(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
04 June 2020 (04.06.2020)

WIPO | PCT

(10) International Publication Number
WO 2020/112396 A2

(51) International Patent Classification:
C03C 3/087 (2006.01) *C03C 3/097* (2006.01)
C03C 3/095 (2006.01)

(21) International Application Number:
PCT/US2019/061917

(22) International Filing Date:
18 November 2019 (18.11.2019)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/771,245 26 November 2018 (26.11.2018) US

(71) Applicant: **OCV INTELLECTUAL CAPITAL, LLC** [US/US]; One Owens Corning Parkway, Toledo, OH 43659 (US).

(72) Inventor: **KORWIN-EDSON, Michelle L.**; 109 Blue Stone Ct., Granville, OH 43023 (US).

(74) Agent: **RAULERSON, Billy C.**; Calfee, Halter & Griswold LLP, The Calfee Building, 1405 East Sixth St., Cleveland, OH 44114 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) Title: HIGH PERFORMANCE FIBERGLASS COMPOSITION WITH IMPROVED SPECIFIC MODULUS

(57) Abstract: Glass fibers formed from the inventive composition may be used in applications that require high stiffness and have a specific modulus between 34 and 40 MJ/kg. Such applications include woven fabrics for use in forming wind turbine blades and aerospace structures

WO 2020/112396 A2

HIGH PERFORMANCE FIBERGLASS COMPOSITION WITH IMPROVED SPECIFIC MODULUS

RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application No. 62/771,245, filed on November 26, 2018, titled HIGH PERFORMANCE FIBERGLASS COMPOSITION WITH IMPROVED SPECIFIC MODULUS, the entire disclosure of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] Glass fibers are manufactured from various raw materials combined in specific proportions to yield a desired composition, commonly termed a "glass batch." This glass batch may be melted in a melting apparatus and the molten glass is drawn into filaments through a bushing or orifice plate (the resultant filaments are also referred to as continuous glass fibers). A sizing composition containing lubricants, coupling agents and film-forming binder resins may then be applied to the filaments. After the sizing is applied, the fibers may be gathered into one or more strands and wound into a package or, alternatively, the fibers may be chopped while wet and collected. The collected chopped strands may then be dried and cured to form dry chopped fibers or they can be packaged in their wet condition as wet chopped fibers.

[0003] The composition of the glass batch, along with the fiberglass manufactured therefrom, is often expressed in terms of the oxides contained therein, which commonly include SiO_2, Al_2O_3, CaO, MgO, B_2O_3, Na_2O, K_2O, Fe_2O_3, TiO_2, Li_2O, and the like. Numerous types of glasses may be produced from varying the amounts of these oxides, or eliminating some of the oxides in the glass batch. Examples of such glasses that may be produced include R-glass, E-glass, S-glass, A-glass, C-glass, and ECR-glass. The glass composition controls the forming and product properties of the glass. Other characteristics of glass compositions include the raw material cost and environmental impact.

[0004] For instance, E-glass is an aluminoborosilicate glass, generally alkali-free, and commonly used in electrical applications. One advantage of E-Glass is that its liquidus temperature allows

operating temperatures for producing glass fibers to be approximately 1900° F to 2400° F (1038° C to 1316° C). The ASTM classification for E-glass fiber yarns used in printed circuit boards and aerospace applications defines the composition to be 52 to 56 weight % SiO_2, 16 to 25 weight % CaO, 12 to 16 weight % Al_2O_3, 5 to 10 weight % B_2O_3, 0 to 5 weight % MgO, 0 to 2 weight % Na_2O and K_2O, 0 to 0.8 weight % TiO_2, 0.05 to 0.4 weight % Fe_2O_3 and 0 to 1.0 weight % Fluorine.

[0005] Boron-free fibers are sold under the trademark ADVANTEX® (Owens Corning, Toledo, Ohio, USA). Boron-Free fibers, such as are disclosed in U.S. Pat. No. 5,789,329, incorporated herein by reference in its entirety, offer a significant improvement in operating temperatures over boron-containing E-glass. Boron-Free glass fibers fall under the ASTM definition for E-glass fibers for use in general-use applications.

[0006] R-Glass is a family of glasses that are composed primarily of the oxides of silicon, aluminum, magnesium, and calcium with a chemical composition that produces glass fibers with a higher mechanical strength than E-Glass fibers. R-Glass has a composition that contains about 58 to about 60 % by weight SiO_2, about 23.5 to about 25.5 % by weight Al_2O_3, about 14 to about 17 % by weight CaO plus MgO, and less than about 2 % by weight of miscellaneous components. R-Glass contains more alumina and silica than E-Glass and requires higher melting and processing temperatures during fiber forming. Typically, the melting and processing temperatures for R-Glass are higher than those for E-Glass. This increase in processing temperature requires the use of a high-cost platinum-lined melter. In addition, the close proximity of the liquidus temperature to the forming temperature in R-Glass requires that the glass be fiberized at a viscosity lower than E-Glass, which is customarily fiberized at or near about 1000 poise. Fiberizing R-Glass at the customary 1000 poise viscosity would likely result in glass devitrification, which causes process interruptions and reduced productivity.

[0007] High performance glass fibers possess higher strength and stiffness, compared to traditional E-glass fibers. In particular, for some products, stiffness is crucial for modeling and performance. For example, composites, such as wind turbine blades, prepared from glass fibers with good stiffness properties would allow for longer wind turbine blades on electrical generating wind stations while keeping flexure of the blade within acceptable limits.

[0008] Additionally, high-performance glass compositions are desired that possess favorable mechanical and physical properties (*e.g.*, specific modulus and tensile strength), while maintain desirable forming properties (*e.g.*, liquidus temperature and fiberizing temperature). Elastic

modulus is a measure of the fiber stiffness, defining a relationship between the stress applied to a material and the strain produced by the same material. A *stiff* material has a high elastic modulus and changes its shape only slightly under elastic loads. A *flexible* material has a low elastic modulus and changes its shape considerably. Specific modulus is a measure of the elastic modulus per mass density of a fiberglass material. It can also be known as the stiffness to weight ratio and is often used to determine glass fibers with minimum weight, while not sacrificing stiffness.

SUMMARY OF THE INVENTION

[0009] Various exemplary embodiments of the present inventive concepts are directed to a glass composition comprising: SiO_2 in an amount from 58.0 to 68.0 % by weight; Al_2O_3 in an amount from 18.0 to 23.0% by weight; CaO in an amount from 1.0 to 9.0% by weight; MgO in an amount from 9.0 to 14.0% by weight; Na_2O in an amount from 0.0 to < 1.0% by weight; K_2O in an amount from 0.0 to 1.0% by weight; Li2O in an amount from 0.0 to 4.0% by weight; TiO_2 in an amount from 0.0 to 4.0% by weight; Y_2O_3 in an amount from 0 to 10.0 % by weight; La_2O_3 in an amount from 0 to 10.0 % by weight; Ce_2O_3 in an amount from 0 to 2.5 % by weight; and Sc_2O_3 in an amount from 0 to 4.0 % by weight.

[00010] In some exemplary embodiments, the glass composition has a ratio MgO/(CaO+SrO) of greater than 2.1.

[00011] In some exemplary embodiments, the glass fiber formed from the glass composition has specific modulus between 34 and 40 MJ/kg.

