

ZEOLITE MATERIAL BASED ON MESOPOROUS ZEOLITE

[0001] The present invention relates to zeolite materials in the form of agglomerates comprising at least one mesoporous zeolite, and also to the process for preparing the said agglomerated zeolite materials.

[0002] Mesoporous zeolites are of great utility in many industrial fields, both as catalysts and catalyst supports, but also as adsorbents, in so far as their large porosity expressed in terms of the [surface area/volume] ratio allows the molecules with which they come into contact readily to access the core of the particles and to react on a large surface area, thus enhancing the catalytic and/or adsorbent properties of these materials.

[0003] The synthesis of inorganic mesoporous solids via a surfactant structuring effect was described for the first time in patent US 3 556 725.

[0004] The Mobil company, in the 1990s, undertook extensive studies relating to mesoporous inorganic solids, especially relating to (alumino)silicic compounds, and more particularly the compound MCM 41 (for Mobil Composition Of Matter 41), for which a synthetic process is described in *Nature*, (1992), Vol. 359, pp.710-712, which were the subject of numerous subsequent scientific patents and articles.

[0005] Such mesoporous materials are now well known at the laboratory scale, both as regards their pore structure and distribution and their modes of synthesis, and as regards the possible applications thereof as catalysts and/or as adsorbents.

[0006] These mesoporous inorganic materials have the major drawback of being thermally unstable in the presence of water, which greatly limits the industrial applications.

[0007] The search for mesoporous inorganic solids led to the development of mesoporous zeolites obtained by various processes, as described, for example, in the article by Feng-Shou Xiao *et al.* (*Hierarchically Structured Porous Materials*, (2012), 435-455, Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany 978-3-527-32788-1).

[0008] One of the routes envisaged is that of post-treatments using initially synthesized zeolite crystals, in powder form. These post-treatments are, for example, treatments with water vapour, followed by acidic and/or basic treatments which lead to dealumination, followed by additional treatments to remove extra-network species.

[0009] Patent US 8 486 369 and patent applications US 2013/0 183 229, US 2013/0 183 231 and patent application WO 2013/106 816 are examples which

illustrate such processes for preparing zeolite of mesoporous structure by various treatments successive to vapour, and then with acids and in the presence of surfactant.

[0010] Such processes have a tendency to create large pore volumes, but, in counterpart, greatly degrade the crystallinity of the initial zeolite powder, which is almost halved. It is moreover necessary to resort to additional cauterization treatments to stabilize the zeolite framework, to remove the extra-network aluminium atoms and thus to be able to perform subsequent heat treatments.

[0011] Such processes are therefore very cumbersome to implement due to the succession of numerous steps, which are sparingly economic and thus difficult to industrialize. In addition, the multitude of steps has a tendency to embrittle the zeolite structure and consequently reduce the intrinsic properties of these zeolites.

[0012] This is why syntheses of mesoporous zeolites directly and without post-treatment known in the prior art are nowadays preferred. Various publications show the feasibility of the laboratory synthesis of mesoporous zeolites, and, by way of example, patent applications WO 2007/043 731 and EP 2 592 049 are noted in particular, in which the synthesis of mesoporous zeolites is performed based on surfactant, and especially that of TPOAC type ([3-(trimethoxysilyl)propyl]octadecyldimethylammonium chloride).

[0013] Yet other publications illustrate such studies, for instance those of R. Ryoo (*Nature Materials*, (2006), Vol. 5, p. 718) which describe a synthesis of LTA with mesopores, or those of W. Schwieger (*Angew. Chem. Int. Ed.*, (2012), **51**, 1962-1965) which describe the synthesis of mesoporous FAU (X) using TPHAC ([3-(trimethoxysilyl)propyl]hexadecyldimethylammonium chloride) as structuring agent.

[0014] However, there is not at the present time any description concerning the preparation of agglomerates based on mesoporous zeolites, in which agglomerates the specific properties of these mesoporous zeolites, in particular their microporosity, are conserved. As a result, there remains at the present time no industrial application, especially in the field of separation of liquids and/or gases, of ion exchange or in the field of catalysis, using such zeolite agglomerates with high microporosity comprising at least one mesoporous zeolite.

[0015] It should be recalled that the industry, and especially the fields of application mentioned above, uses in the majority of cases zeolite agglomerates. In point of fact, synthetic zeolites are usually obtained after a process of nucleation and crystallization of silicoaluminate gels in which the size of the crystallites produced is from about a micrometre to several micrometres: they are then referred to as zeolite crystals in powder form.

[0016] These powders are not easy to use industrially since they are difficult to manipulate on account of their poor flowability, they generate substantial losses of pressure and poor distribution of the streams in the beds, especially in dynamic processes involving fluids in flow.

5 **[0017]** Thus, the agglomerated forms of these powders are preferred, which are more commonly referred to as zeolite agglomerates and which may be in the form of grains, strands, extrudates or other agglomerates, these said forms possibly being obtained by extrusion, pelletizing, atomization or other agglomeration techniques that are well known to those skilled in the art. These agglomerates do not have the drawbacks inherent in
10 pulverulant materials.

[0018] These agglomerates generally consist of zeolite crystals and of a binder, which is usually inert with respect to the application for which the zeolite is intended, the said binder being intended to ensure the cohesion of the zeolite crystals and to give them the sufficient and necessary mechanical strength for the intended industrial application.

15 **[0019]** One object of the embodiments disclosed herein is thus to propose a zeolite material in agglomerated form comprising at least one mesoporous zeolite. As another object, the present disclosure proposes a zeolite material in agglomerated form comprising at least one mesoporous zeolite, and which has improved crystallinity properties when compared with the materials of the prior art.

