Optimal Conditions and Significant Factors of Soda Lime Glass Foam From Industrial Waste Using AlN

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GLASS PRODUCTION OVERVIEW

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Glass

- Glass is an amorphous solid, revealing an ionic character, with properties resembling a very viscous liquid. Its non-metallic network structure is based on silica (SiO$_2$), that is bonded together with metal oxides that act as "network modifiers".
- It is a hard, usually brittle and transparent substance, composed chiefly of silicates and an alkali metal fused at high temperatures. Metallic oxides impart colour.
- It is resistant to attack by most chemicals (except for hydrofluoric acid). The inert properties make it ideal for the storage and transport of most food and liquids.
### Main Glass Types Based Physiochemical Composition

<table>
<thead>
<tr>
<th></th>
<th>Soda-lime glass</th>
<th>Lead crystal glass</th>
<th>Borosilicate glass</th>
<th>E glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siliceous dioxide</td>
<td>71-75%</td>
<td>54-65%</td>
<td>70-80%</td>
<td>52-56%</td>
</tr>
<tr>
<td>(SiO₂)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boron trioxide</td>
<td></td>
<td></td>
<td>7-15%</td>
<td>0-10%</td>
</tr>
<tr>
<td>(B₂O₃)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead oxide (PbO)</td>
<td></td>
<td>25-30%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soda (Na₂O) or Potassium oxide (K₂O)</td>
<td>12-16%</td>
<td>13-15%</td>
<td>4-8%</td>
<td>0-2%</td>
</tr>
<tr>
<td>Lime (CaO)</td>
<td>10-15%</td>
<td></td>
<td>16-25%</td>
<td></td>
</tr>
<tr>
<td>Aluminium trioxide (Al₂O₃)</td>
<td>7%</td>
<td></td>
<td>12-16%</td>
<td></td>
</tr>
</tbody>
</table>

Soda-Lime Glass Composition

Glass industry mainly produces “soda-lime” glass. It is composed of:

- 71-75% silicon dioxide (SiO₂ derived mainly from sand)
- 12-16% sodium oxide (Na₂O derived from soda ash - Na₂CO₃)
- 10-15% calcium oxide (lime, CaO, derived from limestone - CaCO₃)
- Low levels of other components

Sodium carbonate (Na₂CO₃, “soda”) is added to lower the melting point of silica to about 1500 °C.

Additives used to improve the chemical durability of the glass,
- Calcium oxide (CaO, ‘lime’), magnesium oxide (MgO) and aluminium oxide (Al₂O₃) are added.

Major applications of Soda-lime glass
- Container glass (packaging bottles, jars),
- Flat glass (windows of buildings, automotives) and
- Domestic glass (drinkware, dishes)
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Production Line_Schematic Diagram

- Batch Preparation
  - Batch preheating
  - Grinding optimization
  - New grinding equipment
  - Fluxing agents
  - Minimum batch wetting
  - Selective batching
  - ASDs for belts
  - All measures

- Melting & Refining
  - Bubbling
  - Vertical furnace
  - Low-NOx burners
  - High-luminosity burners
  - Top-heating
  - Electrode placement
  - ASDs for combustion fans
  - All measures

- General Measures
  - Compressed air system optimization
  - Motor system optimization

- Conditioning & Forming
  - Efficient forehearts
  - Oxy-fuel fired forehearts
  - Tin bath temp. control
  - All measures

- Finishing
  - Process control
  - Plant layout optimization
  - Minimizing air leakage to lehr
  - Insulation
  - Product drying system upgrade
  - Microwave coating system
World Glass Production in 2007, 138 million tons

- **Container**: 48.9%
- **Flat**: 32.3%
- **Automotive Glass**: 10%
- **Solar Glass**: 0.7%
- **Building Windows**: 70%
- **Furniture & Internal Glass**: ~19%

**Glass Market**: 136mt

**Flat Glass Market**: 44mt
Classifications Based on the Six Broad Sectors of the Glass Manufacturing Industry

(1) Container glass or packaging glass (~56%):
- Bottles and
- Other containers (for packaging of food, drinks, pharmaceuticals, cosmetics, etc.).

(2) Flat glass (Mainly windows in buildings and vehicles) (~25%):
The flat glass products can be roughly categorized into two types:

**Float glass**
It is used for a huge number of applications including glazing for building and transportation, industrial applications, electronics, furniture, appliances, etc.

**Rolled glass**
It is used principally in the manufacture of glass doors, partitions, shower enclosures, and photovoltaic panels.
Classifications Based on the Six Broad Sectors of the Glass Manufacturing Industry Cont.