[00012] The glass composition may further include 0 to 5.0 % by weight Ta_2O_5; 0 to 7.0 % by weight Ga_2O_3; 0 to 5.0 % by weight Nb_2O_5, and 0 to 5.0 % by weight V_2O_5.

[00013] In various exemplary embodiments, the glass composition is essentially free of B_2O_3.

[00014] In various exemplary embodiments, the glass composition comprises 0.1 to 3.5% by weight Li_2O.

[00015] In various exemplary embodiments, the composition includes at least 1% by weight of a combined amount of one or more ofY_2O_3, La_2O_3, Ce_2O_3, and Sc_2O_3.

[00016] In various exemplary embodiments, the composition comprises less than 0.05% by weight of Sm_2O_3+Gd_2O_3.

Further exemplary aspects of the present inventive concepts are directed to a glass fiber formed from a composition comprising: SiO_2 in an amount from 55.0 to 68.0 % by weight; Al_2O_3 in an

amount from 18.0 to 23.0% by weight; CaO in an amount from 1.0 to 9.0% by weight; MgO in an amount from 9.0 to 14.0% by weight; Na_2O in an amount from 0.0 to 1.0% by weight; K_2O in an amount from 0.0 to 1.0% by weight; Li2O in an amount from greater than 1.0 to 4.0% by weight; TiO_2 in an amount from 0.0 to 4.0% by weight; Y_2O_3 in an amount from 0 to 10.0 % by weight; La_2O_3 in an amount from 0 to 10.0 % by weight; Ce_2O_3 in an amount from 0 to 2.5 % by weight; and Sc_2O_3 in an amount from 0 to 4.0 % by weight. The glass fiber has a specific modulus between 34 and 40 MJ/kg. The glass fiber further has a tensile strength according to ASTM D2343-09 of at least 4400 MPa.

[00017] In various exemplary embodiments, the composition comprises 1.5 to 3.5% by weight Li_2O.

[00018] In various exemplary embodiments, the composition comprises 1.0 to 5.0 % by weight CaO.

[00019] In various exemplary embodiments, the composition includes at least 1% by weight of a combined amount of one or more ofY_2O_3, La_2O_3, Ce_2O_3, and Sc_2O_3.

[00020] Further exemplary embodiments are directed to a glass fiber that has a specific modulus of 35 to 36.5 MJ/kg.

[00021] Yet further exemplary aspects of the present inventive concepts are directed to a method of forming a continuous glass fiber comprising providing a molten glass composition; and drawing the molten composition through an orifice to form a continuous glass fiber.

[00022] Yet further exemplary aspects of the present inventive concepts are directed to a reinforced composite product comprising a polymer matrix; and a plurality of glass fibers formed from a glass composition comprising SiO_2 in an amount from 58.0 to 68.0 % by weight; Al_2O_3 in an amount from 18.0 to 23.0% by weight; CaO in an amount from 1.0 to 9.0% by weight; MgO in an amount from 9.0 to 14.0% by weight; Na_2O in an amount from 0.0 to 1.0% by weight; K_2O in an amount from 0.0 to 1.0% by weight; Li2O in an amount from 0.0 to 4.0% by weight; TiO_2 in an amount from 0.0 to 4.0% by weight; Y_2O_3 in an amount from 0 to 10.0 % by weight; La_2O_3 in an amount from 0 to 10.0 % by weight; Ce_2O_3 in an amount from 0 to 2.5 % by weight; and Sc_2O_3 in an amount from 0 to 4.0 % by weight.

[00023] In various exemplary embodiments, the glass composition has a ratio MgO/(CaO+SrO) of greater than 2.1.

[00024] The glass fiber has a specific modulus between 34 and 40 MJ/kg.

[00025] In some exemplary embodiments, the reinforced composite product is in the form of a wind turbine blade.

[00026] The foregoing and other objects, features, and advantages of the invention will appear more fully hereinafter from a consideration of the detailed description that follows.

DETAILED DESCRIPTION

[00027] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which these exemplary embodiments belong. The terminology used in the description herein is for describing exemplary embodiments only and is not intended to be limiting of the exemplary embodiments. Accordingly, the general inventive concepts are not intended to be limited to the specific embodiments illustrated herein. Although other methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, the preferred methods and materials are described herein.

[00028] As used in the specification and the appended claims, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise.

[00029] Unless otherwise indicated, all numbers expressing quantities of ingredients, chemical and molecular properties, reaction conditions, and so forth used in the specification and claims are to be understood as being modified in all instances by the term "about." Accordingly, unless indicated to the contrary, the numerical parameters set forth in the specification and attached claims are approximations that may vary depending upon the desired properties sought to be obtained by the present exemplary embodiments. At the very least each numerical parameter should be construed in light of the number of significant digits and ordinary rounding approaches.

[00030] Notwithstanding that the numerical ranges and parameters setting forth the broad scope of the exemplary embodiments are approximations, the numerical values set forth in the specific examples are reported as precisely as possible. Any numerical value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements. Every numerical range given throughout this specification and claims will include every narrower numerical range that falls within such broader numerical range, as if such narrower numerical ranges were all expressly written herein. Moreover, any numerical value reported in the

Examples may be used to define either an upper or lower end-point of a broader compositional range disclosed herein.

[00031] The present disclosure relates to a high-performance glass composition with improved specific modulus. Such glass compositions are particularly interesting in the field of wind products, such as wind turbines that require longer blades in order to generate more energy. The longer blades require materials with higher specific modulus in order to withstand forces applied to them without breaking and without adding too much additional weight. The subject glass compositions include lithium and optionally rare earth oxides. Additionally, the subject glass compositions include higher levels of magnesium and alumina than other glass compositions in this space.

[00032] The glass compositions disclosed herein are suitable for melting in traditional commercially available refractory-lined glass furnaces, which are widely used in the manufacture of glass reinforcement fibers.

[00033] The glass composition may be in molten form, obtainable by melting the components of the glass composition in a melter. The glass composition exhibits a low fiberizing temperature, which is defined as the temperature that corresponds to a melt viscosity of about 1000 Poise, as determined by ASTM C965-96(2007). Lowering the fiberizing temperature may reduce the production cost of the glass fibers because it allows for a longer bushing life and reduced energy usage necessary for melting the components of a glass composition. Therefore, the energy expelled is generally less than the energy necessary to melt many commercially available glass formulations. Such lower energy requirements may also lower the overall manufacturing costs associated with the glass composition.

[00034] For example, at a lower fiberizing temperature, a bushing may operate at a cooler temperature and therefore does not "sag" as quickly as is typically seen. "Sag" is a phenomenon that occurs when a bushing that is held at an elevated temperature for extended periods of time loses its determined stability. Thus, by lowering the fiberizing temperature, the sag rate of the bushing may be reduced, and the bushing life can be maximized.

[00035] In some exemplary embodiments, the glass composition has a fiberizing temperature of less than 2,650 °F, including fiberizing temperatures of no greater than 2,600 °F, no greater than 2,550 °F, no greater than 2,500 °F, no greater than 2470 °F, no greater than 2420 °F, no greater than 2410 °F, no greater than 2405 °F, no greater than 2400 °F, and no greater than 2390 °F, and no greater than 2385 °F. In some exemplary embodiments, the glass composition has a fiberizing

temperature no greater than 2,300 °F, such as no greater than 2,500 °F, and no greater than 2,200 °F.