20 **[0019a]** In an aspect, there is provided an agglomerated zeolite material comprising at least one mesoporous zeolite with a number-average diameter of between 0.1 μm and 20 μm with an Si/Al atomic ratio of between 1 and 1.4, limits inclusive, and with a mesopore outer surface area, defined by the t-plot method, of between 40 $\text{m}^2.\text{g}^{-1}$ and 400 $\text{m}^2.\text{g}^{-1}$, limits inclusive, the said material having at least the following characteristics:

- 25
- a total zeolite content of at least 70% by weight relative to the total weight of the agglomerate,
 - a content of mesoporous zeolite(s) of greater than or equal to 30%,
 - a binder content, after calcinations performed at 950°C for 1 hour, of less than or equal to 30%,

- a mean volume diameter (D50), or a length (largest dimension when the material is not spherical) of less than or equal to 7 mm, and
- either a bulk crushing strength (BCS) measured according to standard ASTM 7084-04 of between 0.5 MPa and 3 MPa, for a material with a mean volume diameter (D50), or
5 a length (largest dimension when the material is not spherical), of less than 1 mm, limits inclusive,
- or a grain crushing strength, measured according to standards ASTM D 4179 (2011) and ASTM D 6175 (2013), of between 0.5 daN and 30 daN, for a material with a mean
10 volume diameter (D50), or a length (largest dimension when the material is not spherical), of greater than or equal to 1 mm, limits inclusive.

[0020] Yet another object consists in providing a process for preparing a zeolite material in agglomerated form comprising at least one mesoporous zeolite, the said process being readily industrializable, and improved in terms of cost and duration, when compared with the processes for manufacturing agglomerates known in the prior art, while at the same
15 time avoiding degradation of the properties of the mesoporous zeolite(s) present in the said material.

[0020a] In another aspect, there is provided a process for preparing a material as defined above, comprising at least the steps of:

- a) agglomeration of crystals of at least one mesoporous zeolite with a number-average
20 diameter of between 0.1 μm and 20 μm , preferably between 0.1 μm and 10 μm , more preferably between 0.5 μm and 10 μm and even more preferentially between 0.5 μm and 5 μm , with an Si/Al atomic ratio of between 1 and 1.4, limits inclusive, and with a mesopore outer surface area, defined by the t-plot method, of between 40 $\text{m}^2.\text{g}^{-1}$ and 400 $\text{m}^2.\text{g}^{-1}$ and preferably between 60 $\text{m}^2.\text{g}^{-1}$ and 200 $\text{m}^2.\text{g}^{-1}$, limits inclusive, with a
25 binder comprising at least 80% clay or a mixture of clays, which are optionally zeolitizable, and with up to 5% of additives, and also with the amount of water that allows the shaping of the agglomerated material;
- b) drying of the agglomerates at a temperature of between 50°C and 150°C;
- c) calcination of the agglomerates of step b) with flushing with an oxidizing and/or inert
30 gas, especially with gases such as oxygen, nitrogen, air, a dry and/or decarbonated air, an oxygen-depleted air, which is optionally dried and/or decarbonated, at a

temperature above 150°C, typically between 180°C and 800°C and preferentially between 200°C and 650°C, for a few hours, for example from 2 to 6 hours;

d) optionally zeolitization of the binder by placing the agglomerates obtained in step c) in contact with an alkaline basic solution;

5 e) optionally cation exchange(s) of the agglomerates of step c) or of step d) by placing in contact with a solution of at least one alkali metal or alkaline-earth metal salt;

f) and then washing and drying of the agglomerates obtained in steps d) or e) under the conditions described in step b), and

10 g) production of the agglomerated zeolite material by activation of the agglomerates obtained in step f) under the conditions described in step c).

[0021] More particularly, one of the objects of the embodiments disclosed herein consists in proposing an agglomerated zeolite material having the purity, crystallinity and pore distribution properties of the starting mesoporous zeolite(s) and moreover having good mechanical strength and optimized crystallinity, and thus enabling easy and efficient
15 industrial use, for example in the fields of catalysis (catalysts or catalyst supports), or in dynamic or static separation, adsorption or ion exchange processes.

[0022] Yet other objects will emerge in the light of the description of the present disclosure that follows.

[0023] The Applicant has discovered that it is possible to totally or at least partially
20 overcome the drawbacks mentioned in the prior art and to manufacture in an economical

and optimized manner an agglomerated zeolite material which comprises at least one mesoporous zeolite, the initial microporosity properties of which are maintained, i.e. the mesoporous zeolite used to prepare the said agglomerated material conserves all of its microporosity in the said material.

[0024] The agglomerated material has a high level of crystallinity and is endowed with a density and mechanical properties that are sufficient for use in dynamic or static adsorption or ion exchange processes.

[0025] Unless otherwise indicated in the present description, the proportions indicated are weight proportions, counted for the solid constituents as calcined equivalents, on the basis of calcinations performed at 950°C for 1 hour.

[0026] The present invention relates to an agglomerated zeolite material comprising at least one mesoporous zeolite and optionally one or more non-mesoporous zeolites, the said material having at least the following characteristics:

- a total zeolite content of at least 70%, preferably of at least 80%, more preferably of at least 90% by weight relative to the total weight of the agglomerate,
- a content of mesoporous zeolite(s) of greater than or equal to 30%, preferably greater than or equal to 50%, more preferably greater than or equal to 70%, even more preferentially greater than or equal to 80% and advantageously greater than or equal to 90%,
- a binder content expressed as anhydrous percentages, after calcinations performed at 950°C for 1 hour, of less than or equal to 30%, preferably less than or equal to 20% and advantageously less than or equal to 10%,
- a mean volume diameter (D50), or a length (largest dimension when the material is not spherical) of less than or equal to 7 mm, preferably between 0.05 mm and 7 mm, more preferably between 0.2 mm and 5 mm and more preferentially between 0.2 mm and 2.5 mm, limits inclusive, and
- either a bulk crushing strength (BCS) measured according to standard ASTM 7084-04 of between 0.5 MPa and 3 MPa, preferably between 0.75 MPa and 2.5 MPa, for a material with a mean volume diameter (D50), or a length (largest dimension when the material is not spherical), of less than 1 mm, limits inclusive,
- or a grain crushing strength, measured according to standards ASTM D 4179 (2011) and ASTM D 6175 (2013), of between 0.5 daN and 30 daN, preferably between 1 daN and 20 daN, for a material with a mean volume diameter (D50), or a length (largest dimension when the material is not spherical), of greater than or equal to 1 mm, limits inclusive.

[0027] According to a preferred embodiment, the material of the present invention also has an apparent mass per unit volume of between 0.4 g.cm^{-3} and 1 g.cm^{-3} , limits inclusive.

