 of these microfibrils form a fibril.

The fibrils are arranged in different layers (which can contain lignin and/or hemicellulose) to form a fibre. The individual fibres are bound together by lignin as
30 well.

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When fibres become refined under applied energy they become fibrillated as the cell walls are broken and torn into attached strips, i.e. into fibrils. If this breakage is continued to separate the fibrils from the body of the fibre, it releases the fibrils. The
5 breakdown of fibres into microfibrils is referred to as "microfibrillation". This process may be continued until there are no fibres left and only fibrils of nano size (thickness) remain.

If the process goes further and breaks these fibrils down into smaller and smaller
10 fibrils, they eventually become cellulose fragments or nano-fibrillar gels. Depending on how far this last step is taken some nano-fibrils may remain amongst the nano-fibrillar gel. The breakdown to primary fibrils may be referred to as "nano-fibrillation", where there may be a smooth transition between the two regimes. The primary fibrils form in an aqueous environment a gel (meta stable network of
15 primary fibrils) which may be referred to as "nano-fibrillar gel". The gel formed from the nano-fibrils can be considered to contain nanocellulose.

Nano-fibrillar gels are desirable as they usually contain very fine fibrils, considered to be constituted in part of nanocellulose, showing a stronger binding potential to
20 themselves, or to any other material present, than do fibrils which are not so fine or do not exhibit nanocellulosic structure.

From unpublished European patent application No. 09 156 703.2, nano-fibrillar cellulose gels are known. However, there is no teaching with respect to the formation
25 of composite materials.

It has now been found that such cellulose gels can be formed into composite materials, which can be produced easier/faster by the addition of fillers and/or pigments to such gels, and result in an improved runnability, and which are
30 environmentally friendlier compared with many other composite materials.

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Thus, the above problem is solved by a process for the production of composite materials comprising nano-fibrillar cellulose gels, which is characterized by the following steps:

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- a) providing cellulose fibres;
- b) providing at least one filler and/or pigment;
- c) combining the cellulose fibres of step a) and the at least one filler and/or pigment of step b);
- 10 d) fibrillating the cellulose fibres in the presence of the at least one filler and/or pigment until a gel is formed;
- e) providing at least one further filler and/or pigment;
- f) combining the gel of step d) with the at least one further filler and/or pigment of step e).

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Nano-fibrillar cellulose in the context of the present invention means fibres, which are at least partially broken down to primary fibrils. If these primary fibrils are in an aqueous environment, a gel (meta stable network of primary fibrils considered in the limit of fineness to be essentially nanocellulose) is formed, which is designated as

20 "nano-fibrillar gel", wherein there is a smooth transition between nano fibres and nano-fibrillar gel, comprising nano-fibrillar gels containing a varying extent of nano-fibrils, all of which are comprised by the term nano-fibrillar cellulose gels according to the present invention.

- 25 In this respect, fibrillating in the context of the present invention means any process which predominantly breaks down the fibres and fibrils along their long axis resulting in the decrease of the diameter of the fibres and fibrils, respectively.

According to the process of the present invention, the fibrillation of cellulose fibres

30 in the presence of at least one filler and/or pigment provides a nano-fibrillar cellulose

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gel. The fibrillation is performed until the gel is formed, wherein the formation of the gel is verified by the monitoring of the viscosity in dependence of the shearing rate. Upon step-wise increase of the shearing rate a certain curve reflecting a decrease of the viscosity is obtained. If, subsequently the shearing rate is step-wise reduced, the
5 viscosity increases again, but the corresponding values over at least part of the shear rate range as shearing approaches zero are lower than when increasing the shearing rate, graphically expressed by a hysteresis manifest when the viscosity is plotted against the shearing rate. As soon as this behaviour is observed, a nano-fibrillar cellulose gel according to the present invention is formed. Further details with
10 respect to the production of the nano-fibrillar cellulose gel can be taken from unpublished European patent application No. 09 156 703.

Cellulose fibres, which can be used in the process of the present invention may be such contained in natural, chemical, mechanical, chemimechanical,
15 thermomechanical pulps. Especially useful are pulps selected from the group comprising eucalyptus pulp, spruce pulp, pine pulp, beech pulp, hemp pulp, cotton pulp, bamboo pulp, bagasse, and mixtures thereof. In one embodiment, all or part of this cellulose fibre may be issued from a step of recycling a material comprising cellulose fibres. Thus, the pulp may also be recycled and/or deinked pulp.