[00036] Another fiberizing property of a glass composition is the liquidus temperature. The liquidus temperature is defined as the highest temperature at which equilibrium exists between liquid glass and its primary crystalline phase. The liquidus temperature, in some instances, may be measured by exposing the glass composition to a temperature gradient in a platinum-alloy boat for 16 hours (ASTM C829-81(2005)). At all temperatures above the liquidus temperature, the glass is completely molten, *i.e.*, it is free from crystals. At temperatures below the liquidus temperature, crystals may form.

[00037] In some exemplary embodiments, the glass composition has a liquidus temperature below 2,600 °F, including liquidus temperature of no greater than 2,400 °F, no greater than 2,375 °F, no greater than 2,350 °F, no greater than 2,325 °F, no greater than 2,305 °F, no greater than 2,300 °F, no greater than 2,290 °F, no greater than 2,250 °F, no greater than 2,225 °F, and no greater than 2,215 °F. In some exemplary embodiments, the glass composition has a liquidus temperature between 2,050 °F and 2,550 °F, including between 2,150 °F, and 2,490 °F, between 2,190 °F and 2,450 °F, and between 2,250 °F and 2,450 °F.

[00038] A third fiberizing property is "ΔT", which is defined as the difference between the fiberizing temperature and the liquidus temperature. If the ΔT is too small, the molten glass may crystallize within the fiberizing apparatus and cause a break in the manufacturing process. Desirably, the ΔT is as large as possible for a given forming viscosity because it offers a greater degree of flexibility during fiberizing and helps to avoid devitrification both in the glass distribution system and in the fiberizing apparatus. A large ΔT additionally reduces the production cost of the glass fibers by allowing for a greater bushing life and a less sensitive forming process.

[00039] In some exemplary embodiments, the glass composition has a ΔT of at least -60 °F, including at least -20 °F, including at least 40 °F, including at least 80 °F, including at least 100 °F, at least 110 °F, at least 120 °F, at least 135 °F, at least 150 °F, and at least 170 °F. In various exemplary embodiments, the glass composition has a ΔT between 100 °F and 250 °F, including between 120 °F and 200 °F, and between 150 °F and 215 °F.

[00040] The glass composition may include about 55.0 to about 68.0 % by weight SiO_2, about 18.0 to about 23.0 % by weight Al_2O_3, about 9.0 to about 14.0 % by weight MgO, 0 to about 9.0 % by weight CaO, 0.0 to about 1.0 % by weight Na_2O, 0 to about 1.0 % by weight K_2O, 0 to about

4.0 % by weight TiO_2, 0 to about 0.8 % by weight Fe_2O_3, and about 0.0 to about 4.0 % by weight Li_2O. The glass composition may further include 0 to about 10.0 % by weight Y_2O_3, 0 to about 10.0 % by weight La_2O_3, 0 to about 2.5 % by weight Ce_2O_3, and 0 to about 4.0 % by weight Sc_2O_3. The glass composition may further include 0 to about 5.0 % by weight Ta_2O_5, 0 to about 7.0 % by weight Ga_2O_3, 0 to about 5.0 % by weight Nb_2O_5, and 0 to about 5.0 % by weight V_2O_5.

[00041] In some exemplary embodiments, the glass composition may include about 59.0 to about 65.0 % by weight SiO_2, about 18.3 to about 22.0 % by weight Al_2O_3, about 9.3 to about 12.0 % by weight MgO, about 1.0 to about 8.5 % by weight CaO, about 0.01 to about 0.5 % by weight Na_2O, about 0.01 to about 0.5 % by weight K_2O, about 0.01 to about 3.5 % by weight TiO_2, about 0.01 to about 0.6 % by weight Fe_2O_3, and about 0.1 to about 3.5 % by weight Li_2O. In some embodiments, the glass composition is free of ZrO_2. The glass composition may further include about 0.01 to about 7.0 % by weight Y_2O_3, about 0.01 to about 4.0 % by weight La_2O_3, about 0.01 to about 2.0 % by weight Ce_2O_3, and about 0.01 to about 3.5 % by weight Sc_2O_3. The glass composition may further include about 0.01 to about 4.0 % by weight Ta_2O_5, about 0.01 to about 6.0 % by weight Ga_2O_3, about 0.01 to about 4.0 % by weight Nb_2O_5, and about 0.01 to 4.0% by weight V_2O_5.

[00042] The glass composition includes at least 50 % by weight and no greater than about 75 % by weight SiO_2. In some exemplary embodiments, the glass composition includes at least about 55 % by weight SiO_2, including at least 57 % by weight, at least 58 % by weight, at least 58.5 % by weight, and at least 59 % by weight. In some exemplary embodiments, the glass composition includes no greater than about 70 % by weight SiO_2, including no greater than 68 % by weight, no greater than 65.5 % by weight, no greater than 63 % by weight, no greater than 61 % by weight, and no greater than 60.5 % by weight. In some exemplary embodiments, the glass composition includes about 59 % by weight to about 68 % by weight, or about 60 % by weight to about 65 % by weight SiO_2.

[00043] To achieve both the desired mechanical and fiberizing properties, one important aspect of the glass composition is having a Al_2O_3 concentration of at least about 16.0 % by weight and no greater than about 25 % by weight. Including greater than about 25 % by weight Al_2O_3 causes the glass liquidus to increase to a level above the fiberizing temperature, which results in a negative ΔT. Including less than 17 % by weight Al_2O_3 forms a glass fiber with an unfavorably low modulus. In some exemplary embodiments, the glass composition includes at least about 17.0 %

by weight Al_2O_3, including at least 18.0 % by weight, at least 19.0 % by weight, at least 19.5% by weight, and at least 20.0 % by weight. In some exemplary embodiments, the glass composition includes about 18.3 to about 23 wt.% Al_2O_3, including about 18.8 to about 22 wt.% Al_2O_3.

[00044] The glass composition further advantageously includes at least about 8.0 % by weight and no greater than about 15 % by weight MgO. Including greater than about 15 % by weight MgO will cause the liquidus temperature to increase, which also increases the glass's crystallization tendency. Including less than about 8.0 % by weight forms a glass fiber with an unfavorably low modulus if substituted by CaO and an unfavorable increase in viscosity if substituted with SiO_2. In some exemplary embodiments, the glass composition includes at least about 9.0 % by weight MgO, including at least 9.2 % by weight, at least 9.5 % by weight, at least 10 % by weight, at least 11 % by weight, at least 11.25 % by weight, at least 12.5 % by weight, and at least 13 % by weight MgO. In some exemplary embodiments, the glass composition comprises an MgO concentration between about 9.3 and about 14 % by weight, or between about 9.6 and about 12 % by weight.

[00045] The glass composition may optionally include CaO at concentrations up to about 10.0 wt.%. Including greater than about 10 % by weight CaO forms a glass with a lower than desired elastic modulus. In some exemplary embodiments, the glass composition includes between 0 and about 9 % by weight CaO, including between 0.5 and 8.8 % by weight, between 1.0 and 8.5 % by weight, between 1.5 and 8.0 % by weight, and between 2.0 and 5.5 % by weight. In some exemplary embodiments, the glass composition includes a CaO concentration between 1.0 % by weight and 5.5% by weight.

