زانکۆی سەلاحەدین - هەولێر
Salahaddin University-Erbil

Experimental study on mechanical properties of tempered glass using Vickers hardness tester

A Research Project
Submitted to the department of Physics in partial fulfillment of the requirements for the degree of BSc. in Physics

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April– 2024

EXPERIMENTAL STUDY ON MECHANICAL PROPERTIES OF TEMPERED GLASS USING VICKERS HARDNESS TESTER

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Date Approved: April 1, 2020

DEDICATION

I dedicate my dissertation work to my family and many friends. A special feeling of gratitude to my loving parents, whose words of encouragement and push for tenacity ring in my ears they have never left my side and are very special.

- To my brothers, sisters, friends, and classmates who shared their words of advance and encouragement to finish this study.

- And lastly I dedicate to the almighty god, thank you for the guidance, strength, power of mind, protection, and skill and for giving us a healthy life.

All of these we offer to you.

ACKNOWLEDGEMENTS

First of all, praise is due to almighty ALLAH with His compassion and mercifulness to allow me finalizing this B.Sc. project. I would like to express my teacher, who taught me how to perform an optical study. With out their help and kindness, this achievement would have been far away.

I would like to express my sincere gratitude to the Kurdistan regional government, higher council and presidency of the Salahaddin university. I would like to express my deepest thanks and gratitude to my supervisor Assist. Prof. Dr. Saman Qadir Mawlud, for his keen supervision initiating and planning this study, great help, and scientific guidance, I am grateful for his patient and valuable comments sincere thanks and appreciation to all my friends in the physics department who supported me during my study last but not least. Last but not least I cannot forget to send great thanks for my family which they stood beside me in all steps in my life specially of this research.

SUMMARY

Tempered glass is widely utilized in various industries due to its enhanced mechanical properties compared to untreated glass. Understanding these properties, particularly hardness, is crucial for ensuring its effectiveness and safety in applications. This experimental study focuses on investigating the mechanical properties of tempered glass using a Vickers hardness tester. The methodology involves subjecting tempered glass specimens to controlled pressure through a series of indentations at different locations on the surface. Consistency was maintained by keeping load and dwell time constant throughout the testing process. Results from the Vickers hardness test provide valuable data on the material's resistance to deformation and ability to withstand external forces. The findings highlight the uniformity of hardness across the tempered glass surface, indicating the effectiveness of the tempering process in enhancing its mechanical strength. This study contributes to a better understanding of tempered glass properties, which is essential for its application in industries such as construction and automotive. Further research could explore additional factors influencing the mechanical properties of tempered glass, facilitating its optimization for diverse applications.

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CHAPTER ONE
INTRODUCTION

1.1 Introduction and Background

During the past 100 years, commercial flat glasses have acquired a reputation as being among the most durable of materials used in the construction and fabrication industries. As far as packaged food products are concerned, people, more often than not, tend to concentrate only on the quality of the food product itself and seem to overlook relevant quality issues in respect to the packaging. The latter is far from a trivial issue. Indeed, inappropriate packaging can lead to grievous health risks, not to mention the adverse effects it can have on both the quality of the food product and its characteristics, for example its flavor and aroma. As such it should not come as a surprise that glass bottle packaging has attracted, especially in recent years, the attention of the food industry (Mauro, 2010). All glass materials can react with the surrounded environmental (e.g., temperature, pH, solution composition and flow, glass composition) these reactions will cause degradation in their optical and structural properties; the amount of the degradation depends mainly on the glass material composition types and mole ratio as well as the surrounded environment. The corrosion of soda-lime glasses has received great attention. Glass is thought of as a corrosion proof material but under certain exposure conditions its chemistry, structure and properties are affected (Agrawal, 2013). Whenever water is permitted to remain on a glass surface for longer than a moment, several unique chemical reactions can occur that cause corrosion damage, or stain. The first of these begins almost immediately after water contacts the glass, even at room temperature.