20 The size of the cellulose fibres in principle is not critical. Useful in the present invention generally are any fibres commercially available and processable in the device used for their fibrillation. Depending on their origin, cellulose fibres may have a length of from 50 mm to 0.1 μm . Such fibres, as well as such having a length
25 of preferably 20 mm to 0.5 μm , more preferably from 10 mm to 1 mm, and typically from 2 to 5 mm, can be advantageously used in the present invention, wherein also longer and shorter fibres may be useful.

It is advantageous for the use in the present invention that the cellulose fibres are
30 provided in the form of a suspension, especially an aqueous suspension. Preferably,

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such suspensions have a solids content of from 0.2 to 35 wt-%, more preferably 0.25 to 10 wt-%, even more preferably 0.5 to 5 wt-%, especially 1 to 4 wt-%, most preferably 1.3 to 3 wt-%, e.g. 1.5 wt-%.

- 5 The at least one filler and/or pigment of steps b) and e) are independently selected from the group comprising precipitated calcium carbonate (PCC); natural ground calcium carbonate (GCC); surface modified calcium carbonate; dolomite; talc; bentonite; clay; magnesite; satin white; sepiolite, huntite, diatomite; silicates; and mixtures thereof.

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Precipitated calcium carbonate, which may have vateritic, calcitic or aragonitic crystal structure, and/or natural ground calcium carbonate, which may be selected from marble, limestone and/or chalk, are especially preferred.

- 15 In a special embodiment, the use of ultrafine discrete prismatic, scalenohedral or rhombohedral precipitated calcium carbonate may be advantageous.

The filler(s) and/or pigment(s) can be provided in the form of a powder, although they are preferably added in the form of a suspension, such as an aqueous

- 20 suspension. In this case, the solids content of the suspension is not critical as long as it is a pumpable liquid.

In a preferred embodiment, the filler and/or pigment particles of step b) have a median particle size of from 0.01 to 15 μm , preferably 0.1 to 10 μm , more preferably

25 0.3 to 5 μm , especially from 0.5 to 4 μm and most preferably 0.7 to 3.2 μm , e.g. 2 μm .

- For the determination of the weight median particle size d_{50} , for particles having a d_{50} greater than 0.5 μm , a Sedigraph 5100 device from the company Micromeritics, USA
- 30 was used. The measurement was performed in an aqueous solution of 0.1 wt-%

Na₄P₂O₇. The samples were dispersed using a high-speed stirrer and ultrasound. For the determination of the volume median particle size for particles having a $d_{50} \leq 500$ nm, a Malvern Zetasizer Nano ZS from the company Malvern, UK was used. The measurement was performed in an aqueous solution of 0.1 wt% Na₄P₂O₇. The
5 samples were dispersed using a high-speed stirrer and ultrasound.

It has turned out especially advantageous, if the filler(s) and/or pigment(s) added in step e) is a rather fine product in terms of the particle size, and especially preferably comprises at least a fraction of particles having a median diameter d_{50} in the
10 nanometer range, contrary to the pigment(s) and/or filler(s) used in the gel formation, which are rather coarse ones.

Thus, it is furthermore preferred that the filler and/or pigment particles of step e) have a median particle size of from 0.01 to 5 μm , preferably 0.05 to 1.5 μm , more
15 preferably 0.1 to 0.8 μm and most preferably 0.2 to 0.5 μm , e.g. 0.3 μm , wherein the particle size is determined as mentioned above.

The filler(s) and/or pigment(s) may be associated with dispersing agents such as those selected from the group comprising homopolymers or copolymers of
20 polycarboxylic acids and/or their salts or derivatives such as esters based on, e.g., acrylic acid, methacrylic acid, maleic acid, fumaric acid, itaconic acid; e.g. acryl amide or acrylic esters such as methylmethacrylate, or mixtures thereof; alkali polyphosphates, phosphonic-, citric- and tartaric acids and the salts or esters thereof; or mixtures thereof.

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The combination of fibres and at least one filler and/or pigment of steps b) and/or e) can be carried out by adding the filler and/or pigment to the fibres in one or several steps. As well, the fibres can be added to the filler and/or pigment in one or several steps. The filler and/or pigment of step b) as well as the fibres can be added entirely

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or in portions before or during the fibrillating step. However, the addition before fibrillating is preferred.

During the fibrillation process, the size of the filler(s) and/or pigment(s) as well as
5 the size of the fibres can change.