[00046] In some exemplary embodiments, the total concentration of MgO and CaO is at least about 10 % by weight and no greater than about 22 % by weight, including between 12.0 % by weight and 20 % by weight, and between 14 % by weight and 19.5 % by weight.

[00047] The glass composition may include up to about 5.0 % by weight TiO_2. In some exemplary embodiments, the glass composition includes 0 % by weight to about 4.0 % by weight TiO_2, including about 0.01 % by weight to about 3.5 % by weight and about 0.1 to about 0.75 % by weight.

[00048] The glass composition may include up to about 1.0 % by weight Fe_2O_3. In some exemplary embodiments, the glass composition includes 0% by weight to about 0.8 % by weight Fe_2O_3, including about 0.01 % by weight to about 0.6 % by weight and about 0.1 to about 0.35 % by weight.

[00049] The glass composition may include up to about 5.0 % by weight Li_2O. In some exemplary embodiments, the glass composition includes about 0.0 % by weight to about 4.0 % by weight Li_2O, including about 0.1 % by weight to about 3.5 % by weight and about 0.5 to about 3.0 % by weight. In some exemplary embodiments, the glass composition includes about 1.0 to about 4.0 wt.% Li_2O, or about 1.5 to about 3.8 wt.% Li_2O.

[00050] In some exemplary embodiments, the glass composition includes less than about 2.0 % by weight of the alkali metal oxides Na_2O and K_2O, including between 0 and about 1.5 % by weight, between 0.05 and 0.75 % by weight, and between 0.1 and 0.3 % by weight. The glass composition may include both Na_2O and K_2O in an amount greater than about 0.01 % by weight of each oxide. In some exemplary embodiments, the glass composition includes about 0 to about 1 % by weight Na_2O, including about 0.01 to about 0.5 % by weight, about 0.03 to about 0.3 % by weight, and 0.04 to about 0.15 % by weight. In some exemplary embodiments, the glass composition includes about 0 to about 1 % by weight K_2O, including about 0.01 to about 0.5 % by weight, about 0.03 to about 0.3 % by weight, and 0.04 to about 0.15 % by weight. In some exemplary embodiments, the glass composition includes less than 1.0 % by weight K_2O, such as less than 0.75 % by weight, or less than 0.50 % by weight.

[00051] The glass composition may include up to about 1.5 % by weight ZrO_2. In some exemplary embodiments, the glass composition includes about 0.01 % by weight to about 1.0 % by weight ZrO_2, including about 0.05 % by weight to about 0.8 % by weight and about 0.1 to about 0.5 % by weight.

[00052] In some exemplary embodiments, the glass composition includes up to about 10.0 % by weight of the rare earth oxides Y_2O_3, La_2O_3, Ce_2O_3, and Sc_2O_3 ("R_2O_3"), including between 0 and 10.0 % by weight, or between 0.1 and 7.0 % by weight. The glass composition may include any of the R_2O_3 oxides in an amount greater than about 0.01 % by weight. In some exemplary embodiments, the glass composition includes about 0 to about 10 % by weight Y2O3, including about 0.01 to about 7.0 % by weight, about 0.05 to about 4.0 % by weight, and 0.8 to about 3.5 % by weight. In some exemplary embodiments, the glass composition includes about 0 to about 10 % by weight La2O3, including about 0.01 to about 4.0 % by weight, about 0.05 to about 3.5 % by weight, and 0.1 to about 3.0 % by weight. In some exemplary embodiments, the glass composition includes about 0 to about 2.5 % by weight Ce_2O_3, including about 0.01 to about 2.0 % by weight, about 0.05 to about 1.8 % by weight, and 0.1 to about 1.5 % by weight. In some exemplary

embodiments, the glass composition includes about 0 to about 4 % by weight Sc_2O_3, including about 0.01 to about 3.5 % by weight, about 0.05 to about 3.2 % by weight, and 0.1 to about 3.0 % by weight.

[00053] In some exemplary embodiments, the glass composition includes a total concentration of $CeO_2 + Sc_2O_3$ that is at least 1.0 % by weight, including at least 1.5 % by weight, at least 1.75 % by weight, at least 2.0 % by weight, at least 2.1 % by weight, at least 2.2 % by weight, and at least 2.5 % by weight.

[00054] The glass composition may include up to about 5.0 % by weight Ta_2O_5. In some exemplary embodiments, the glass composition includes about 0.01 % by weight to about 4.0 % by weight Ta_2O_5, including about 0.05 % by weight to about 3.5 % by weight and about 0.1 to about 3.0 % by weight.

[00055] The glass composition may include up to about 7.0 % by weight Ga_2O_3. In some exemplary embodiments, the glass composition includes about 0.01 % by weight to about 6.0 % by weight Ga_2O_3, including about 0.05 % by weight to about 5.5 % by weight and about 0.1 to about 5.0 % by weight.

[00056] The glass composition may include up to about 5.0 % by weight Nb_2O_5. In some exemplary embodiments, the glass composition includes about 0.01 % by weight to about 4.0 % by weight Nb_2O_5, including about 0.05 % by weight to about 3.5 % by weight and about 0.1 to about 3.0 % by weight.

[00057] The glass composition may include up to about 5.0 % by weight V_2O_5. In some exemplary embodiments, the glass composition includes about 0.01 % by weight to about 4.0 % by weight V_2O_5, including about 0.05 % by weight to about 3.5 % by weight and about 0.1 to about 3.0 % by weight.

[00058] The glass compositions may include up to about 1.0% by weight of Sm_2O_3 and/or Gd_2O_3. However, various exemplary embodiments limit the total concentration of Sm_2O_3 and Gd_2O_3 to less than 0.5% by weight, including less than 0.1% by weight, and less than 0.05% by weight.

[00059] The glass composition may include up to about 5.0 % by weight ZnO. In some exemplary embodiments, the glass composition includes 0 % by weight to about 2.5 % by weight ZnO, including about 0.01 % by weight to about 2.0% by weight and about 0.1 to about 1.0 % by weight.

[00060] The inventive glass compositions may be free or substantially free of B_2O_3 and fluorine, although any may be added in small amounts to adjust the fiberizing and finished glass properties

and will not adversely impact the properties if maintained below several percent. As used herein, substantially free of B_2O_3 and fluorine means that the sum of the amounts of B_2O_3 and fluorine present is less than 1.0 % by weight of the composition. The sum of the amounts of B_2O_3 and fluorine present may be less than about 0.5 % by weight of the composition, including less than about 0.2 % by weight, less than about 0.1 % by weight, and less than about 0.05 % by weight.

[00061] The glass compositions may further include impurities and/or trace materials without adversely affecting the glasses or the fibers. These impurities may enter the glass as raw material impurities or may be products formed by the chemical reaction of the molten glass with furnace components. Non-limiting examples of trace materials include strontium, barium, and combinations thereof. The trace materials may be present in their oxide forms and may further include fluorine and/or chlorine. In some exemplary embodiments, the inventive glass compositions contain no more than than about 1.0 % by weight, including less than 0.5 % by weight, less than 0.2 % by weight, and less than 0.1 % by weight of each of BaO, SrO, P_2O_5, and SO_3. Particularly, the glass composition may include less than about 5.0 % by weight of BaO, SrO, P_2O_5, and/or SO_3 combined, wherein each of BaO, SrO, P_2O_5, and SO_3 if present at all, is present in an amount of less than 1.0 % by weight.

