CLAIMS

1. A cation exchange membrane, comprising:

a porous support membrane, wherein the porous support membrane is in the form of a non-woven fabric or mesh, veil, knit fabric, woven fabric or mesh, open-cell structure, fibril and node structure, or open-cell foam; and

a silica-based ceramic that forms a coating on and/or within the porous support membrane, wherein the silica-based ceramic comprises sulfonate and/or sulfonic acid groups covalently bound to the silica-based ceramic, ~~and~~ wherein the cation exchange membrane has a sodium ion (Na^+) conductivity of greater than or equal to 0.00001 S/cm, and wherein the weight ratio of the silica-based ceramic to the porous support membrane in the cation exchange membrane is greater than or equal to 1:10.

~~2. A cation exchange membrane, comprising:~~

~~a silica-based ceramic, wherein the cation exchange membrane has a water uptake of greater than or equal to 10 wt% and a linear expansion of less than or equal to 10%.~~

2~~3~~. A cation exchange membrane, comprising:

a porous support membrane, wherein the porous support membrane is in the form of a non-woven fabric or mesh, veil, knit fabric, woven fabric or mesh, open-cell structure, fibril and node structure, or open-cell foam; and

a silica-based ceramic that coats at least a portion of the porous support membrane, wherein the silica-based ceramic comprises sulfonate and/or sulfonic acid groups covalently bound to the silica-based ceramic, and wherein the silica-based ceramic has an average pore diameter of less than or equal to 10 nm.

~~4. A cation exchange membrane, comprising:~~

~~a porous support membrane; and~~

~~a silica-based ceramic that forms a coating on and/or within the porous support membrane, wherein the silica-based ceramic comprises sulfonate and/or sulfonic acid groups covalently bound to the silica-based ceramic, and wherein the sulfonate and/or sulfonic acid~~

groups are substantially homogeneously distributed within the silica-based ceramic across a thickness of the coating.

5. A cation exchange membrane, comprising:

a porous support membrane;

a silica-based ceramic that forms a coating on and/or within the porous support membrane, wherein the silica-based ceramic comprises sulfonate and/or sulfonic acid groups covalently bound to the silica-based ceramic, and wherein the sulfonate and/or sulfonic acid groups are directly adjacent to a surface of the porous support membrane; and

an edging material comprising a polymeric material along at least a portion of an edge of the cation exchange membrane.

6. A cation exchange membrane, comprising:

a porous support membrane;

a silica-based ceramic that coats at least a portion of the porous support membrane, wherein the silica-based ceramic comprises sulfonate and/or sulfonic acid groups covalently bound to the silica-based ceramic, and wherein greater than or equal to 50% of the pore volume of the porous support membrane is filled by the silica-based ceramic; and

an edging material comprising a polymeric material along at least a portion of an edge of the cation exchange membrane.

7. A cation exchange membrane, comprising:

a porous support membrane; and

a silica-based ceramic that forms a coating on and/or within the porous support membrane, wherein the silica-based ceramic comprises sulfonate and/or sulfonic acid groups covalently bound to the silica-based ceramic, and wherein the cation exchange membrane has a cation exchange capacity of greater than or equal to 0.01 meq/g.

8. A cation exchange membrane, comprising:

a porous support membrane; and

~~a silica-based ceramic that coats at least a portion of the porous support membrane, wherein the silica-based ceramic comprises sulfonate and/or sulfonic acid groups covalently bound to the silica-based ceramic, and wherein the sulfonate and/or sulfonic acid groups are present in the cation exchange membrane in an amount of greater than or equal to 0.01 mmol per gram of the cation exchange membrane.~~

~~9. A cation exchange material, comprising:~~

~~a silica-based ceramic that comprises sulfonate and/or sulfonic acid groups covalently bound to the silica-based ceramic, wherein the silica-based ceramic comprises Si in an amount greater than or equal to 6 wt% of the silica-based ceramic,~~

~~wherein the cation exchange material has a cation exchange capacity of greater than or equal to 0.01 meq/g, and~~

~~wherein the silica-based ceramic has an average pore diameter of less than 10 nm.~~

~~10. A cation exchange membrane, comprising:~~

~~a silica-based ceramic comprising Si in an amount greater than or equal to 6 wt% of the silica-based ceramic, wherein the cation exchange membrane has a cation exchange capacity of greater than or equal to 0.1 meq/g.~~

~~11. A cation exchange membrane, comprising:~~

~~a silica-based ceramic, wherein the cation exchange membrane has a cation exchange capacity of greater than or equal to 0.01 meq/g and a linear expansion of less than or equal to 10%.~~

~~12. A cation exchange membrane, comprising:~~

~~a silica-based ceramic comprising Si in an amount greater than or equal to 6 wt% of the silica-based ceramic, wherein the cation exchange membrane has a cation permselectivity of greater than or equal to 65%.~~

~~13. A cation exchange membrane, comprising:~~

a silica-based ceramic comprising Si in an amount greater than or equal to 6 wt% of the silica-based ceramic, wherein the cation exchange membrane has a Na^+ conductivity of greater than or equal to 0.00001 S/cm.