Preferably, the weight ratio of fibres to filler(s) and/or pigment(s) of step b) on a dry weight basis is from 1:33 to 10:1, more preferably 1:10 to 7:1, even more preferably 1:5 to 5:1, typically 1:3 to 3:1, especially 1:2 to 2:1 and most preferably 1:1.5 to
10 1.5:1, e.g. 1:1.

The dosage of filler and/or pigment in step b) may be critical. If there is too much of the filler and/or pigment, this may influence the formation of the gel. Thus, if no gel formation is observed in specific combination, it might be necessary to reduce the
15 amount of filler and/or pigment.

Furthermore, in one embodiment, the combination is stored for 2 to 12 hours, preferably 3 to 10 hours, more preferably 4 to 8 hours, e.g. 6 hours, prior to fibrillating it, as this ideally results in swelling of the fibres facilitating the
20 fibrillation.

Fibre swelling may be facilitated by storage at increased pH, as well as by addition of cellulose solvents like e.g. copper(II)ethylenediamine, iron-sodium-tartrate or lithium-chlorine/dimethylacetamine, or by any other method known in the art.
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Fibrillating is carried out by means of any device useful therefore. Preferably the device is a homogenizer. It may also be an ultra fine friction grinder such as a Supermasscolloider from Masuko Sangyo Co. Ltd, Japan or one as described in US 6,214,163 or US 6,183,596.

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Suitable for the use in the present invention are any commercially available homogenizers, especially high pressure homogenizers, wherein the suspensions are pressed under high pressure through a restricted opening, which may comprise a valve, and are discharged from the restricted opening at high pressure against a hard impact surface directly in front of the restricted opening. The pressure may be generated by a pump such as a piston pump, and the impact surface may comprise an impact ring extending around the annular valve opening. An example for an homogenizer which can be used in the present invention is Ariete NS2006L of GEA Niro Soavi. However, inter alia, also homogenizers such as of the APV Gaulin Series, HST HL Series or the Alfa Laval SHL Series can be used.

Furthermore, devices such as ultra-fine friction grinders, e.g. a Supermasscolloider, can be advantageously used in the present invention.

It is furthermore preferred that the weight ratio of fibres to filler and/or pigment of step e) on a dry weight basis is from 1:9 to 99:1, preferably from 1:3 to 9:1, more preferably from 1:2 to 3:1, e.g. 2:1.

Regarding the total content of filler and/or pigment it is especially preferred that the filler and/or pigment of steps b) and e) are present in an amount of from 10 wt-% to 95 wt-%, preferably from 15 wt-% to 90 wt-%, more preferably from 20 to 75 wt-%, even more preferably from 25 wt-% to 67 wt-%, especially from 33 to 50 wt.-% on a dry weight basis of the composite material.

The combination of the gel of step d) with the at least one further filler and/or pigment of step e) may be carried out just by mixing the combination, e.g. by means of a spatula. Furthermore, it may advantageous to mix the components by means of a stirrer with a mounted dissolver disc.

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Subsequently the resulting combination may be dewatered. In this respect, generally any commonly used method of dewatering known to the person skilled in the art, may be used, such as e.g. heat drying, pressure drying, vacuum drying, freeze drying, or drying under supercritical conditions. The dewatering step may be carried out in
5 well-known devices such as in a filter press, e.g. as described in the Examples. Generally, other methods that are well known in the field of moulding of aqueous systems can be applied to obtain the inventive composites.

The use of the nano-fibrillar cellulose gels as defined above for the production of a
10 compacted composite material is a further aspect of the invention, wherein the gel is combined with at least one further filler and/or pigment and the resulting combination is dewatered as described in detail above.

Another aspect of the present invention is the composite material obtained by the
15 process according to the invention, or by the use of the nano-fibrillar cellulose gels for the production of the composite material as mentioned.

The composite material can be advantageously used in applications such as in plastics, paints, rubber, concrete, ceramics, pannels, housings, foils, films, coatings,
20 extrusion profiles, adhesives, food, or in wound-healing applications, and can readily replace certain materials such as plastics used as e.g. construction material, packaging, etc.

EXAMPLES

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Material

OC-GCC: Omyacarb® 10-AV available from Omya AG; Fine calcium carbonate
powder manufactured from a high purity, white marble; the weight
30 median particle size d_{50} is 10 μm measured by Malvern Mastersizer X.

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HO-ME: Hydrocarb[®] HO - ME available from Omya AG; Selected, natural ground calcium carbonate (marble), microcrystalline, rhombohedral particle shape of high fineness in the form of a pre-dispersed slurry (solids content 62 wt-%); the weight median particle size d_{50} is 0.8 μm measured by Sedigraph 5100.