[00062] In some exemplary embodiments, the glass composition comprises a ratio of MgO/(CaO+SrO) that is at least 1.5, including at least 1.7, at least 2.0, at least 2.1, at least 2.2, and at least 2.3.

[00063] As used herein, the terms “weight percent,” “% by weight,” “wt.%,” and “percent by weight” may be used interchangeably and are meant to denote the weight percent (or percent by weight) based on the total composition.

[00064] As indicated above, the inventive glass compositions unexpectedly demonstrate an optimized specific modulus, while maintaining desirable forming properties.

[00065] The fiber tensile strength is also referred herein simply as “strength.” In some exemplary embodiments, the tensile strength is measured on pristine fibers (*i.e.*, unsized and untouched laboratory produced fibers) using an Instron tensile testing apparatus according to ASTM D2343-09. Exemplary glass fibers formed form the above described inventive glass composition may have a fiber tensile strength of at least about 3,500 MPa, including at least 4,000 MPa, at least 4,400 MPa, at least 4,500 MPa, at least 4,800 MPa, at least 4,900 MPa, at least 4,950 MPa, at least 5,000 MPa, at least 5,100 MPa, at least 5,150 MPa, and at least 5,200 MPa. In some exemplary

embodiments, the glass fibers formed from the above described composition have a fiber tensile strength of from about 3500 to about 5500 MPa, including about 4000 MPa to about 5,350 MPa, about 4,600 to about 5,315 MPa. Advantageously, the combination of compositional parameters disclosed herein makes it possible to produce glass fibers having tensile strengths of at least about 4,800 MPa, including at least 4,900 MPa, and at least 5,000, which has not yet been achieved by the prior art with a glass composition having desirable fiberizing properties.

[00066] The elastic modulus of a glass fiber may be determined by taking the average measurements on five single glass fibers measured in accordance with the sonic measurement procedure outlined in the report "Glass Fiber Drawing and Measuring Facilities at the U.S. Naval Ordnance Laboratory", Report Number NOLTR 65-87, June 23, 1965.

[00067] The exemplary glass fibers formed from the inventive glass composition may have an elastic modulus of at least about 85 GPa, including at least about 88 GPa, at least about 88.5 GPa, at least about 89 GPa, and at least about 89.5 GPa. In some exemplary embodiments, the exemplary glass fibers formed from the inventive glass composition have an elastic modulus of between about 85 GPa and about 115 GPa, including between about 87 GPa and about 100 GPa, and between about 88 GPa and about 98 GPa.

[00068] The elastic modulus may then be used to determine the specific modulus. It is desirable to have a specific modulus as high as possible to achieve a lightweight composite material that adds stiffness to the final article. Specific modulus is important in applications where stiffness of the product is an important parameter, such as in wind energy and aerospace applications. As used herein, the specific modulus is calculated by the following equation:

$$\text{Specific Modulus (MJ/kg)} = \text{Modulus (GPa)}/\text{Density (kg/cubic meter)}$$

[00069] The exemplary glass fibers formed from the inventive glass composition has an optimized specific modulus of about 33.0 MJ/kg to about 40.0 MJ/kg, including about 34.5 MJ/kg to about 37 MJ/kg, and about 35.8 MJ/kg to about 36.5 MJ/kg.

[00070] The density may be measured by any method known and commonly accepted in the art, such as the Archimedes method (ASTM C693-93(2008)) on unannealed bulk glass. The glass fibers have a density of from about 2.0 to about 3.0 g/cc. In other exemplary embodiments, the glass fibers have a density of from about 2.3 to about 2.8 g/cc, including from about 2.4 to about 2.78 g/cc, and about 2.49 to about 2.75 g/cc.

[00071] According to some exemplary embodiments, a method is provided for preparing glass fibers from the glass composition described above. The glass fibers may be formed by any means known and traditionally used in the art. In some exemplary embodiments, the glass fibers are formed by obtaining raw ingredients and mixing the ingredients in the appropriate quantities to give the desired weight percentages of the final composition. The method may further include providing the inventive glass composition in molten form and drawing the molten composition through orifices in a bushing to form a glass fiber.

[00072] The components of the glass composition may be obtained from suitable ingredients or raw materials including, but not limited to, sand or pyrophyllite for SiO_2, limestone, burnt lime, wollastonite, or dolomite for CaO, kaolin, alumina or pyrophyllite for Al_2O_3, dolomite, dolomitic quicklime, brucite, enstatite, talc, burnt magnesite, or magnesite for MgO, and sodium carbonate, sodium feldspar or sodium sulfate for the Na_2O. In some exemplary embodiments, glass cullet may be used to supply one or more of the needed oxides.

[00073] The mixed batch may then be melted in a furnace or melter and the resulting molten glass is passed along a forehearth and drawn through the orifices of a bushing located at the bottom of the forehearth to form individual glass filaments. In some exemplary embodiments, the furnace or melter is a traditional refractory melter. By utilizing a refractory tank formed of refractory blocks, manufacturing costs associated with the production of glass fibers produced by the inventive composition may be reduced. In some exemplary embodiments, the bushing is a platinum alloy-based bushing. Strands of glass fibers may then be formed by gathering the individual filaments together. The fiber strands may be wound and further processed in a conventional manner suitable for the intended application.

[00074] The operating temperatures of the glass in the melter, forehearth, and bushing may be selected to appropriately adjust the viscosity of the glass, and may be maintained using suitable methods, such as control devices. The temperature at the front end of the melter may be automatically controlled to reduce or eliminate devitrification. The molten glass may then be pulled (drawn) through holes or orifices in the bottom or tip plate of the bushing to form glass fibers. In accordance with some exemplary embodiments, the streams of molten glass flowing through the bushing orifices are attenuated to filaments by winding a strand formed of a plurality of individual filaments on a forming tube mounted on a rotatable collet of a winding machine or

chopped at an adaptive speed. The glass fibers of the invention are obtainable by any of the methods described herein, or any known method for forming glass fibers.

[00075] The fibers may be further processed in a conventional manner suitable for the intended application. For instance, in some exemplary embodiments, the glass fibers are sized with a sizing composition known to those of skill in the art. The sizing composition is in no way restricted, and may be any sizing composition suitable for application to glass fibers. The sized fibers may be used for reinforcing substrates such as a variety of plastics where the product's end use requires high strength and stiffness and low weight. Such applications include, but are not limited to, woven fabrics for use in forming wind turbine blades; infrastructure, such as reinforcing concrete, bridges, etc.; and aerospace structures.

[00076] In this regard, some exemplary embodiments of the present invention include a composite material incorporating the inventive glass fibers, as described above, in combination with a hardenable matrix material. This may also be referred to herein as a reinforced composite product. The matrix material may be any suitable thermoplastic or thermoset resin known to those of skill in the art, such as, but not limited to, thermoplastics such as polyesters, polypropylene, polyamide, polyethylene terephthalate, and polybutylene, and thermoset resins such as epoxy resins, unsaturated polyesters, phenolics, vinylesters, and elastomers. These resins may be used alone or in combination. The reinforced composite product may be used for wind turbine blade, rebar, pipe, filament winding, muffler filling, sound absorption, and the like.