[0028] In the present invention, the agglomerates comprise at least one mesoporous zeolite, the said mesoporous zeolite advantageously being chosen from mesoporous zeolites of LTA, EMT and FAU structure with an Si/Al atomic ratio of between 1 and 1.4, limits inclusive, and preferably from mesoporous zeolites of FAU structure of X, MSX and LSX type. The term “zeolite MSX” (Medium Silica X) means a zeolite of FAU type with an Si/Al atomic ratio of between about 1.05 and about 1.15, limits inclusive. The term “zeolite LSX” (Low Silica X) means a zeolite of FAU type with an Si/Al atomic ratio equal to about 1.

[0029] The said mesoporous zeolite is in the form of crystals with a mean numerical diameter, measured with a scanning electron microscope (SEM), of less than $20 \mu\text{m}$, preferably between $0.1 \mu\text{m}$ and $20 \mu\text{m}$, preferably between 0.1 and $10 \mu\text{m}$, preferably between $0.5 \mu\text{m}$ and $10 \mu\text{m}$ and more preferably between $0.5 \mu\text{m}$ and $5 \mu\text{m}$, limits inclusive.

[0030] In the present invention the term “mesoporous zeolite” means a zeolite with a mesoporous outer surface area, defined by the t-plot method described later, of between $40 \text{ m}^2.\text{g}^{-1}$ and $400 \text{ m}^2.\text{g}^{-1}$ and preferably between $60 \text{ m}^2.\text{g}^{-1}$ and $200 \text{ m}^2.\text{g}^{-1}$, limits inclusive. By extension, for the purposes of the present invention, a “non-mesoporous zeolite” is a zeolite optionally having a mesoporous outer surface area, defined by the t-plot method described later, strictly less than $40 \text{ m}^2.\text{g}^{-1}$.

[0031] The mesopores of the zeolite adsorbent according to the invention are easily identifiable by observation using a transmission electron microscope (TEM), as described, for example, in US 7 785 563.

[0032] According to a preferred embodiment, the process according to the invention uses a zeolite adsorbent comprising mesoporous crystals of zeolite LTA, EMT and FAU, and preferably FAU. The term “mesoporous” means zeolite crystals (microporous) which have, in combination with the microporosity, internal cavities of nanometric size (mesoporosity), which are readily identifiable by observation using a transmission electron microscope (TEM), as described, for example, in US 7 785 563.

[0033] As indicated in US 7 785 563, observation by transmission electron microscopy (TEM) makes it possible to check whether the zeolite particles are solid zeolite crystals (i.e. non-mesoporous) or solid zeolite crystal aggregates or mesoporous crystals. Preferably, the adsorbents of the process according to the invention contain an amount of greater than equal to 30%, preferably greater than or equal to 50%, more preferably

greater than or equal to 70%, more preferentially even more preferentially greater than or equal to 80% and advantageously greater than or equal to 90%, by number of mesoporous zeolite crystals and not solid crystals, relative to all of the crystals. This statistical analysis is advantageously performed by analysis of at least 50 TEM images.

5 **[0034]** The crystals of the mesoporous zeolite(s) included in the zeolite material of the invention, alone or as a mixture with other non-mesoporous zeolite crystals, are agglomerated with a binder. According to a preferred aspect of the invention, the binder content is as low as possible, so as to optimize the zeolite content of the zeolite material.

10 **[0035]** The binder included in the zeolite agglomerated material of the present invention comprises, and preferably consists of, a clay or a mixture of clays. These clays are preferably chosen from kaolins, kaolinites, nacrites, dickites, halloysites, attapulgites, sepiolites, montmorillonites, bentonites, illites and metakaolins, and also mixtures of two or more thereof in all proportions.

15 **[0036]** In the present invention, the term “binder” means an agglomeration binder which ensures the cohesion of the zeolite crystals in the agglomerated zeolite material of the invention. This binder is also distinguished from the zeolite crystals in that they do not have any zeolite crystalline structure after calcination, for which reason the binder is often referred to as being inert, and more precisely inert with respect to adsorption and/or ion exchange.

20 **[0037]** According to a particularly preferred aspect, the binder present in the agglomerated zeolite material of the invention consists solely of one or more clays, and preferably of only one clay.

25 **[0038]** The agglomerated zeolite material according to the present invention may also comprise one or more other components, in an amount of between 0 and 5%, preferably between 0 and 1% and more preferably between 0 and 0.5%, limits inclusive, the percentages being expressed on a weight basis relative to the total weight of the agglomerated zeolite material. This or these other component(s) are generally the residues of the additives, and other auxiliary agents for the synthesis of the said agglomerated zeolite material, and in particular those that will be described later in the
30 present description.

35 **[0039]** Examples of such other components especially include ash of the additives after calcination, silica, and the like. It should be understood that these other components are generally present in the form of residues or traces and are not used to provide any binding or cohesive nature to the agglomerated zeolite materials comprising at least one mesoporous zeolite of the invention.

[0040] The agglomerated zeolite material of the present invention may be in various forms such as those that are well known to a person skilled in the art, who is a specialist in the agglomeration of powders or crystals, especially zeolite crystals, and, for example, and in a non-limiting manner, the agglomerated zeolite material of the invention may be in the form of beads, strands, extrudates or the like.

[0041] Moreover, it is observed that, in the case of zeolites in which the mesoporosity is obtained by post-treatment (for instance in WO 2013/106 816), the micropore volume decreases greatly when the mesoporous outer surface area increases. On the other hand, in the case of the zeolites of the present invention, the mesoporosity is created during the synthesis of the crystals (direct synthesis) and it is observed that the micropore volume of the adsorbents remains substantially constant, even when the mesoporous outer surface area increases. This shows that the zeolite adsorbents according to the invention have, unlike the mesoporous zeolite adsorbents of the prior art, both a high mesoporous outer surface area and a high micropore volume.

[0042] According to another aspect, a subject of the present invention is also a process for preparing the agglomerated zeolite material described previously, comprising at least the steps of mixing at least one mesoporous zeolite, optionally with one or more additives, with at least one binder, in the proportions indicated previously, and shaping the agglomerated material, according to any method known to those skilled in the art, for example by extrusion, pelletizing, atomization or other agglomeration techniques that are well known to those skilled in the art.