(3) Continuous filament glass fibres (~2%):
• Supplied in a variety of forms such as mat, chopped strand, roving, yarn, tissue or milled fibre.
• The main end use (approximately 75%) is the reinforcement for many polymer materials.
• The main markets for the resulting composite materials are the building industry, the automotive and transport sectors, and the electrical and electronics industry. Continuous-filament glass fibres are predominantly made of E glass.

(4) Domestic glass, also called tableware (~4%):
• Used for tableware, glassware, decorative glass, etc.
• Most important components are soda-lime, lead crystal, crystal glass, and opaque and glass ceramics.

(5) Insulation mineral wool (~10%):
• Insulation mineral wool is made of short fibres of glass (typically borosilicate glass or alkaline earth - alumina - silicate stonewool) and ceramic materials. It is used for insulation, filtering and firestop applications.

(6) Special glass (<3%)
### Sectors of Glass Industry, Applications, Types

<table>
<thead>
<tr>
<th>Glass manufacturing sector</th>
<th>Application or use</th>
<th>Type of glass</th>
<th>Production in the EU-27 in 2007</th>
<th>Share of total production</th>
</tr>
</thead>
</table>
| Container glass or packaging glass | ▪ 75% beverage packaging  
▪ 20% other food packaging  
▪ 5% packaging cosmetics, pharmaceuticals and technical products | Soda-lime glass | ~21 Mt | ~56% |
| Flat glass | ▪ 95% float glass:  
  ▪ 75-85% buildings industry  
  ▪ 15-25% automotive industry  
  ▪ 5% rolled glass (wired or patterned) | Soda-lime glass | ~9.5 Mt | ~25% |
| Continuous filament glass fibre | ▪ Roving, mat, chopped strand, textile, tissue, milled fibre (90% used for composite materials) | E glass | ~0.7 Mt | ~2% |
| Domestic glass | ▪ Tableware, cookware, vases, ornaments | Soda-lime glass, lead glass | ~1.5 Mt | ~4% |
| Mineral wool | ▪ Insulation material | Borosilicate glass | ~3.7 Mt | ~10% |
| Special glass (CRT not produced in EU anymore) | ▪ 75% monitor glass  
▪ 25% light bulbs/tubes, ceramic glass, high-temperature domestic glass | Soda-lime, borosilicate glasses | ~1 Mt | ~3% |
| Total | | | ~37.4 Mt | |

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GLASS WASTE OVERVIEW
### Statics on EU-27 Glass Production, & Waste Glass Generation, Collection, and Recycling (2007)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Container glass or packaging glass</td>
<td>~21 Mt</td>
<td>~17 Mt</td>
<td>~11 Mt</td>
<td>~8 Mt</td>
</tr>
<tr>
<td>Flat glass</td>
<td>~9.5 Mt</td>
<td>~5.1 Mt</td>
<td>~2.9 Mt</td>
<td>~2.9 Mt</td>
</tr>
<tr>
<td>Domestic glass (tableware)</td>
<td>~1.5 Mt</td>
<td>~0.8 Mt</td>
<td>~0.5 Mt</td>
<td>~0.5 Mt</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>~3.7 Mt</td>
<td>~2.0 Mt</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Continuous filament glass fibre</td>
<td>~0.7 Mt</td>
<td>~0.4 Mt</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Special glass</td>
<td>~1 Mt</td>
<td>~0.5 Mt</td>
<td>~0.45 Mt</td>
<td>~0.40 Mt</td>
</tr>
<tr>
<td>Total</td>
<td>~37.4 Mt</td>
<td>~25.8 Mt</td>
<td>~14.85 Mt</td>
<td>~11.8 Mt</td>
</tr>
</tbody>
</table>
Classification of **WASTE** Glass According to European Waste Catal

- Glass packaging and other waste glass from municipal/commercial/industrial sources (II) 67%
- End-of-life vehicles (ELV) waste glass (V) 1%
- Mixed municipal solid waste and bulky waste (I) 20%
- Construction & Demolition waste glass (III) 5%
- Industrial sources (IV) 7%

Utilisation or Incorporation Rate
D/A = 32%

Recycling Rate
D/B = 46%

Collection Rate
C/B = 58%

B/A = 86.9 %

Glass Recycling
D = 11.8 Mt
Landfill disposal + net extra-EU exports of cullet (-0.02 Mt)

Waste Glass Collection
C = 14.85 Mt

Waste Glass Generation
B = 25.8 Mt
Landfill disposal
Long-life glass products + net extra-EU exports of glass products (-0.1 Mt)