[00077] In accordance with further exemplary embodiments, the invention provides a method of preparing a composite product as described above. The method may include combining at least one polymer matrix material with a plurality of glass fibers. Both the polymer matrix material and the glass fibers may be as described above.

EXAMPLES

[00078] Exemplary glass compositions according to the present invention were prepared by mixing batch components in proportioned amounts to achieve a final glass composition with the oxide weight percentages set forth in Tables 1-8, below.

[00079] The raw materials were melted in a platinum crucible in an electrically heated furnace at a temperature of 1,650 °C for 3 hours.

[00080] The fiberizing temperature was measured using a rotating cylinder method as described in ASTM C965-96(2007), entitled "Standard Practice for Measuring Viscosity of Glass Above the

Softening Point," the contents of which are incorporated by reference herein. The liquidus temperature was measured by exposing glass to a temperature gradient in a platinum-alloy boat for 16 hours, as defined in ASTM C829-81(2005), entitled "Standard Practices for Measurement of Liquidus Temperature of Glass," the contents of which are incorporated by reference herein. Density was measured by the Archimedes method, as detailed in ASTM C693-93(2008), entitled "Standard Test Method for Density of Glass Buoyancy," the contents of which are incorporated by reference herein.

[00081] The specific modulus was calculated by dividing the measured modulus in units of GPa by the density in units of kg/m^3.

[00082] The strength was measured on pristine fibers using an Instron tensile testing apparatus according to ASTM D2343-09 entitled, "Standard Test Method for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics," the contents of which are incorporated by reference herein.

TABLE 1

Component	**Ex. 1 (% by wt.)**	**Ex. 2 (% by wt.)**	**Ex. 3 (% by wt.)**	**Ex. 4 (% by wt.)**	**Ex. 5 (% by wt.)**	**Ex. 6 (% by wt.)**
SiO_2	60.00	64.00	65.00	64.50	63.00	63.50
Al_2O_3	22.00	21.00	21.00	20.50	21.00	20.50
MgO	14.0	12.00	12.00	12.00	12.00	12.00
CaO	0.00	1.00	0.00	1.00	2.00	2.00
Li_2O	4.00	2.00	2.00	2.00	2.00	2.00
Fe_2O_3	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00
TiO_2	0.00	0.00	0.0	0.00	0.00	0.00
Property						
Fiberizing Temperature (°F)	2258	2481	2520	2510	2459	2456

Liquidus Temperature (°F)	2262	2267	2434	2381	2341	2330
ΔT (°F)	-4	115	86	123	119	126
Density (g/cc)	2.540	2.517	2.495	2.522	2.529	2.564
Elastic Modulus (GPa)	92.4	91.4	90.5	91.4	91.6	92.0
Specific Modulus (MJ/kg)	36.40	36.30	36.3	36.3	36.2	36.1
Strength (MPa)	4936	5132	4923	5315	5224	5186

TABLE 2

Component	**Ex. 7 (% by wt.)**	**Ex. 8 (% by wt.)**	**Example 9 (% by wt.)**	**Example 10 (% by wt.)**	**Example 11 (% by wt.)**
SiO_2	62.00	59.00	62.4	62.50	65.50
Al_2O_3	21.00	22.0	20.30	20.50	20.50
MgO	12.00	12.00	12.00	12.00	12.00
CaO	3.00	3.00	3.30	3.00	0.00
Li_2O	2.00	2.00	2.00	2.00	2.00
Fe_2O_3	0.00	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.00
Na_2O	0.00	0.00	0.00	0.00	0.00
TiO_2	0.00	2.00	0.00	0.00	0.00
Property					
Fiberizing Temperature (°F)	2420	2321	2388	2398	2499

Liquidus Temperature (°F)	2310	2316	2268	2281	2407
ΔT (°F)	111	6	121	117	93
Density (g/cc)	2.545	2.571	2.540	2.543	2.494
Elastic Modulus (GPa)	91.9	92.8	91.6	91.6	89.7
Specific Modulus (MJ/kg)	36.1	36.1	36.0	36.0	36.0
Strength (MPa)	5234	5035	5026	5197	5018

TABLE 3

Component	**Example 12 (% by wt.)**	**Example 13 (% by wt.)**	**Example 14 (% by wt.)**	**Example 15 (% by wt.)**	**Example 16 (% by wt.)**
SiO_2	59.95	60.00	61.20	60.50	61.00
Al_2O_3	19.45	20.5	19.85	20.50	20.50
MgO	11.15	12.00	9.82	12.00	12.00
CaO	5.13	1.50	5.23	1.50	2.50
Li_2O	1.85	2.00	1.89	2.00	2.00
Fe_2O_3	0.00	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.00
Na_2O	0.00	0.00	0.00	0.00	0.00
TiO_2	0.00	0.00	0.00	0.00	0.00
Sc_2O_3	4.00	0.00	2.00	0.00	0.00
Y_2O_3	0.00	3.00	0.00	3.50	0.00
ZrO_2	0.00	1.00	0.00	0.00	0.00
Nb_2O_5	0.00	0.00	0.00	0.00	2.00

La_2O_3	0.00	0.00	0.00	0.00	0.00
Ga_2O_3	0.00	0.00	0.00	0.00	0.00
Property					
Fiberizing Temperature (°F)	2350	2355	2381	2367	2356
Liquidus Temperature (°F)	2405	2310	2235	2308	2317
ΔT (°F)	176	45	146	59	40
Density (g/cc)	2.602	2.600	2.577	2.593	2.558
Elastic Modulus (GPa)	93.5	93.1	92.2	92.8	91.3
Specific Modulus (MJ/kg)	35.9	35.8	35.8	35.8	35.7
Strength (MPa)	4818	4984	5056	5058	----

TABLE 4

Component	**Example 17 (% by wt.)**	**Example 18 (% by wt.)**	**Example 19 (% by wt.)**	**Example 20 (% by wt.)**	**Example 21 (% by wt.)**
SiO_2	50.89	61.00	61.00	60.0	61.83
Al_2O_3	22.92	20.5	20.5	20.0	20.06
MgO	12.46	12.0	12.00	12.00	9.92
CaO	4.47	2.50	2.50	2.00	5.29
Li_2O	2.20	2.00	2.00	2.00	1.91
Fe_2O_3	0.01	0.00	0.00	0.00	0.00

K_2O	0.01	0.00	0.00	0.00	0.00
Na_2O	0.03	0.00	0.00	0.00	0.00
TiO_2	0.01	0.00	0.00	0.00	0.00
Sc_2O_3	0.00	0.00	0.00	0.00	0.00
Y_2O_3	5.49	0.00	0.00	0.00	0.00
ZrO_2	0.00	0.00	0.00	1.00	1.00
Nb_2O_5	0.00	0.00	0.00	0.00	0.00
La_2O_3	1.50	0.00	0.00	0.00	0.00
Ga_2O_3	0.00	2.00	0.00	0.00	0.00
Ta_2O_5	0.00	0.00	2.00	0.00	0.00
V_2O_5	0.00	0.00	0.00	0.00	0.00
Property					
Fiberizing Temperature (˚F)	2193	2375	2380	2371	2443
Liquidus Temperature (˚F)	2217	2299	2287	2321	2230
ΔT (˚F)	-24	77	94	50	213
Density (g/cc)	2.744	2.562	2.571	2.596	2.559
Elastic Modulus (GPa)	98.0	91.3	91.6	92.3	92.3
Specific Modulus (MJ/kg)	35.7	35.6	35.6	35.5	35.5
Strength (MPa)	-----	-----	---	----	5016