[0043] According to a preferred embodiment, the process of the invention comprises at least the steps of:

- a) agglomeration of crystals of at least one mesoporous zeolite with a number-average diameter of between 0.1 μm and 20 μm , preferably between 0.1 μm and 20 μm , preferably between 0.1 μm and 10 μm , more preferably between 0.5 μm and 10 μm and even more preferentially between 0.5 μm and 5 μm , with an Si/Al atomic ratio of between 1 and 1.4, limits inclusive, and with a mesopore outer surface area, defined by the t-plot method described later, of between 40 $\text{m}^2.\text{g}^{-1}$ and 400 $\text{m}^2.\text{g}^{-1}$ and preferably between 60 $\text{m}^2.\text{g}^{-1}$ and 200 $\text{m}^2.\text{g}^{-1}$, limits inclusive, with a binder comprising at least 80% clay or a mixture of clays, which are optionally zeolitizable, and with up to 5% of additives, and also with the amount of water that allows the shaping of the agglomerated material;
- b) drying of the agglomerates at a temperature of between 50°C and 150°C;

- c) calcination of the agglomerates of step b) with flushing with an oxidizing and/or inert gas, especially with gases such as oxygen, nitrogen, air, a dry and/or decarbonated air, an oxygen-depleted air, which is optionally dry and/or decarbonated, at a temperature above 150°C, typically between 180°C and 800°C and preferentially between 200°C and 650°C, for a few hours, for example from 2 to 6 hours;
- d) optionally zeolitization of the binder by placing the agglomerates obtained in step c) in contact with an alkaline basic solution;
- e) optionally cation exchange(s) of the agglomerates of step c) or of step d) by placing in contact with a solution of at least one alkali metal or alkaline-earth metal salt;
- f) and then washing and drying of the agglomerates obtained in steps d) or e) under the conditions described in step b), and
- g) production of the agglomerated zeolite material by activation of the agglomerates obtained in step f) under the conditions described in step c).

[0044] It would not constitute a departure from the context of the invention if the at least one mesoporous zeolite used in the agglomeration step a) were to undergo beforehand one or more cation exchanges. In this case, step e) consequently becomes unnecessary.

[0045] According to a preferred mode of the invention, the powder (zeolite crystals) thus obtained is agglomerated in its existing form, after drying and/or after calcination and/or after ion exchange, by means of an inert binder for the purposes of the adsorption.

[0046] According to an entirely preferred embodiment of the process of the present invention, in step a) agglomeration of the zeolite crystals prepared is performed in the presence of a sacrificial template which is intended to be removed according to the methods known to those skilled in the art, for example by calcination, for the purpose of creating mesoporosity in the zeolite and thus obtaining a mesoporous zeolite.

[0047] The sacrificial template used may be of any type known to those skilled in the art and especially those described in patent application WO 2007/043 731. According to a preferred embodiment, the sacrificial template is advantageously chosen from organosilanes and more preferentially from [3-(trimethoxysilyl)propyl]-octadecyldimethylammonium chloride, [3-(trimethoxysilyl)propyl]hexadecyldimethylammonium chloride, [3-(trimethoxysilyl)propyl]dodecyldimethylammonium chloride, [3-(trimethoxysilyl)propyl]octylammonium chloride, N-[3-(trimethoxysilyl)propyl]aniline, 3-[2-(2-aminoethylamino)ethylamino]propyltrimethoxysilane, N-[3-(trimethoxysilyl)propyl]-N'-(4-vinylbenzyl)ethylenediamine, triethoxy-3-(2-imidazolin-1-yl)propylsilane, 1-[3-(trimethoxysilyl)propyl]urea, N-[3-(trimethoxysilyl)propyl]ethylenediamine, [3-(diethylamino)propyl]trimethoxysilane, (3-glycidyloxypropyl)trimethoxysilane, 3-(trimethoxysilyl)propyl

methacrylate, [2-(cyclohexenyl)ethyl]triethoxysilane, dodecyltriethoxysilane, hexadecyltriméthoxysilane, (3-aminopropyl)trimethoxysilane, (3-mercaptopropyl)trimethoxysilane, (3-chloropropyl)trimethoxysilane, and mixtures of two or more thereof in all proportions.

5 **[0048]** Among the sacrificial templates listed above, [3-(trimethoxysilyl)propyl]octadecyldimethylammonium chloride, or TPOAC, is most particularly preferred.

[0049] Use may also be made of sacrificial templates of higher molar mass, for example PPDAs (Polymer PolyDiallyldimethylAmmonium), PVB (polyvinyl butyral) and other
10 oligomeric compounds known in the field for increasing the diameter of mesopores.

[0050] The additional step of removing the sacrificial template may be performed at any moment during the process for preparing the agglomerated zeolite material of the invention. The removal of the said sacrificial template may thus be advantageously performed by calcination of the zeolite crystals before the agglomeration step a), or
15 alternatively concomitantly with step c).

[0051] It would not constitute a departure from the context of the invention if the zeolite(s) before agglomeration were to undergo one or more successive exchanges with alkaline metal or alkaline-earth metal salts.

[0052] The dried crystals are then subjected to calcination, this step being necessary to
20 release both the microporosity (removal of water) and the mesoporosity (removal of the structuring agent). In addition, calcination makes it possible to remove the sacrificial template. This calcination step may be performed according to any calcination method known to those skilled in the art, for example, in a non-limiting manner, the calcination of zeolite crystals comprising the sacrificial template may be performed under a flush of
25 oxidizing and/or inert gas, especially with gases such as oxygen, nitrogen, air, a dry and/or decarbonated air, an oxygen-depleted air, which is optionally dry and/or decarbonated, at one or more temperatures above 150°C, typically between 180°C and 800°C and preferentially between 200°C and 650°C, for a few hours, for example between 2 and 6 hours. The nature of the gases, the temperature increase ramps and the
30 successive temperature steady stages and the durations thereof will be adapted as a function of the nature of the sacrificial template.