Nano-GCC: Natural ground calcium carbonate (marble from Vermont); dispersed slurry (solids content 50 wt-%); the volume median particle size is d_{50} of 246 nm measured by Malvern Zetasizer Nano ZS.

Pulp: Eucalyptus pulp with 25 °SR.

Gel Formation

120 g Eucalyptus pulp in the form of dry mats was torn into pieces and mixed with 5880 g tap water and the respective amount of OC-GCC (see Table 1) was added. The resulting mixture was stirred for at least 15 minutes using a Pendraulik (dissolver disk) at 4000 rpm. The fibrillar content of the formulations was 3 wt%.

The resulting mixtures subsequently were fibrillated in an ultra-fine friction grinder (Supermasscolloider from Masuko Sangyo Co. Ltd, Japan (Model MKCA 6-2) in single passes at a "gap" of -50 μm (dynamic 0-point) with the following setup:

5 passes at 2500 rpm,
2 passes at 2000 rpm,
2 passes at 1500 rpm,
2 passes at 1000 rpm,
2 passes at 750 rpm,
2 passes at 500 rpm.

The grinding stones were silicon carbide with a grit class of 46 (grit size 297 – 420 μm).

5 Table 1: Composition and characteristics of the gel used for compact formulations

Sample	Parts GCC on pulp fibres [dry/dry]	Energy input [MWh/dmt]	Brookfield viscosity at 2 wt-% solids content [MPa·s]
1	1	5.38	1612

Production of formulations

- 10 In order to obtain and test compacts of the nano cellulosic gels, the following formulations for the specimen production were produced according to Table 2.

Table 2: Composition of compact formulations

Sample	GCC in gel formulation [parts dry on fibres dry] (wt% on overall formulation)	Additional GCC [parts dry on fibres dry] (wt% on overall formulation)	Total GCC in formulation [parts dry on fibres dry] (wt% on overall formulation)
1	1 p (50 wt%)	0 p (0 wt%)	1 p (50 wt%)
2 (sample 1 + 2p Nano)	1 p (25 wt%)	2p nano GCC (50 wt%)	3p (75 wt%)
3 (sample 1 + 2p HO-ME (disp.))	1 p (25 wt%)	2p HO-ME (50 wt%)	3p (75 wt%)

- 15 The gel of sample 1 was mixed with the corresponding amount of additional GCC as mentioned in Table 2 and blended by hand with a spatula.

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Subsequently, the formulations were put into a small filter press (filter paper of Whatman Schleicher & Schuell, 589/2, white ribbon; filter press: fann filter press, series 3000, fann instrument company, Houston Texas, USA) in such amounts that a final thickness of the specimen of about 3 mm (calculated via densities) was achieved. A PMMA disc (thickness: 10 mm, diameter: 78 mm (fitting the inner diameter of the filter press) was placed on top of the formulation which again was covered by additional material of the same formulation (around 10-20 wt% of the amount of formulation already present).

10 The filter press then was closed and the following pressure profile was applied:

15 min at 1 bar,
120 min at 4 bar,
45 min at 6 bar.

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Subsequently, the "semi-dry" disc (solids content: about 50 wt%) was taken out of the filter press and cut into five identical rectangles (40 mm x 10 mm). These rectangles were placed between two filter papers and two aluminium plates weighted with steel balls (about 3000 g), and dried in an oven at about 80 °C over night.

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Claims

1. A process for the production of composite materials comprising nano-fibrillar cellulose gels, **characterized by** the steps of:

- 5 a) providing cellulose fibres;
b) providing at least one filler and/or pigment;
c) combining the cellulose fibres of step a) and the at least one filler and/or pigment of step b);
d) fibrillating the cellulose fibres in the presence of the at least one filler and/or
10 pigment until a gel is formed;
e) providing at least one further filler and/or pigment;
f) combining the gel of step d) with the at least one further filler and/or pigment of step e).

- 15 2. The process according to claim 1,
characterized in that the combination of step f) is dewatered in dewatering step g).

3. The process according to any one of claims 1 or 2,
characterized in that the cellulose fibres are such contained in pulps selected from
20 the group comprising eucalyptus pulp, spruce pulp, pine pulp, beech pulp, hemp pulp, cotton pulp, bamboo pulp, bagasse, as well as recycled and/or deinked pulp, and mixtures thereof.