TABLE 5

Component	Example 22 (% by wt.)	Example 23 (% by wt.)	Example 24 (% by wt.)	Example 25 (% by wt.)	Example 26 (% by wt.)
SiO_2	58.00	61.00	63.50	64.00	60.00
Al_2O_3	20.00	20.50	20.50	21.00	20.50
MgO	12.00	12.00	11.70	11.70	12.00
CaO	2.00	2.50	4.00	3.00	1.50
Li_2O	2.00	2.00	0.00	0.00	2.00
Fe_2O_3	0.00	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.00
Na_2O	0.00	0.00	0.30	0.30	0.00
TiO_2	0.00	0.00	0.00	0.00	0.00
Sc_2O_3	0.00	0.00	0.00	0.00	0.00
Y_2O_3	4.00	0.00	0.00	0.00	0.00
ZrO_2	0.00	0.00	0.00	0.00	1.00
Nb_2O_5	0.00	0.00	0.00	0.00	0.00
La_2O_3	3.00	0.00	0.00	0.00	3.00
Ga_2O_3	0.00	2.00	0.00	0.00	0.00
Ta_2O_5	3.00	0.00	2.00	0.00	0.00
V_2O_5	0.00	2.00	0.00	0.00	0.00
Property					
Fiberizing Temperature (˚F)	2326	2360	2545	2573	2360
Liquidus Temperature (˚F)	2248	2311	2454	2490	2289
ΔT (˚F)	79	49	92	84	71
Density (g/cc)	2.656	2.540	2.536	2.520	2.597

Elastic Modulus (GPa)	94.3	90.2	89.7	89.1	91.8
Specific Modulus (MJ/kg)	35.5	35.5	35.4	35.4	35.4
Strength (MPa)	4919	-----	---	----	4953

TABLE 6

Component	**Example 27 (% by wt.)**	**Example 28 (% by wt.)**	**Example 29 (% by wt.)**	**Example 30 (% by wt.)**	**Example 31 (% by wt.)**
SiO_2	61.00	61.00	58.00	60.50	61.00
Al_2O_3	20.00	20.00	20.00	20.50	20.00
MgO	11.50	11.50	12.00	12.00	11.50
CaO	2.00	2.00	2.00	1.50	2.00
Li_2O	1.50	1.50	2.00	2.00	1.50
Fe_2O_3	0.00	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.00
Na_2O	0.00	0.00	0.00	0.00	0.00
TiO_2	0.00	0.00	0.00	0.00	0.00
Sc_2O_3	0.00	0.00	0.00	0.00	0.00
Y_2O_3	0.00	0.00	3.00	0.00	0.00
ZrO_2	0.00	0.00	0.00	0.00	0.00
Nb_2O_5	4.00	0.00	0.00	0.00	0.00
La_2O_3	3.00	0.00	0.00	0.00	0.00
Ga_2O_3	0.00	4.00	0.00	0.00	0.00
Ta_2O_5	3.00	0.00	3.00	0.00	4.00
V_2O_5	0.00	2.00	0.00	0.00	0.00
Property					

Fiberizing Temperature (˚F)	2404	2423	2319	2367	2380
Liquidus Temperature (˚F)	2264	2376	2256	2310	2374
ΔT (˚F)	41	48	63	57	7
Density (g/cc)	2.570	2.577	2.651	2.597	2.593
Elastic Modulus (GPa)	90.9	91.9	93.7	91.7	91.5
Specific Modulus (MJ/kg)	35.4	35.3	35.3	35.3	35.3
Strength (MPa)	----	-----	4929	4959	----

TABLE 7

Component	**Example 32 (% by wt.)**	**Example 33 (% by wt.)**	**Example 34 (% by wt.)**	**Example 35 (% by wt.)**	**Example 36 (% by wt.)**
SiO_2	60.26	57.33	61.20	61.20	58.00
Al_2O_3	19.55	19.61	19.85	19.85	20.00
MgO	9.67	10.94	9.82	9.82	11
CaO	5.15	8.83	5.23	5.23	3.00
Li_2O	1.87	2.00	1.89	1.89	2.00
Fe_2O_3	0.00	0.34	0.00	0.00	0.00
K_2O	0.00	0.13	0.00	0.00	0.00
Na_2O	0.00	0.12	0.00	0.00	0.00

TiO_2	0.00	0.68	2.00	0.00	0.00
CeO_2	0.00	0.00	0.00	2.00	0.00
Sc_2O_3	0.00	0.00	0.00	0.00	0.00
Y_2O_3	3.50	0.00	0.00	0.00	3.00
ZrO_2	0.00	0.00	0.00	0.00	1.00
Nb_2O_5	0.00	0.00	0.00	0.00	0.00
La_2O_3	0.00	0.00	0.00	0.00	2.00
Ga_2O_3	0.00	0.00	0.00	0.00	0.00
Ta_2O_5	0.00	0.00	0.00	0.00	0.00
V_2O_5	0.00	0.00	0.00	0.00	0.00
Property					
Fiberizing Temperature (°F)	2378	2236	2359	2391	2323
Liquidus Temperature (°F)	2191	2190	2330	2242	2222
ΔT (°F)	188	47	30	149	101
Density (g/cc)	2.607	2.620	2.565	2.580	2.649
Elastic Modulus (GPa)	92.0	92.4	90.4	90.6	93.0
Specific Modulus (MJ/kg)	35.3	35.3	35.2	35.1	35.1
Strength (MPa)	4927	-----	4898	5021	----

TABLE 8

Component	Example 37 (% by wt.)	Example 38 (% by wt.)	Example 39 (% by wt.)	Example 40 (% by wt.)	Example 41 (% by wt.)	Comparative Example
SiO_2	59.95	61.00	55.50	58.08	59.50	60.70
Al_2O_3	19.45	20.00	21	18.84	20.00	15.80
MgO	9.62	11.50	11.00	9.32	11.00	8.00
CaO	5.13	2.00	3.50	4.97	2.00	13.40
Li_2O	1.85	1.50	2.00	1.79	1.50	0.75
Fe_2O_3	0.00	0.00	0.00	0.00	0.00	0.27
K_2O	0.00	0.00	0.00	0.00	0.00	0.10
Na_2O	0.00	0.00	0.00	0.00	0.00	0.23
TiO_2	4.00	0.00	0.00	0.00	0.00	0.48
Sc_2O_3	0.00	0.00	0.00	0.00	0.00	----
Y_2O_3	0.00	0.00	4.00	7.00	0.00	----
ZrO_2	0.00	0.00	0.00	0.00	0.00	----
Nb_2O_5	0.00	0.00	0.00	0.00	0.00	----
La_2O_3	0.00	0.00	3.00	0.00	0.00	----
Ga_2O_3	0.00	2.00	0.00	0.00	6.00	----
Ta_2O_5	0.00	0.00	0.00	0.00	0.00	----
V_2O_5	0.00	4.00	0.00	0.00	0.00	----
Property						----
Fiberizing Temperature (°F)	2350	2392	2277	2338	2403	2324
Liquidus Temperature (°F)	2241	2346	2293	2130	2380	2140
ΔT (°F)	110	47	-16	208	28	184