Glass is optically transparent solid material which is typically hard, fragile and show glass transition. It is prepared by cooling molten constituents fast enough, to avoid visible crystallization formation. Glasses are usually poor conductor of heat and electricity and the incorporation of certain metal oxides in glasses give them colors. New Science and technology have dynamically given great improvement in glass manufacture and their new technological applications. The main advantages of this will be to provide the fundamental base of new optical glasses with number of applications especially, tellurite-glass base solid state lasers, optical fibers and amplifiers. Great research attention is needed for the development of new material for solid state lasers, optical switches, third order nonlinear optical materials, optical amplifiers, light emitting diodes and up-conversion glasses (Agrawal, 2013).

There is variety of techniques used for manufacturing of glass material such as thermal evaporation, sputtering, chemical reaction, amorphization, irradiation, melt quenching, sol gel, etc. (Cao and Wang, 2011). Among these techniques the melt quenching technique is most important and widely used technique. In last few decades, research on glass has been very active due to the increasing awareness of industry that from fabrication point of view, glasses are better than crystalline material and glasses can play important role in electronics development (Agrawal, 2013). Glass is usually used to store materials that would be corrosive to other materials or it is used for the packaging foods and other materials, but it's not impervious to corrosion altogether. According to several researches, glass is, in fact, quite susceptible to degradation under particular conditions. the study aimed to identify the impact of the types of the transition metal elements (glass) to food and the effect of acid and storage in the concentration of these elements. The study focus on the selection of the type of the glass composition for the food packaging, and their positive, as well as negative, which may harm human health and make it defenseless to many diseases, including cancer.

1.2 History of Glass

Glass is a non- crystalline (amorphous) solid material that mostly exhibit glass transition and typically hard, brittle, optically transparent and clear with different colors. It can be used for various kinds of utensils such as mirrors, windows and bottles, etc. It is thought that glass has been first created during the

Bronze Age around 3000 BC. But according to the evidence of archeologist, the first true man-made glass was found in coastal north Syria, Mesopotamia. Around 1500BC, first glass container was made in Egypt and Mesopotamia. For the next 300 years, the glass industry was developed rapidly and then it declined. It was revitalized in the 700BC in Mesopotamia and in 500's BC in Egypt. Egypt, Syria and the eastern coast of the Mediterranean Sea were glass manufacturing centers for next 500 years (Agrawal, 2013).

Glass has been found around 3000 BC in the Middle East. It is one of the oldest as well as newest material that is man's most valuables and versatile material in everyday life. A great research interest in the science and technology of glasses has received a great attention. Progress in the development of the glasses for different scientific applications was rapid and advanced through and early 20th century, in parallel with many other technology areas. Unfortunately, until 20th century mostly development was made experimentally by using common sense to guide experiment. The significant theoretical problems are amplified in non-crystalline solids specially, in glasses to understand their optical, structural and thermal properties due to lack of precise experimental information. There is tremendous need to accelerate the research to fill this gap.

Glass is one of the most common and versatile materials made by Man in our1 daily lives where millions of tons are produced annually. The word 'glass' is defined as a solid material, typically brittle and optically transparent substance. The 'glass' derivation from an Indo-European root which mean shiny, glare, glow or glaze. It is not known where, when or how the exactly time glass was first manufactured, although there is little doubt that the industry was established since 1500 B.C. The American Society for Testing and Materials (ASTM) standards defined that "Glass is an organic product of fusion which has been cooled to a rigid condition without crystallization". Glasses and glazes were manufactured far back in human history where natural glasses have been used by human being from the earliest times, which there is the archeological evidence found. The earliest pure glass dated from about 7000 B.C. where it was found in Egypt.

Glass manufacturing was very difficult and slow in the beginning because glass melting furnaces were very small and they produced hardly enough heat to melt glass. But in the 1st century BC, blow pipe was invented by Syrian craftsmen and this discovery, made glass manufacturing process easier, faster and cheaper. The most important center of glass manufacturing was the Egyptian city of Alexandria in 1000 AD. The first glass factory was built in Jamestown, Virginia in 1608. In the early 1800's, there was a big demand for window glass. Discovery of glass as a building material was first marked by Joseph Paxton's Crystal Palace in 1851 at the Great Exhibition. After 1890, glass manufacture and development began to increase rapidly along with its application in many other fields of technology.