14. A cation exchange membrane, comprising:

a silica-based ceramic, wherein the cation exchange membrane has a Na^+ conductivity of greater than or equal to 0.00001 S/cm and a linear expansion of less than or equal to 10%.

15. A cation exchange membrane, comprising:

a silica-based ceramic comprising Si in an amount greater than or equal to 6 wt% of the silica-based ceramic, wherein the cation exchange membrane has an osmotic water permeance of less than or equal to 100 mL/(hr·bar·m^2).

16. A cation exchange membrane, comprising:

a silica-based ceramic comprising Si in an amount greater than or equal to 6 wt% of the silica-based ceramic, the silica-based ceramic comprising pores, wherein an average diameter of the pores of the silica-based ceramic is larger when the cation exchange membrane is in a hydrated state than when the cation exchange membrane is in a dry state by a factor of greater than or equal to 1.1.

17. A cation exchange membrane, comprising:

a silica-based ceramic comprising Si in an amount greater than or equal to 6 wt% of the silica-based ceramic, the silica-based ceramic comprising pores, wherein:

when the cation exchange membrane is in a dry state, the pores of the silica-based ceramic fit a model of small-angle scattering spectra with intensity (I) as a function of a scattering vector, q, as follows:

$$I(q) = \frac{1}{a + c_1 q^2 + c_2 q^4} + bck,$$

wherein a, c_1, and c_2 are adjustable parameters and bck is background scattering; and

~~when the cation exchange membrane is in a hydrated state the pores of the silica-based ceramic fit a core-shell model of small angle scattering spectra with intensity (*I*) as a function of a scattering vector, q, as follows:~~

~~$$I(q) = P(q)S(q) + bck,$$~~

~~$$S(q) = 1 + \frac{D_f \Gamma(D_f - 1)}{[1+1/q\xi)^2]^{(D_f-1)/2}} \frac{sin[(D_f-1)tan^{-1}(q\xi)]}{(qR_0)^{D_f}},$$~~

~~$$P(q) = \frac{scale}{V_s}\left[3V_e(\rho_e - \rho_s)\frac{[sin(qr_e) - qr_e cos(qr_e)]}{(qr_e)^3} + 3V_s(\rho_s - \rho_{Block})\frac{[sin(qr_s) - qr\, cos(qr_s)]}{(qr_s)^3}\right]^2 + bck,$$~~

~~wherein R_0 is a radius of the building blocks (pores), $\rho_{solvent}$ is a scattering length density of the silica based ceramic, D_f is a fractal dimension, ξ is a correlation length, Γ is the standard mathematical gamma function, *scale* is a volume fraction of building blocks of the measured silica-based ceramic, V_e is a volume of the core, V_s is a volume of the shell, ρ_e is a scattering length density of the core, ρ_s is a scattering length density of the shell, ρ_{block} is a scattering length density of the pores, r_e is a radius of the core, r_s is a radius of the shell, and *bck* is background scattering.~~

~~18. A method for forming a cation exchange membrane, comprising:~~

~~exposing a porous support membrane, coated with a silica-based ceramic comprising an oxidizable functional group, to an oxidizing agent, wherein the silica-based ceramic comprises Si in an amount greater than or equal to 6 wt% of the silica-based ceramic; and~~

~~oxidizing the oxidizable functional group to form a sulfonate or sulfonic acid group.~~

~~19. A method for forming a cation exchange material, comprising:~~

~~exposing a resin comprising a silica-based ceramic comprising an oxidizable functional group, to an oxidizing agent, wherein the silica-based ceramic comprises Si in an amount greater than or equal to 6 wt% of the silica-based ceramic; and~~

~~oxidizing the oxidizable functional group to form a sulfonate or sulfonic acid group.~~

~~20. The cation exchange membrane, cation exchange material, or method of any preceding claim, further comprising a porous support membrane coated by the silica-based ceramic.~~

3. The cation exchange membrane of any one of claims 1-2, wherein the sulfonate and/or sulfonic acid groups are present in the cation exchange membrane in an amount of greater than or equal to 0.01 mmol per gram of the cation exchange membrane.

4. The cation exchange membrane of any one of claims 1-3, wherein the cation exchange membrane has a cation exchange capacity of greater than or equal to 0.1 meq/g.