Density (g/cc)	2.581	2.533	2.690	2.673	2.605	2.614
Elastic Modulus (GPa)	90.6	88.9	94.1	93.5	91.0	87.5
Specific Modulus (MJ/kg)	35.1	35.1	35.0	35.0	35.0	33.5
Strength (MPa)	4719	-----	---	4830		4637

[00083] Tables 1-8 illustrate the improvement in specific modulus that the inventive glass compositions have over commercial high-performance glass (Comparative Example). The Comparative Example demonstrates a specific modulus of 33.5 MJ/kg, which is below the minimum specific modulus seen from any of the inventive compositions. Instructively, each of the inventive compositions demonstrate a specific modulus of at least 34 MJ/kg, and more specifically at least 35 MJ/kg.

[00084] The invention of this application has been described above both generically and with regard to specific embodiments. Although the invention has been set forth in what is believed to be the preferred embodiments, a wide variety of alternatives known to those of skill in the art can be selected within the generic disclosure. The invention is not otherwise limited, except for the recitation of the claims set forth below.

CLAIMS

1. A glass composition comprising:

SiO_2 in an amount from 58.0 to 68.0 % by weight;

Al_2O_3 in an amount from 18.0 to 23.0% by weight;

CaO in an amount from 1.0 to 9.0% by weight;

MgO in an amount from 9.0 to 14.0% by weight;

SrO in an amount from 0.0 to 1.0% by weight;

Na_2O in an amount from 0.0 to 1.0% by weight;

K_2O in an amount from 0.0 to < 1.0% by weight;

Li2O in an amount from 0.0 to 4.0% by weight;

TiO_2 in an amount from 0.0 to 4.0 % by weight,

Y_2O_3 in an amount from 0 to 10.0 % by weight;

La_2O_3 in an amount from 0 to 10.0 % by weight;

Ce_2O_3 in an amount from 0 to 2.5 % by weight; and

Sc_2O_3 in an amount from 0 to 4.0 % by weight, wherein the glass composition has a ratio MgO/(CaO+SrO) of greater than 2.1, and a glass fiber formed from said glass composition has specific modulus between 34.0 and 40.0 MJ/kg.

2. The glass composition of claim 1, further including:

0 to about 5.0 % by weight Ta_2O_5;

0 to about 7.0 % by weight Ga_2O_3;

0 to about 5.0 % by weight Nb_2O_5, and

0 to about 5.0 % by weight V_2O_5.

3. The glass composition of claim 2, wherein said composition includes 1.0 to 3.5% by weight Y_2O_3.

4. The glass composition according to any one of claims 1 to 3, wherein the combined amounts of MgO and CaO is between 12.0 and 20% by weight.

5. The glass composition according to any one of claims 1 to 4, wherein said composition comprises 18.3 to 22.0 % by weight Al_2O_3.

6. The glass composition according to any one of claims 1 to 5, wherein said composition is essentially free of one or more of B_2O_3, F, K_2O, and Na_2O.

7. The glass composition according to any one of claims 1 to 6, wherein said composition comprises 0.1 to 3.5% by weight Li_2O.

8. The glass composition according to any one of claims 1 to 7, wherein said composition comprises less than 0.05% by weight of Sm_2O_3+Gd_2O_3.

9. The glass composition according to any one of claims 1 to 8, wherein the composition includes at least 1% by weight of a combined amount of Y_2O_3, La_2O_3, Ce_2O_3, and Sc_2O_3.

10. The glass composition according to any of claims 1 to 9, wherein the composition has a fiberizing temperature less than 2,650 °F.

11. A glass fiber formed from a composition comprising:
SiO_2 in an amount from 55.0 to 68.0 % by weight;
Al_2O_3 in an amount from 18.0 to 23.0% by weight;
CaO in an amount from 1 to 5.5% by weight;
MgO in an amount from 9.0 to 14.0% by weight;
Na_2O in an amount from 0.0 to 1.0% by weight;
K_2O in an amount from 0.0 to 1.0% by weight;
Li_2O in an amount from greater than 1.0 to 4.0% by weight;
TiO_2 in an amount from 0.0 to 4.0 % by weight,
Y_2O_3 in an amount from 0 to 10.0 % by weight;
La_2O_3 in an amount from 0 to 10.0 % by weight;
Ce_2O_3 in an amount from 0 to 2.5 % by weight; and

Sc_2O_3 in an amount from 0 to 4.0 % by weight, wherein the glass fiber has specific modulus between 34.0 and 40.0 MJ/kg and a tensile strength according to ASTM D2343-09 of at least 4400 MPa.

12. The glass fiber according to claim 11, wherein the glass composition comprises 1.0 to 5.0 % by weight CaO.

13. The glass fiber according to any one of claims 11 to 12, wherein said composition is essentially free of one or more of B_2O_3, F, K_2O, and Na_2O.

14. The glass fiber according to any one of claims 11 to 13, wherein said composition comprises 1.5 to 3.5% by weight Li_2O.

15. The glass fiber according to any one of claims 11 to 14, wherein the composition includes at least 1% by weight of a combined amount of Y_2O_3, La_2O_3, Ce_2O_3, and Sc_2O_3.

16. The glass fiber according to any one of claims 11 to 15, wherein the composition includes greater than 2.0 wt.% CeO_2+Sc_2O_3.

17. A glass fiber according to any one of claims 11 to 16, wherein said glass fiber has a specific modulus of 35 to 36.5 MJ/kg.

18. A method of forming a continuous glass fiber comprising:
providing a molten composition according to claim 1; and
drawing said molten composition through an orifice to form a continuous glass fiber.

19. A reinforced composite product comprising;
a polymer matrix; and
a plurality of glass fibers formed from a glass composition comprising:
SiO_2 in an amount from 58.0 to 68.0 % by weight;
Al_2O_3 in an amount from 18.0 to 23.0% by weight;

CaO in an amount from 1.0 to 9.0% by weight;

MgO in an amount from 9.0 to 14.0% by weight;

SrO in an amount from 0.0 to 1.0% by weight;

Na_2O in an amount from 0.0 to 1.0% by weight;

K_2O in an amount from 0.0 to < 1.0% by weight;

Li2O in an amount from 0.0 to 4.0% by weight;

TiO_2 in an amount from 0.0 to 4.0 % by weight,

Y_2O_3 in an amount from 0 to 10.0 % by weight;

La_2O_3 in an amount from 0 to 10.0 % by weight;

Ce_2O_3 in an amount from 0 to 2.5 % by weight; and

Sc_2O_3 in an amount from 0 to 4.0 % by weight, wherein the glass composition has a ratio MgO/(CaO+SrO) of greater than 2.1, and the glass fibers have specific modulus between 34.0 and 40.0 MJ/kg.

20. A reinforced composite product according to claim 19, wherein said reinforced composite product is in the form of a wind turbine blade.