Glass Production
A = 37.4 Mt

## Glass Waste Composition

<table>
<thead>
<tr>
<th>Compound</th>
<th>Composition, Wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_2$O</td>
<td>23.745</td>
</tr>
<tr>
<td>MgO</td>
<td>11.361</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>1.015</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>55.641</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.014</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>0.23</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.01</td>
</tr>
<tr>
<td>CaO</td>
<td>7.797</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.04</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>0.084</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.019</td>
</tr>
<tr>
<td>SrO</td>
<td>0.008</td>
</tr>
<tr>
<td>ZrO$_2$</td>
<td>0.017</td>
</tr>
</tbody>
</table>
Processing Soda Lime Glass Waste + AlN:

1. MIXING
2. FORMING (850—950°C)
3. FIRING
Determination of Porosity

- Determination of mass, diameter, and length
- Estimating the bulk density of dense glass to $\rho_{dg} = 3.2 \text{ g/cm}^3$
- Determination of absolute density of porous glass $\rho_{pg} = \text{mass/volume}$
- Determination of relative density $RD = \rho_{pg}/\rho_{dg}$
- Determination of porosity by $\varepsilon = (1-RD)$
Determinations of Mean Pore Diameter/Cell Density

- Cell density determined by counting pores along two arbitrary distances $l_1$ and $l_2$
- Mean pore size $z$ computed by $z = (n_1/l_1 + n_2/l_2)/2$
- PPI-number by $N_{PPI} = 25.4/z$

sample #3
Thermophysical Properties: Methodology

- Transient Plane Source Technique (Hot Disk)
- Sample volume partially heated by Nickel double spiral
- Measured volumes up to $\varnothing 50 \cdot 20$ mm
- Two identical samples for each measurement necessary
- Single sided technique by averaging
Thermophysical Properties: Methodology cont.

- Temperature increase between samples measured
- Evaluation by Numerical Procedure
- Results as
  - Thermal conductivity (W/mK)
  - Thermal Diffusivity (mm²/s)
  - Specific Heat Capacity (MJ/m³K)
Permeability: Methodology

• Air flow through sample generated with blower and pipe system

• Precise measurement of temperature mass flow and pressure drop over sample
Permeability: Methodology cont.

- Sample mounted and connected with steel pipe by taping
- Superficial fluid velocity calculated from volume flow and air density
- Pressure drop over sample measured for various mass-flow rates
Permeability: Methodology cont.

- Specific pressure drop (pressure difference/sample length) versus superficial velocity plots generated
- Extended Darcy equation fits computed

\[ \frac{dP}{dx} = \frac{\eta_{Dyn}}{K_1} v + \frac{\rho}{K_2} v^2 \]

- Permeability coefficients K1 and K2 computed from viscosity and density of air
SS FOAM BASED SODA LIME GLASS & AlN_Photos

2.5 wt.%AlN@850°C

2.5 wt.%AlN@900°C

2.5 wt.%AlN@950°C

5 wt.%AlN@850°C

5 wt.%AlN@900°C

5 wt.%AlN@950°C

7.5 wt.%AlN@850°C

7.5 wt.%AlN@900°C

7.5 wt.%AlN@950°C

2AlN (s) → 2Al (s) + N₂(g)

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Amorphous structure
PS Increases with T

2.5 wt.% AlN@850°C

2.5 wt.% AlN@900°C

2.5 wt.% AlN@950°C

PS Increases with T
5 wt.% AlN@900°C

PS Increases with T

5 wt.% AlN@900°C

5 wt.% AlN@950°C

5 wt.% AlN@850°C

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SS FOAM BASED SODA LIME GLASS_BSE _5 wt.% AlN
PS Increases with T

7.5 wt.% AlN@850°C

7.5 wt.% AlN@900°C

7.5 wt.% AlN@950°C
SS FOAM BASED SODA LIME GLASS_BSE

PS Increases With AlN content

SS FOAM BASED SODA LIME GLASS_BSE

5 wt.% AlN@9000°C

PS Increases With AlN content

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**SS FOAM BASED SODA LIME GLASS_CCS**

- **2.5% AlN – 850°C:** 1.83 MPa
- **5.0% AlN – 850°C:** 1.39 MPa
- **7.5% AlN – 850°C:** 1.39 MPa

**13.9-18.3 MPa@850°C**

- **2.5% AlN – 900°C:** 2.48 MPa
- **5.0% AlN – 900°C:** 1.47 MPa
- **7.5% AlN – 900°C:** 1.6 MPa