4. The process according to any one of the preceding claims,
25 **characterized in that** the cellulose fibres are provided in the form of a suspension, preferably having a solids content of from 0.2 to 35 wt-%, more preferably 0.25 to 10 wt-%, even more preferably 0.5 to 5 wt-%, especially 1 to 4 wt-%, most preferably 1.3 to 3 wt-%, e.g. 1.5 wt-%.

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5. The process according to any one of the preceding claims,
characterized in that the filler(s) and/or pigment(s) of steps b) and e) are
independently selected from the group comprising precipitated calcium carbonate
(PCC); surface-modified calcium carbonate; natural ground calcium carbonate
5 (PCC), dolomite; talc; bentonite; clay; magnesite; satin white; sepiolite, huntite,
diatomite; silicates; and mixtures thereof; and preferably is selected from the group
of precipitated calcium carbonate having vateritic, calcitic or aragonitic crystal
structure, especially ultrafine discrete prismatic, scalenohedral or rhombohedral
precipitated calcium carbonate; natural ground calcium carbonate being selected
10 from marble, limestone and/or chalk; and mixtures thereof.

6. The process according to any one of the preceding claims,
characterized in that the filler and/or pigment particles of step b) have a median
particle size of from 0.01 to 15 μm , preferably 0.1 to 10 μm , more preferably 0.3 to 5
15 μm , especially from 0.5 to 4 μm and most preferably 0.7 to 3.2 μm , e.g. 2 μm .

7. The process according to any one of the preceding claims,
characterized in that the filler and/or pigment particles of step e) have a median
particle size of from 0.01 to 5 μm , preferably 0.05 to 1.5 μm , more preferably 0.1 to
20 0.8 μm and most preferably 0.2 to 0.5 μm , e.g. 0.3 μm .

8. The process according to any one of the preceding claims,
characterized in that the filler and/or pigment of steps b) and/or e) is associated
with dispersing agents selected from the group comprising homopolymers or
25 copolymers of polycarboxylic acids and/or their salts or derivatives such as esters
based on, e.g., acrylic acid, methacrylic acid, maleic acid, fumaric acid, itaconic acid;
e.g. acryl amide or acrylic esters such as methylmethacrylate, or mixtures thereof;
alkali polyphosphates, phosphonic-, citric- and tartaric acids and the salts or esters
thereof; or mixture thereof.

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9. The process according to any one of the preceding claims,
characterized in that the combination of fibres and of at least one filler and/or
pigment of steps b) and/or e) is carried out by adding the filler and/or pigment to the
fibres, or the fibres to the filler and/or pigment, in one or several steps.

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10. The process according to any one of the preceding claims,
characterized in that the filler and/or pigment of step b) and/or the fibres are added
entirely or in portions before or during the fibrillating step (d), preferably before the
fibrillation step (d).

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11. The process according to any one of the preceding claims,
characterized in that the weight ratio of fibres to filler and/or pigment of step b) on
a dry weight basis is from 1:33 to 10:1, more preferably 1:10 to 7:1, even more
preferably 1:5 to 5:1, typically 1:3 to 3:1, especially 1:2 to 2:1 and most preferably
1:1.5 to 1.5:1, e.g. 1:1.

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12. The process according to any one of the preceding claims,
characterized in that the fibrillating is carried out by means of a homogenizer or an
ultra fine friction grinder.

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13. The process according to any one of the preceding claims,
characterized in that the weight ratio of fibres to filler and/or pigment of step e) on
a dry weight basis is from 1:9 to 99:1, preferably from 1:3 to 9:1, more preferably
from 1:2 to 3:1, e.g. 2:1.

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14. The process according to any one of the preceding claims,
characterized in that the total content of filler and/or pigment of steps b) and e) on
a dry weight basis of the composite material is from 10 wt-% to 95 wt-%, preferably
from 15 wt-% to 90 wt-%, more preferably from 20 to 75 wt-%, even more
preferably from 25 wt-% to 67 wt-%, especially from 33 to 50 wt.-%.

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15. The use of a nano-fibrillar cellulose gel as defined in any one of claims 1 to 14 for the production of a composite material by combining the gel with at least one further filler and/or pigment and dewatering this combination.

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16. A composite material obtained by the process according to any one of claim 1 to 14 or the use according to claim 15.

10 17. The use of the composite material according to claim 16 in applications such as in plastics e.g. as construction or packaging material, paints, rubber, concrete, ceramics, pannels, housings, foils, films, coatings, extrusion profiles, adhesives, food, or in wound-healing applications.