5. The cation exchange membrane of any one of claims 1-4, wherein the silica-based ceramic comprises Si in an amount greater than or equal to 6 wt% of the silica-based ceramic.

6. The cation exchange membrane of any one of claims 1-5, wherein the cation exchange membrane has a linear expansion of less than or equal to 5%.

7. The cation exchange membrane of any one of claims 1-6, wherein the cation exchange membrane has a cation permselectivity of greater than or equal to 65%.

8. The cation exchange membrane of any one of claims 1-7, wherein the silica-based ceramic comprises pores, and wherein an average diameter of the pores of the silica-based ceramic is larger when the cation exchange membrane is in a hydrated state than when the cation exchange membrane is in a dry state by a factor of greater than or equal to 1.1.

9. The cation exchange membrane of claim 8, wherein the silica-based ceramic comprises pores, and wherein an average diameter of the pores of the silica-based ceramic is larger when the cation exchange membrane is in a hydrated state than when the cation exchange membrane is in a dry state by a factor of less than or equal to 5.

10. The cation exchange membrane of any one of claims 1-9, wherein the silica-based ceramic comprises pores, and wherein:

when the cation exchange membrane is in a dry state, the pores of the silica-based ceramic fit a model of small angle scattering spectra with intensity (*I*) as a function of a scattering vector, *q*, as follows:

$$I(q) = \frac{1}{a+c_1q^2+c_2q^4} + bck,$$

wherein *a*, c_1, and c_2 are adjustable parameters and *bck* is background scattering; and

when the cation exchange membrane is in a hydrated state the pores of the silica-based ceramic fit a core-shell model of small angle scattering spectra with intensity (*I*) as a function of a scattering vector, *q*, as follows:

$$I(q) = P(q)S(q) + bck,$$

$$S(q) = 1 + \frac{D_f\Gamma(D_f-1)}{[1+1/q\xi)^2]^{(D_f-1)/2}} \frac{sin[(D_f-1)tan^{-1}(q\xi)]}{(qR_0)^{D_f}},$$

$$P(q) = \frac{scale}{V_s}\left[3V_c(\rho_c-\rho_s)\frac{[sin(qr_c)-qr_c\,cos(qr_c)]}{(qr_c)^3} + 3V_s(\rho_s - \rho_{block})\frac{[sin(qr_s)-qr\,cos(qr_s)]}{(qr_s)^3}\right]^2 + bck,$$

wherein R_o is a radius of the building blocks (pores), $\rho_{solvent}$ is a scattering length density of the silica-based ceramic, D_f is a fractal dimension, ξ is a correlation length, Γ is the standard mathematical gamma function, *scale* is a volume fraction of building blocks of the measured silica-based ceramic, V_c is a volume of the core, V_s is a volume of the shell, ρ_c is a scattering length density of the core, ρ_s is a scattering length density of the shell, ρ_{block} is a scattering length density of the pores, r_c is a radius of the core, r_s is a radius of the shell, and *bck* is background scattering.

11. The cation exchange membrane of any one of claims 1-10, wherein the silica-based ceramic is derived from a mixture comprising (3-mercaptopropyl)triethoxysilane.

12. The cation exchange membrane of any one of claims 1-11, wherein the silica-based ceramic has an average pore diameter of less than or equal to 2 nm.

13. The cation exchange membrane of any one of claims 1-12, wherein the porous support membrane has a volumetric porosity of greater than or equal to 10%.

14. The cation exchange membrane of any one of claims 1-13, wherein the porous support membrane has a volumetric porosity of less than or equal to 99%.

15. The cation exchange membrane of any one of claims 1-14, wherein greater than or equal to 50% of the pore volume of the porous support membrane is filled by the silica-based ceramic.

16. The cation exchange membrane of any one of claims 1-15, wherein the porous support membrane has a mechanical burst pressure of greater than or equal to 2.0 pounds per square inch (PSI).

17. The cation exchange membrane of any one of claims 1-16, wherein the porous support membrane comprises an outer surface, and wherein the cation exchange membrane comprises a layer comprising the silica-based ceramic that forms a coating on at least a portion of the outer surface of the porous support membrane.

18. The cation exchange membrane of claim 17, wherein the porous support membrane comprises an interior, and wherein the cation exchange membrane further comprises the silica-based ceramic present within at least a portion of the interior of the porous support membrane.

19. The cation exchange membrane of any one of claims 2-18, wherein the weight ratio of the silica-based ceramic to the porous support membrane in the cation exchange membrane is greater than or equal to 1:10.

20. A method for using the cation exchange membrane of any one of claims 1-19 in an electrochemical application, comprising:

contacting the cation exchange membrane with an electrolyte; and

passing current through an electrode in electrical communication with the electrolyte.