The trend of basic scientific understanding of glasses in order to their manufacturing improvement and develop their new application has occurred only in last few decades. Micheal Faraday (1830) studied the conductivity and electrolysis of various glasses and he was among the researchers who initially studied the glasses in more basic way. By following the Fraday's Law the electrolysis of the glasses was evaluated by Warburg and Tegetmeier in 1984. At the same time, work on glass viscosity, glass transitions and the relationship between viscosity and crystallization rate was initiated by Tammann (1884).

The optical glasses were successfully prepared by Joseph Fraunhopper (1826). A great theoretical and experimental research on glass technology was carried out by a group, Department at Shelfeild University England under the supervision of W.E.S.Turner. This group was actively measuring the properties of optical glasses such as density, chemical durability, viscosity, electrical conductivity, and thermal expansion of wide variety of lab and commercial glasses. In the recent years, great research interest on rare earth doped glass technology has received great attention due to their potential applications such as sensors, detectors, receivers, optical amplifiers and solid-state laser sources. (Atkins, 2010).

1.3 Definition of Glass

In everyday language the term glass designates a transparent substance, possessing the properties of hardness, rigidity, and brittleness, and, apart from transparency, these are the typical properties one normally associates with a solid. Glass also possesses a number of properties which are characteristic of the liquid state, and classification of glass as a liquid of very high viscosity rather than a solid would be in accordance with modern views (McMillan, 1979). Unlike crystals, glass does not have a sharp melting point, but like crystalline solids, glasses show elasticity (Paul, 1990). Due to the complexity of the structure of glass, it is not altogether surprising that an exact, all-encompassing definition for glass remains elusive, and instead a number of definitions have been suggested over the years. A more generally accepted definition is that offered by ASTM (C162) which states “a glass is an inorganic product of fusion which has cooled to a rigid condition without crystallization.” However, the ASTM definition limits the definition of glass to inorganic constituents, which fails to explain organic and molecular glasses that now represent a rapidly growing area of study (Varshneya and Mauro,2010; Doremus,1994). Newly developed solution-based sol–gel synthesis of oxide materials occurs at much lower temperature than traditional solid-state fusion processes and also allows powder lessnon-fusion processing of glasses. X-ray and electronic diffraction studies have shown that glass lacks long-range periodic atomic arrangement, and every type of glass exhibits time-dependent glass transformation behavior (Paul, 1990; Shelby and Lopes,2005). Pointing this out, Varshneya and Mauro (2010) suggest a scientific definition of glass as “a solid having a non-crystalline structure, which continuously converts to a liquid up on heating.” Zarzycki (1991) favors a more simplified definition: “a glass is a non-crystalline solid exhibiting the phenomenon of glass transition.” There by this definition also conveniently separates non-crystalline materials into the categories of glass and amorphous materials.

1.3.1 The Glass Transition

Glass is usually formed on solidification from the melting stage. The cooling is so rapid that crystallization does not have the time to occur. With a further decrease in temperature, viscosity continues to increase, resulting in a progressive freezing of the liquid to its final solidification. The relationship between crystal, liquid , and glass can be explained by means of specific volume as a function of temperature(see Figure 1.1).