**14.7-24.8 MPa@900°C**

- **2.5% AlN – 950°C:** 0.65 MPa
- **5.0% AlN – 950°C:** 0.74 MPa
- **7.5% AlN – 950°C:** 0.85 MPa
## Geometrical Properties

<table>
<thead>
<tr>
<th>Temperature</th>
<th>AlN Content</th>
<th>Cellularity (exact PPI)</th>
<th>Cellularity (app. PPI)</th>
<th>Density (kg/m³)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>850°C</td>
<td>2.5%</td>
<td>24.19048</td>
<td>20</td>
<td>229.02</td>
<td>0.92843</td>
</tr>
<tr>
<td></td>
<td>5.0%</td>
<td>56.30843</td>
<td>60</td>
<td>229.51</td>
<td>0.92828</td>
</tr>
<tr>
<td></td>
<td>7.5%</td>
<td>25.9562</td>
<td>30</td>
<td>224.99</td>
<td>0.92969</td>
</tr>
<tr>
<td>900°C</td>
<td>2.5%</td>
<td>45.76577</td>
<td>50</td>
<td>248.12</td>
<td>0.92246</td>
</tr>
<tr>
<td></td>
<td>5.0%</td>
<td>24.69444</td>
<td>20</td>
<td>183.85</td>
<td>0.94255</td>
</tr>
<tr>
<td></td>
<td>7.5%</td>
<td>17.92339</td>
<td>20</td>
<td>189.52</td>
<td>0.94078</td>
</tr>
<tr>
<td>950°C</td>
<td>5.0%</td>
<td>19.84375</td>
<td>20</td>
<td>204.24</td>
<td>0.93618</td>
</tr>
<tr>
<td></td>
<td>7.5%</td>
<td>11.81395</td>
<td>10</td>
<td>202.5</td>
<td>0.93672</td>
</tr>
</tbody>
</table>

- Porosities between 92 and 94%
- Cell densities from 12 to 46 PPI
- Rel. porosity decreases with cellularity
## Thermophysical and Permeability Data

<table>
<thead>
<tr>
<th></th>
<th>Th. cond. W/mK</th>
<th>Th. diff. mm²/s</th>
<th>Spec. heat MJ/m³K</th>
<th>Perm. K1 m²</th>
<th>Perm. K1 *10e12 m²</th>
<th>K2 m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2.5% AlN@850°C</strong></td>
<td>0.10616</td>
<td>0.5947</td>
<td>0.178798</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>5.0% AlN@850°C</strong></td>
<td>0.10125</td>
<td>0.5521</td>
<td>0.182971</td>
<td>1.1E-12</td>
<td>1.076018</td>
<td>-8.66E-07</td>
</tr>
<tr>
<td><strong>7.5% AlN@850°C</strong></td>
<td>0.10855</td>
<td>0.555</td>
<td>0.194795</td>
<td>3.3E-13</td>
<td>0.331759</td>
<td>-3.8E-07</td>
</tr>
<tr>
<td><strong>2.5% AlN@900°C</strong></td>
<td>0.10343</td>
<td>0.7023</td>
<td>0.148825</td>
<td>1.9E-13</td>
<td>0.190528</td>
<td>0.0016939</td>
</tr>
<tr>
<td><strong>5.0% AlN@900°C</strong></td>
<td>0.09412</td>
<td>0.5612</td>
<td>0.168356</td>
<td>1.2E-12</td>
<td>1.159163</td>
<td>1.513E-06</td>
</tr>
<tr>
<td><strong>7.5% AlN@900°C</strong></td>
<td>0.10616</td>
<td>0.6303</td>
<td>0.167855</td>
<td>1.3E-12</td>
<td>1.307696</td>
<td>-4.23E-06</td>
</tr>
<tr>
<td><strong>5.0% AlN@950°C</strong></td>
<td>0.09061</td>
<td>0.575</td>
<td>0.15865</td>
<td>5.8E-12</td>
<td>5.826184</td>
<td>3.274E-05</td>
</tr>
<tr>
<td><strong>7.5% AlN@950°C</strong></td>
<td>0.0974</td>
<td>1.1631</td>
<td>0.05918</td>
<td>4E-13</td>
<td>0.397308</td>
<td>1.038E-06</td>
</tr>
</tbody>
</table>
Structure-Property Relations

- Very low effective thermal conductivity (TC) values (< 0.1 W/mK) due to high porosity and predominantly closed porosity
- TC decreases with porosity
- Permeability increases with porosity
Conclusions: Density

Density, kg/m³: 184 - 229 kg/m³
THANK YOU FOR YOUR ATTENTION

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