[0053] The size of the mesoporous zeolite crystals used in step a) and of the mesoporous zeolite crystals in the agglomerates is measured by observation with a scanning electron microscope (SEM). This SEM observation also makes it possible to
35 confirm the presence of a non-zeolite phase comprising, for example, residual binder (not

converted during the zeolitization step) or any other amorphous phase in the agglomerates. In the description of the present invention, the term “numerical mean diameter” or “size” is used for the zeolite crystals. The method for measuring these magnitudes is explained later in the description.

5 **[0054]** The agglomeration and shaping (step a) may be performed according to any technique known to those skilled in the art, such as extrusion, compacting, agglomeration on a granulating plate, a granulating drum, atomization and the like. The proportions of agglomeration binder and of zeolites used are typically those of the prior art, i.e. between 5 parts and 30 parts by weight of binder per 95 parts to 70 parts by weight of zeolite. The
10 agglomerates used in step a), whether they are in the form of beads, extrudates or the like, generally have a number-average volume diameter, or a length (largest dimension when they are not spherical), of less than or equal to 7 mm, preferably between 0.05 mm and 7 mm, more preferably between 0.2 mm and 5 mm and more preferentially between 0.2 mm and 2.5 mm.

15 **[0055]** During step a), besides the zeolite crystal(s) and the binder, one or more additives may also be added. The additives are preferentially organic, for example lignin, starch, carboxymethylcellulose, surfactant (cationic, anionic, non-ionic or amphoteric) molecules, intended to facilitate the handling of the zeolite/clay pulp by modification of the rheology and/or the bonding power or to give the final agglomerates satisfactory
20 properties, especially in terms of macroporosity. Mention may preferentially be made, but not exhaustively, of methylcelluloses and derivatives thereof, lignosulfonates, polycarboxylic acids and carboxylic acid copolymers, amino derivatives thereof and salts thereof, especially alkali metal salts and ammonium salts. The additives are introduced in a proportion of from 0 to 5% and preferably from 0.1% to 2%.

25 **[0056]** The additives may also be a source of liquid and/or solid silica, preferably representing from 1% to 5% of the total mass of the said solids. The optional source of silica may be of any type known to a person skilled in the art, who is a specialist in the synthesis of zeolites, for example colloidal silica, diatomaceous earths, perlite, flyash, sand or any other form of solid silica.

30 **[0057]** During the calcination step c), the nature of the gases, the temperature increase ramps and the successive temperature steady stages, and also the respective durations thereof, will be adapted as a function of the nature of the sacrificial template to be removed and as a function of the nature of the binder used in the agglomeration step a).

[0058] During the optional step d), the zeolitization of the agglomeration binder is
35 performed according to any method that is now well known to those skilled in the art and

may be performed, for example, by immersing the product of step c) in an alkaline basic solution, which is generally aqueous, for example an aqueous sodium hydroxide and/or potassium hydroxide solution.

[0059] The agglomerated zeolite materials according to the present invention have both the characteristics of mesoporous zeolites, but also especially the mechanical properties of the conventional agglomerated zeolites known from the prior art, i.e. in which the zeolite is non-mesoporous.

[0060] More particularly, the agglomerated zeolite materials of the invention show that it is possible to maintain the crystallinity and the mesoporosity of zeolite within an agglomerated zeolite material, and to obtain an undegraded and mechanically strong agglomerated zeolite material. In addition, the process for preparing the agglomerated zeolite materials with mesoporous zeolite(s) according to the invention is a process that is easy, rapid and economical to implement and thus readily industrializable with a minimum of steps.

[0061] The examples that follow illustrate the subject of the invention, and are given purely as a guide, without, however, being intended to limit the various embodiments of the present invention in any way.

[0062] In the examples that follow, the physical properties of the agglomerates are evaluated by the methods known to those skilled in the art, the main ones of which are recalled hereinbelow.

Loss on ignition of zeolite adsorbents:

[0063] The loss on ignition is determined in an oxidizing atmosphere, by calcination of the sample in air at a temperature of $950^{\circ}\text{C} \pm 25^{\circ}\text{C}$, as described in standard NF EN 196-2 (April 2006). The measurement standard deviation is less than 0.1%.

Measurement of the purity:

[0064] The purity of the zeolite phases in the agglomerates is evaluated by X-ray scattering analysis, which is known to those skilled in the art by the abbreviation XRD. This identification is performed on an XRD machine of Brüker.

[0065] This analysis makes it possible to identify the crystalline phases present in the analysed solid since each of the zeolite structures has a unique diffraction spectrum (or diffractogram) defined by the position of the diffraction peaks and by their relative intensities.

[0066] The agglomerated zeolite materials are ground and then spread out and smoothed on a sample holder by simple mechanical compression.

[0067] The conditions for the acquisition of the diffraction spectrum (or diffractogram) performed on the Br ker D5000 machine are as follows:

- Cu tube used at 40 kV – 30 mA;
- Slit size (divergent, diffusion and analysis) = 0.6 mm;
- 5 • filter: Ni;
- rotating sample device: 15 rpm;
- measuring range: $3^\circ < 2\theta < 50^\circ$;
- increment: 0.02° ;
- counting time per increment: 2 seconds.

10 **[0068]** Interpretation of the diffraction spectrum (or diffractogram) obtained is performed under EVA with identification of the phases using the base ICDD PDF-2 release 2011.

[0069] The amount of the zeolite X fractions is measured by XRD analysis. This analysis is performed on a Br ker brand machine, and the amount of zeolite X fractions is then evaluated using the TOPAS software from the company Br ker.

15 **Qualitative and quantitative analysis by X-ray diffraction**

[0070] This analysis makes it possible to identify the crystalline phases present in the analysed solid since each of the zeolite structures has a unique diffractogram (or diffraction spectrum) defined by the position of the diffraction peaks and by their relative intensities.

20 **[0071]** The agglomerated zeolite materials are ground and then spread out and smoothed on a sample holder by simple mechanical compression. The acquisition conditions for the diffractogram performed on the D5000 Br ker machine are as follows:

- Cu tube used at 40 kV – 30 mA;
- slit size (divergent, scattering and analysis) = 0.6 mm;
- 25 • filter: Ni;
- rotating sample device: 15 rpm;
- measurement range: $3^\circ < 2\theta < 50^\circ$;
- increment: 0.02° ;
- counting time per increment: 2 seconds.