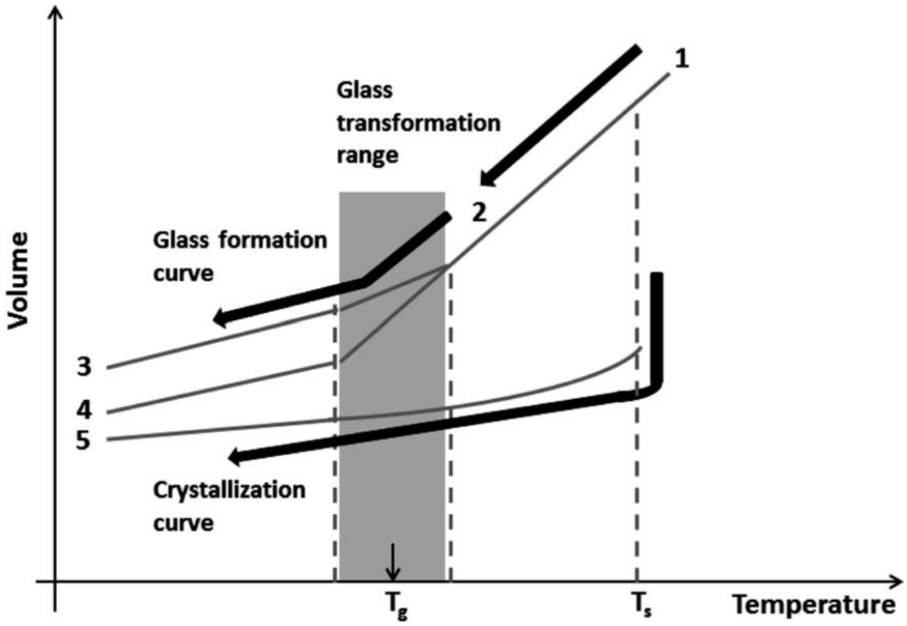

Figure 1.1 Schematic specific volume–temperature relationships for crystallization and glass formation. 1: liquid, 2: super cooled liquid, 3: glass on fast cooling, 4: glass on slow cooling, 5: crystal; Ts: melting temperature, Tg: glass transition temperature.

On cooling from an elevated temperature (Ts), at the point of solidification (or freezing), two phenomena may occur. There is either a discontinuous change in volume at the melting point if the liquid crystallizes, or crystallization is a voided and liquid passes to a super cooled state (between Ts and Tg) and the volume of the liquid decreases steadily until there is a decrease in the expansion coefficient at arrange in temperature called the glass transformation range. Below this temperature range the glass structure does not relax and the expansion coefficient is usually same as that for the crystalline solid. The intersection between the curve of the glassy state and that for the super cooled liquid is known as the glass transition temperature, Tg (Kingery and Uhlmann et al., 1976). This Tg varies with cooling rate (see Figure 1) and thus it is more accurate to call it a transformation range rather than a fixed point (Lancry and Régnier et al., 2012). The glass transition temperature increases with increasing cooling rate. The specific volume of the formed glass follows this same trend, increasing with increased cooling rate. With a slower cooling rate, the time available for the structure to relax increases and the super cooled liquid persists to a lower temperature resulting in a higher- density glass.

1.3.2 The Structure of Glass

Glasses exhibit broad, smeared out spectral transitions with typical bandwidths of tens of nanometers compare to crystals which possess sharp line spectra. These differences emerge from inhomogeneous broadening in glasses. The optically active ions inserted into the glass network experienced different environments due to the amorphous structure. In contrast, in crystals the optically active ions experienced nearly uniform environments as illustrated in Figure 1.2(a). The inhomogeneous broadening for crystals is much weaker than in glasses. Glasses often exhibit lower absorption and emission cross-sections due to the strong inhomogeneous broadening. The choice of raw materials, the mode and degree of heating, the method and rate of cooling of the host glass in terms of annealing highly affects the glass properties (Funabiki *et al.*, 2012).

Figure 1.2(b) displays the internal atomic arrangements of atoms or molecules in an amorphous and disordered network called glass in the absence of any periodicity. Glass structure is viewed as continuous non-periodic or irregular three-dimensional network without long range order. The short ranged order signifies more or less symmetrical array of atoms is in a local region generally less than 1.0 nm, but the lattice for each atom is not exactly uniform. The local short range order in oxide glasses mostly occurs around the elements of network former such as Te, Si, B, and P. Usually, the structural units having short ranged order are polyhedrons coordinated by strong covalent bonds and definite nearest ligands (Greenwood and Earnshaw, 1984).

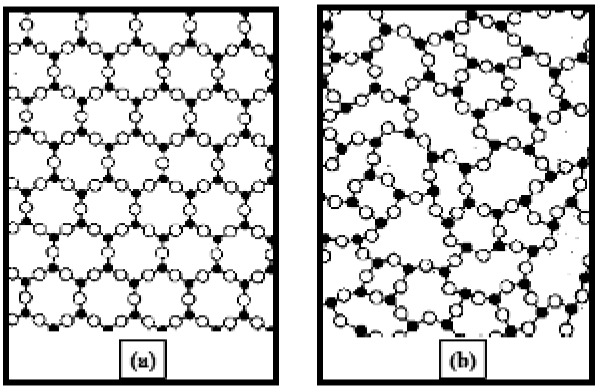

Figure 1.2: Schematic two-dimensional representation of atomic arrangements in a (a) crystal (regular) and (b) in glass (irregular).

1.4 Common Glass Systems

The primary glass formers in commercial oxide glasses are silica (SiO_2), boron oxide (B_2O_3), and phosphorus pentoxide (P_2O_5), all of which readily form single component glasses (Kuzmany, 2009). Of these, other than silica, only boron oxide has some commercial importance and only when mixed with silica. Silica is the most important glass former and silicate glasses represent more than 95% of industrial glass production. Silica-based glass is technically important for its excellent chemical resistance (except HF and alkali) and small expansion coefficient which makes it a very good candidate for thermal shock resistance. Glass can be classified in different groups according to their intended usage or by their chemical composition (Shelby, 2005). The following sections describe the most common types of glass according to their chemical composition.

1.4.1 Soda-Lime Glass or Commercial Glass

Soda-lime glass is the most common commercial glass. It is comparatively inexpensive and amenable to recycling. The material Soda-lime glass is the glass of windows, bottles, and lightbulbs, used in vast quantities, the most common of them all. A typical composition of this glass is:

13-17% NaO (the “soda”), 5-10% CaO (the “lime”), and 70-75% SiO2

A small percentage of other reagents can be added for specific properties and application requirements. The principal addition in this type of glass, other than silica (SiO2), is sodium oxide or soda (Na2O). Even though sodium oxide contains oxygen atoms, it is held together by ionic rather than covalent bonds. The sodium atoms in the mixture donate electrons to the oxygen atom, producing a mixture of negatively charged oxygen ions and positively charged sodium ions. The oxygen atom with an extra electron binds to one silicon atom and does not form a bridge between pairs of silicon atoms. Therefore, the melting temperature of the mixture is considerably reduced. Relatively high amount of alkali content in the glass also causes an increase of the thermal expansion coefficient by about 20 times. Since sodium ions are so soluble in aqueous solution, calcium oxide (CaO) is added to the mixture to improve its insolubility (Shelby, 2005). Soda-lime glass is produced on a large scale and used for bottles, drinking glasses, and windows. Its light transmission properties, as well as low melting temperature, make it suitable for use as window glass. Its smooth and non-reactive surface makes it excellent as containers for food and drinks. Nowadays recycled glass, also known as cullet, is used to make green glass, which helps to save energy and reduce emissions.

Soda-Lime glass has a low melting point, is easy to blow and mold, and is cheap. It is optically clear unless impure, when it is typically green or brown. Windows today have to be flat and that was not until 1950 easy to do; now the float-glass process, solidifying glass on a bed of liquid tin, makes “plate” glass cheaply and quickly. Soda-lime glass, also called soda-lime-silica glass, is the most prevalent type of glass. It is composed of SiO_4 tetrahedra connected at the oxygen atoms. The chemical ordering is very strong; each silicon atom is connected to four oxygen atoms and each oxygen atom is shared by two silicon atoms, as shown in Fig. 1.3.

In soda-silica glass, the continuity of the network is disrupted by the addition of network modifiers, such as monovalent Na_2O ions. These network modifiers make the network more sophisticated so that when the components are melted together during the cooling process, it is more difficult for the atoms to arrange themselves in suitable configurations for crystallization to occur. Fig. 1.4 shows adjacent SiO_4 tetrahedral-type unit cells forming part of a continuous random network.