30 **[0072]** The interpretation of the diffraction spectrum (or diffractogram) obtained is performed with the EVA software with identification of the phases using the base ICDD PDF-2, release 2011, which makes it possible to demonstrate a perfectly crystalline phase.

[0073] The quantity of the zeolite X fractions by weight is measured by XRD analysis:
35 this method is also used for measuring the amount of zeolite LTA, EMT and other FAU

fractions. This analysis is performed on a Brüker machine, and the weight amount of zeolite X, or LTA, EMT and other FAU, fractions is then evaluated by means of the TOPAS software from the company Brüker.

Measurement of the micropore volume:

5 **[0074]** The measurement of the micropore volume is estimated via standard methods such as measurement of the Dubinin-Raduskevitch volumes (adsorption of liquid nitrogen at 77 K or of liquid argon at 87 K).

[0075] The Dubinin-Raduskevitch volume is determined from the measurement of the isotherm of adsorption of a gas, such as nitrogen or argon, at its liquefaction temperature,
10 as a function of the pore aperture of the zeolite structure: argon will be chosen for LTA and nitrogen will be chosen for FAU. Prior to the adsorption, the zeolite adsorbent is degassed at between 300°C and 450°C for a time of between 9 hours and 16 hours, under vacuum ($P < 6.7 \times 10^{-4}$ Pa). The measurement of the adsorption isotherms is then performed on a machine of ASAP 2020 type from Micromeritics, taking at least 35
15 measurement points at P/P_0 relative ratio pressures of between 0.002 and 1. The micropore volume is determined according to Dubinin and Raduskevitch from the isotherm obtained, by applying standard ISO 15901-3 (2007). The micropore volume evaluated according to the Dubinin-Raduskevitch equation is expressed in cm^3 of liquid adsorbate per gram of adsorbent. The measurement uncertainty is $\pm 0.003 \text{ cm}^3 \cdot \text{g}^{-1}$.

20 Measurement of the mesopore outer surface area (m^2/g) via the t-plot method:

[0076] The t-plot calculation method exploits the data of the adsorption isotherm $Q_{\text{ads}} = f(P/P_0)$ and makes it possible to calculate the micropore surface area. The outer surface area may be deduced therefrom by determining the difference with the BET surface area which calculates the total pore surface area in m^2/g ($\text{BET } S = \text{micropore surface area} +$
25 $\text{mesopore outer surface area}$).

[0077] To calculate the micropore surface area via the t-plot method, the curve Q_{ads} ($\text{cm}^3 \cdot \text{g}^{-1}$) is plotted as a function of t = thickness of the layer dependent on the partial pressure P/P_0 which would be formed on a reference non-porous solid (t function of $\log(P/P_0)$): Harkins-Jura equation applied: $[13.99/(0.034 - \log(P/P_0))^{0.5}]$. In the interval t
30 between 0.35 nm and 0.5 nm, a straight line may be plotted which defines a y-axis at the origin Q_{adsorbed} which makes it possible to calculate the micropore surface area. If the solid is not microporous, the straight line passes through 0.

Observation of the mesopore structure by transmission electron microscopy

[0078] After grinding the adsorbents with a mortar, the powder obtained is dispersed in ethanol for 1 minute with ultrasonication. One drop of the solution is placed on a microscope grate. The sample is left to dry under the ambient conditions.

[0079] The observation is performed with a transmission electron microscope (CM 200 from FEI) at a voltage of 120 kV. Figures 1a and 1b show TEM images obtained at a magnification of $\times 220\,000$ of a reference adsorbent (Figure 1a) and of the adsorbent according to the invention (Figure 1b). The image of Figure 1b makes it possible to visualize the presence of the mesopores and to estimate their diameters.

Particle size of the crystals:

[0080] The estimation of the number-average diameter of the mesoporous zeolite crystals used in step a) and of the zeolite crystals contained in the agglomerates is performed as indicated previously by observation with a scanning electron microscope (SEM).

[0081] In order to estimate the size of the zeolite crystals on the samples, a set of images is taken at a magnification of at least 5000. The diameter of at least 200 crystals is then measured using dedicated software, for example the Smile View software from the editor LoGraMi. The accuracy is about 3%.

Bulk crushing strength:

[0082] The crushing strength of a bed of zeolite adsorbents as described in the present invention is characterized according to the Shell method series SMS1471-74 (Shell Method Series SMS1471-74 "Determination of Bulk Crushing Strength of Catalysts. Compression-Sieve Method"), combined with the "BCS Tester" machine sold by the company Vinci Technologies. This method, originally intended for characterizing catalysts between 3 mm and 6 mm in size, is based on the use of a 425 μm screen which makes it possible especially to separate the fines created during the crushing. The use of a 425 μm screen remains suitable for particles with a diameter of greater than 1.6 mm, but must be adapted according to the particle size of the agglomerates that it is desired to characterize.

Grain crushing strength:

[0083] The mechanical grain crushing strengths are determined using a Grain Crushing Strength machine sold by Vinci Technologies, according to standards ASTM D 4179 and D 6175.

Measurement of the Si/Al ratio:

[0084] The agglomerated zeolite material of the invention was evaluated as regards the Si/Al ratio by elemental chemical analysis of the said agglomerated zeolite material, and

more precisely by X-ray fluorescence chemical analysis as described in standard NF EN ISO 12677 (2011) on a wavelength dispersive spectrometer (WDXRF), for example the Tiger S8 machine from the company Brüker. The X-ray fluorescence spectrum has the advantage of being very little dependent on the chemical combination of the element, which offers precise determination, both quantitatively and qualitatively.

[0085] A measurement uncertainty of less than 0.4% by weight is conventionally obtained after calibration for each oxide, inter alia for SiO_2 and Al_2O_3 . The measurement uncertainty of the Si/Al atomic ratio is $\pm 5\%$.