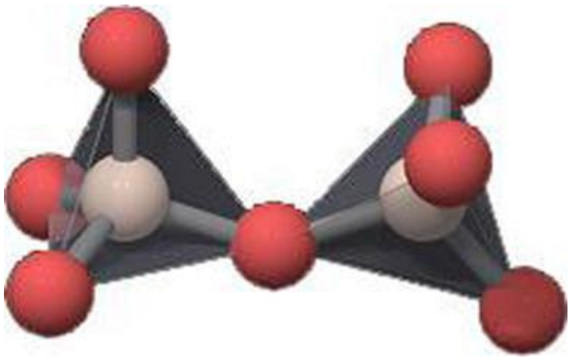

Fig. 1.3 The Si–O–Si bond

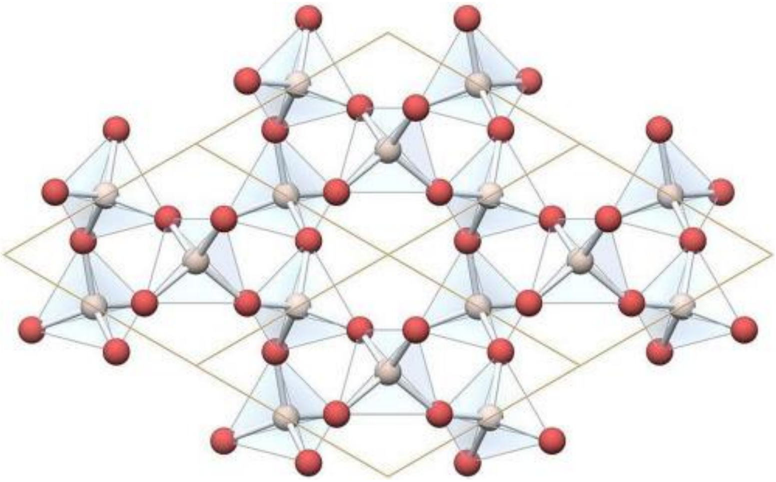

Fig. 1.4 Adjacent SiO_4 tetrahedral-type unit cells.

Composition:
73% SiO2+1% Al2O3+17% Na2O+4% MgO+5% CaO

General properties	
Density	2.440-2.490 kg/m^3
Price	0.8-1.7 USD/kg
Mechanical properties	
Young’s modulus	68-72 GPa
Yield strength (elastic limit)	30-35 MPa
Tensile strength	31-35 MPa
Elongation	0 %
Hardness-Vickers	439-484 HV

Fatigue strength at	107 cycles 29.4-32.5 MPa
Fracture toughness	0.55-0.7 MPa

Thermal properties

Maximum service temperature	443-673 K
Thermal conductor or insulator	Poor insulator
Thermal conductivity	0.7-1.3 W/m K
Specific heat capacity	850-950 J/kg K

Electrical properties

Electrical conductor or insulator	Good insulator
Electrical resistivity	$7.943*10^{17}$-$7.943*10^{18}$ μohm cm
Dielectric constant	7-7.6
Dissipation factor	0.007-0.01
Dielectric strength	12-14 10^{6} V/m

Eco properties: material

Global production, main component	$843*10^{6}$ metric ton/yr
Reserves	$13*10^{12}$ metric ton

Typical uses: Windows, bottles, containers, tubing, lamp bulbs, lenses and mirrors, bells, glazes on pottery and tiles.

1.4.2 Lead Glass

Lead glass is similar to soda-lime glass where lime is replaced by a larger part of lead oxide (PbO). Lead glass typically contains 55– 65 wt% SiO_2, 18–38 wt% of PbO, and 13–15 wt% Na_2O or K_2O. Lead glass is usually used for decorative glassware. It is also included in special optical glasses for their high refractive index. The networks in lead glass are more complete than those in soda-lime glass and thus they are stronger and have less internal friction. Lead oxide also makes the glass dense, hard, and X-ray absorbing, and therefore suitable for use in radiation shielding.