Example 1: Synthesis of mesoporous zeolite of type X with addition of nucleation gel and of growth gel with a TPOAC/ Al_2O_3 ratio = 0.04

a) Preparation of the growth gel in a stirred reactor with an Archimedean screw at 300 rpm.

[0086] A growth gel is prepared in a stainless-steel reactor equipped with a heating jacket, a temperature probe and a stirrer, by mixing an aluminate solution containing 119 g of sodium hydroxide (NaOH), 128 g of alumina trihydrate ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$, containing 65.2% by weight of Al_2O_3) and 195.5 g of water at 25°C for 25 minutes with a stirring speed of 300 rpm in a silicate solution containing 565.3 g of sodium silicate, 55.3 g of NaOH and 1997.5 g of water at 25°C.

[0087] The stoichiometry of the growth gel is as follows: 3.48 $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3/3.07 \text{SiO}_2/180 \text{H}_2\text{O}$. Homogenization of the growth gel is performed with stirring at 300 rpm for 25 minutes at 25°C.

b) Addition of the nucleation gel

[0088] 61.2 g of nucleation gel (i.e. 2% by weight) of composition 12 $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3/10 \text{SiO}_2/180 \text{H}_2\text{O}$ prepared in the same manner as for the growth gel, and matured for 1 hour at 40°C, are added to the growth gel at 25°C with stirring at 300 rpm. After homogenization for 5 minutes at 300 rpm, the stirring speed is reduced to 100 rpm and stirring is continued for 30 minutes.

c) Introduction of the structuring agent into the reaction medium

[0089] 27.3 g of a 60% solution of TPOAC in methanol (MeOH) are introduced into the reaction medium with a stirring speed of 300 rpm (TPOAC/ Al_2O_3 mole ratio = 0.04). A maturation step is performed at 25°C for 1 hour at 300 rpm before starting the crystallization.

d) Crystallization

[0090] The stirring speed is lowered to 50 rpm and the nominal temperature of the reactor jacket is set at 80°C so that the temperature of the reaction medium rises to 75°C over 80 minutes. After a steady stage at 75°C for 22 hours, the reaction medium is cooled by circulating cold water through the jacket to stop the crystallization.

e) Filtration/washing

[0091] The solids are recovered on a sinter and then washed with deionized water to neutral pH.

f) Drying/calcination

[0092] In order to characterize the product, drying is performed in an oven at 90°C for 8 hours, and the loss on ignition of the dried product is 23% by weight.

[0093] The calcination of the dried product necessary to release both the microporosity (water) and the mesoporosity by removing the structuring agent is performed with the following temperature profile: 30 minutes of temperature increase to 200°C, then 1 hour at a steady stage of 200°C, then 3 hours of temperature increase to 550°C, and finally 1.5 hours of steady stage at 550°C.

[0094] 255 g of anhydrous equivalent solid of zeolite XPH are thus obtained; which represents a yield of 99 mol% relative to the amount of aluminium engaged. The Si/Al ratio of the ZPH determined by X-ray fluorescence is equal to 1.24.

[0095] For comparative purposes for the preparation of an agglomerated zeolite material, a non-mesoporous commercial zeolite with an Si/Al atomic ratio equal to 1.25 is used. This reference zeolite is, for example, Siliporite® G5 AP, sold by the company CECA.

[0096] The characteristics of the mesoporous zeolite X prepared in this Example 1 and the characteristics of the reference zeolite indicated above are collated in Table 1 below:

-- Table 1 --

	Reference	Non-mesoporous zeolite X	Mesoporous zeolite X (Example 1)
Synthesis	TPOAC/Al ₂ O ₃ mole ratio	-	0.04
	Synthesis time (h)	-	24
Nitrogen adsorption isotherm at 77 K	Micropore volume (cm ³ /g)	0.342	0.335
	Mesopore outer surface area (m ² /g)	35	105
	Mesopore size (nm)	-	5 to 10
XRD spectrum	Crystalline phase	Pure X	Pure X

(diffractogram)	Crystallinity X (%)	100	100
SEM	Crystal size (μm)	1.5	1 to 3

[0097] The size distribution of the mesopores is characterized by the Density Functional Theory (DFT) method with the cylindrical pore model. The percentage of crystallinity is calculated by means of the TOPAS software using the base ICDD PDF-2, release 2011.

5

Example 2: Preparation of mesoporous zeolite X agglomerates (according to the invention)

[0098] In the text hereinbelow, the masses given are expressed as anhydrous equivalent.

10 **[0099]** A homogeneous mixture consisting of 1600 g of mesoporous zeolite X crystals obtained in Example 1, 350 g of kaolin, 130 g of colloidal silica sold under the trade name Klebosol® 30 (containing 30% by weight of SiO₂ and 0.5% of Na₂O) and also an amount of water which allows extrusion of the mixture, is prepared. The loss on ignition of the pulp before extrusion is 44%.

15 **[0100]** Extrudates 1.6 mm in diameter are formed. The extrudates are dried overnight in a ventilated oven at 80°C. They are then calcined for 2 hours at 550°C under a flush of nitrogen, and then for 2 hours at 550°C under a flush of dry decarbonated air.

[0101] The mechanical grain crushing strength of the mesoporous zeolite X extrudates is 2.6 daN. Their apparent mass per unit volume is 0.64 g/cm³.

20

Example 3: Preparation of non-mesoporous zeolite X agglomerates (comparative)

[0102] The operations of Example 2 are repeated in an identical manner, replacing the mesoporous zeolite X with the reference non-mesoporous zeolite X. The mechanical grain crushing strength of the reference non-mesoporous zeolite X extrudates is 2.5 daN. Their
25 apparent mass per unit volume is 0.66 g/cm³.

[0103] It is thus observed that the agglomerated zeolite material according to the invention comprising a mesoporous zeolite X has mechanical properties and an apparent density that are entirely comparable to those of an agglomerated zeolite material comprising a non-mesoporous zeolite.

30 **[0104]** It is thus entirely noteworthy that the present invention provides agglomerated zeolite materials combining both the properties of mesoporous zeolites, the properties associated with the microporosity and the mechanical properties of the zeolite agglomerates known hitherto. It is thus possible to envisage without problem the use of

the agglomerated zeolite materials of the invention in all fields of industrial application such as catalysis, separation, adsorption and the like.

Example 4: Comparison of the agglomerates of Examples 2 and 3 relative to an agglomerate of the prior art

[0105] The mesoporous zeolite obtained by post-treatment of a non-mesoporous zeolite X, described in patent application WO 2013/106 816 (PCT/US 2013/021 420), in Example 4, Table 4, last line of the table, is used for this comparative study.

[0106] An agglomerate is prepared from this zeolite NaX according to the procedure described in Example 2 above.

[0107] The results of the comparative analysis are presented in Table 2 below:

-- Table 2 --

<i>Agglomerate</i>	Nitrogen adsorption isotherm at 77 K		XRD spectrum (diffractogram)	
	<i>Micropore volume (cm³/g)</i>	<i>Mesopore outer surface area (m²/g)</i>	<i>Crystalline phase</i>	<i>Crystallinity (%)</i>
Example 2 (according to the invention)	0.279	108	X	100%
Example 3 (comparative)	0.277	37	X	100%
According to Table 4 of WO 2013/106 816 (PCT/US 2013/021 420), (comparative)	0.170	90	X	46%

[0108] The percentage of crystallinity is calculated with the TOPAS software using the base ICDD PDF-2, release 2011.

[0109] The agglomerates according to the invention have micropore volumes that are markedly greater than those of the prior art and at least equivalent mesopore outer surface areas. These results show that the agglomerates comprising a zeolite whose mesoporosity has been obtained by post-treatment have markedly less efficient porosity characteristics than the agglomerates prepared according to the invention.

CLAIMS

1. Agglomerated zeolite material comprising at least one mesoporous zeolite with a number-average diameter of between 0.1 μm and 20 μm with an Si/Al atomic ratio of between 1 and 1.4, limits inclusive, and with a mesopore outer surface area, defined by the t-plot method, of between 40 $\text{m}^2.\text{g}^{-1}$ and 400 $\text{m}^2.\text{g}^{-1}$, limits inclusive, the said material having at least the following characteristics:

- a total zeolite content of at least 70% by weight relative to the total weight of the agglomerate,
- a content of mesoporous zeolite(s) of greater than or equal to 30%,
- a binder content, after calcinations performed at 950°C for 1 hour, of less than or equal to 30%,
- a mean volume diameter (D50), or a length (largest dimension when the material is not spherical) of less than or equal to 7 mm, and
- either a bulk crushing strength (BCS) measured according to standard ASTM 7084-04 of between 0.5 MPa and 3 MPa, for a material with a mean volume diameter (D50), or a length (largest dimension when the material is not spherical), of less than 1 mm, limits inclusive,
- or a grain crushing strength, measured according to standards ASTM D 4179 (2011) and ASTM D 6175 (2013), of between 0.5 daN and 30 daN, for a material with a mean volume diameter (D50), or a length (largest dimension when the material is not spherical), of greater than or equal to 1 mm, limits inclusive.

2. Material according to Claim 1, also having an apparent mass per unit volume of between 0.4 $\text{g}.\text{cm}^{-3}$ and 1 $\text{g}.\text{cm}^{-3}$, limits inclusive.

3. Material according to Claim 1 or Claim 2, in which said mesoporous zeolite is chosen from mesoporous zeolites of LTA, EMT and FAU structure with an Si/Al atomic ratio of between 1 and 1.4, limits inclusive.

4. Material according to any one of Claims 1 to 3, in which the zeolite crystals are agglomerated with a binder comprising a clay or a mixture of clays chosen from kaolins, kaolinites, nacrites, dickites, halloysites, attapulgites, sepiolites, montmorillonites, bentonites, illites and metakaolins, and also mixtures of two or more thereof in all proportions.

5. Material according to any one of Claims 1 to 4, having both the characteristics of mesoporous zeolites, but also the mechanical properties of conventional zeolite agglomerates in which the zeolite is non-mesoporous.

6. Process for preparing a material according to any one of Claims 1 to 5, comprising at least the steps of:

- a) agglomeration of crystals of at least one mesoporous zeolite with a number-average diameter of between 0.1 μm and 20 μm , preferably between 0.1 μm and 10 μm , more preferably between 0.5 μm and 10 μm and even more preferentially between 0.5 μm and 5 μm , with an Si/Al atomic ratio of between 1 and 1.4, limits inclusive, and with a mesopore outer surface area, defined by the t-plot method, of between 40 $\text{m}^2.\text{g}^{-1}$ and 400 $\text{m}^2.\text{g}^{-1}$ and preferably between 60 $\text{m}^2.\text{g}^{-1}$ and 200 $\text{m}^2.\text{g}^{-1}$, limits inclusive, with a binder comprising at least 80% clay or a mixture of clays, which are optionally zeolitizable, and with up to 5% of additives, and also with the amount of water that allows the shaping of the agglomerated material;
- b) drying of the agglomerates at a temperature of between 50°C and 150°C;
- c) calcination of the agglomerates of step b) with flushing with an oxidizing and/or inert gas, especially with gases such as oxygen, nitrogen, air, a dry and/or decarbonated air, an oxygen-depleted air, which is optionally dried and/or decarbonated, at a temperature above 150°C, typically between 180°C and 800°C and preferentially between 200°C and 650°C, for a few hours, for example from 2 to 6 hours;
- d) optionally zeolitization of the binder by placing the agglomerates obtained in step c) in contact with an alkaline basic solution;
- e) optionally cation exchange(s) of the agglomerates of step c) or of step d) by placing in contact with a solution of at least one alkali metal or alkaline-earth metal salt;
- f) and then washing and drying of the agglomerates obtained in steps d) or e) under the conditions described in step b), and
- g) production of the agglomerated zeolite material by activation of the agglomerates obtained in step f) under the conditions described in step c).

7. Process according to Claim 6, in which, in step a), agglomeration of crystals of a zeolite prepared in the presence of a sacrificial template is performed.
8. Process according to Claim 7, in which the sacrificial template is chosen from compounds of organosilane type and oligomers, and the like.
9. Process according to Claim 8, in which the removal of the said sacrificial template is performed by calcination of the zeolite crystals before the agglomeration step a), or concomitantly with step c).