1.4.3 Aluminosilicate Glass

Aluminosilicate glasses are usually prepared from a ternary system with a typical composition 52–58 wt% SiO_2, 15–25 wt% of Al_2O_3, and 4–18 wt% CaO.

With low thermal expansion and high softening temperature, this glass can tolerate high temperature better than soda-lime glass and is used in thermometers, combustion tubes, cookware, halogen lamps, furnaces, and fiberglass insulation.

1.4.4 Borosilicate Glass

Borosilicate glass contains substantial amounts of silica (SiO_2) and boron oxide ($B_2O_3$48%) as glass network formers, and are typically composed of 70–80 wt% SiO_2, 7–13 wt% of B_2O_3 4–8 wt% Na_2O or K_2O, and 2–8 wt% of Al_2O_3. Glass containing 7–13 wt% of B_2O_3 is known as low-borate borosilicate glass, and is mainly used to produce chemical apparatus, lamps, and tube envelopes. Glasses containing 15–25% B_2O_3, is known as high-borate borosilicate glass (Zachariasen, 1932). High-borate borosilicate glass is also known as leachable alkali-borosilicate glass with an optimum composition of 62.7 wt% SiO_2, 26.9 wt% of B_2O_3, 6.6 wt% Na_2O, and 3.5 wt% of Al_2O_3. This glass can be further processed to produce Controlled Pore Glass (CPG) which is widely used as a stationary media in chromatography, or alternatively, the pores can be closed up to yield a clear impervious glass known as Vycor 96% silica glass, commonly used in cookware. The increase of B_2O_3 content,with a very fine-scale secondary phase separation within the silica phase increases the chemical resistance, and in this aspect high-borate borosilicate glass differs greatly from low-borate (Shelby, 2005).

1.4.5 Silicon Dioxide (SiO_2)

Silicon dioxide is the glass former in borosilicate glass composition. Higher levels of silica increase the melting temperature as well as the working point, and reduces the coefficient of thermal expansion. With lower levels of silica, the resistance to acids deteriorates.

1.4.6 Boron trioxide (B_2O_3)

Boron trioxide reduces melting and working temperatures and improves hydrolytic stability when used below 13% by weight in the composition. Higher boron trioxide contents have an adverse effect on acid resistance and increases highly volatile alkali metal borates. On the other hand, lower borate contents increase the melting point of the glass by creating secure bonds with alkali metal ions. This helps to reduce the susceptibility to crystallization. Borate also play a major role in reducing the dielectric constant of glass (Zachariasen, 1932).

1.4.7 Alkali Metal Oxides

Sodium oxide (Na_2O) is widely used as a flux, especially in borosilicate glass composition, along with other alkali metal oxides like potassium dioxide (K_2O), lithium dioxide (Li_2O), and lead oxide (PbO). Alkali metal oxide reduces the working temperature and plays an important role in setting the thermal expansion. If the alkali metal oxides content is above a certain limit, glasses exhibit a high coefficient of thermal expansion. A higher level of alkali oxide also causes an adverse effect on hydrolytic stability. El-Malawany (2004) also discussed the role of alkali metal oxides on crystallization and suggested using at least two alkali metal oxides, even in small amounts, in order to have a positive effect on resisting unwanted crystallization. They also reported that beyond 1000 ^{o}C, potassium borates evaporate more easily than sodium borates.

1.4.8 Alkali Earth Metal Oxides

Calcium oxide (CaO) is most commonly used as a property modifier component in glass composition. Small amounts of magnesium oxide (MgO), zinc oxide (ZnO), strontium oxide (SrO), and barium oxide (BaO) are also added separately based on application requirements. Calcium oxide can help greatly to accelerate the phase separation of borosilicate glasses. It also has a stabilizing effect on acid resistance. It has been found that limiting CaO to small amounts reduces the evaporation of highly volatile sodium and potassium borate compounds during hot forming (Rasmussen, 2012). If the amount of CaO exceeds certain limit, devitrification is likely to take place. Moreover, heat resistance and alkali resistance also deteriorate with high contents of CaO.

1.5 General Properties of Glass

1. Glass is hard and Brittleness It is a hard material as it has great impact resistance against applied load. However, at the same time, it is a brittle material as its breaks immediately when subjected to load.
2. Transparency The transparency is one such property of glass which creates a visual connect with the outside world
3. Refractive index of glass is probability the most common aptical property, is defined the ratio of the speed of light in a vacuum devised by speed of light in a medium
4. Absorption The next important property of glass is absorption and this is what is a key determinant of color in objects.
5. Reflection is an optical property that is seen when light flows from air to glass and a part of the incident light is reflected back from the glass surface.
6. Transmittance occurs when light is incident from air to glass and a part of the light gets transmitted through it. Optical glasses have excellent transmittance from the near UV and IR regions
7. Solarization The influence of visible and UV radiation (less than 380 nm wavelength) on glass is called solarization
8. Insulation It is an excellent insulator against heat, electricity and electromagnetic radiation because of its good insulating response against visible light transmission.
9. Color and shape varieties It can be blown, drawn and pressed to any colour, shape, and variety and is available in the market depending upon their use, dimensional requirements, and safety requirement.
10. Glass is 100% recyclable and one of the safest packaging materials due to its composition and properties.

CHAPTER TWO
EXPERIMENTAL PART

2.1 Toughening Glass

Toughened glass is a safety glass that has undergone processes of controlled thermal treatment to increase its strength. Also known as 'Tempered glass', toughened glass is made from annealed glass that has been heated to approximately 650ºC and then rapidly cooled, making it four times stronger than the ordinary glass.

In this project the glass toughening process carried out with the following steps:

1. **Preparation**: The glass is cut to the desired dimensions of 4 mm thickness and 20mmX30mm of width and length respectively. Any edges are smoothed or rounded to reduce the risk of breakage during tempering.
2. **Heat Treatment**: The glass is heated to different high temperatures 300, 350, 400, 450, 500, 550 and 600 ºC, and then rapidly cooled. This process, known as quenching.
3. **Cooling**: The rapid cooling process causes the outer surface of the glass to cool much faster than the center. As a result, the outer layers of the glass are compressed, while the inner core remains in tension.
4. **Result**: This creates a glass with increased strength and toughness compared to untreated glass. Tempered glass is typically four to five times stronger than regular glass of the same thickness.
5. **Breakage Pattern**: When tempered glass does break, it shatters into small, blunt pieces rather than sharp shards, reducing the risk of injury.

2.2 Sample Preparation

The preparation of the sample and the experimental procedures are summarized in several steps as the following:

1. Collecting the commercial soda Soda-Lime glass.
2. The samples were cut into the dimension 20×30×4 mm regular shape of four pieces in order to be ready for each for the mechanical and physical properties test.

3. Measuring the weight of each piece of the sample by using an analytical digital balance.
4. One of the samples will be kept as a reference (R), and the other three pieces will be annealed at different degrees of temperature for the toughening process.
5. Characterizing the samples with a Vickers hardness tester.

2.3 Density and molar volume of glass

The density of a material is defined as the mass of the substance per unit of volume and can be determined using Archimedes method. Density of glass is being measured to understand their physical properties that can finally be related to the change in the glass structure. Glass density can be determined either by Archimedes method or by the floatation method. Even though an Archimedes method is the most popular method, but floatation method will give a greater precision than Archimedes displacement method. However, an Archimedes method does not need so much information about the dimension of the glass (El-Mallawany, 2002). The glass sample is weighted in the air, W_a and then was immerse in an immersion liquid of density ρ_L. If the weight in the liquid is W_L, then the density of sample, ρ_s can be obtained through this relationship:

$$\rho_s = \frac{\rho_L W_a}{W_a - W_L} \quad \text{……………………} \ (2.1)$$

The choice of the immersion liquid is based on the chemical durability of the sample.

2.4 Vickers hardness test

The Vickers hardness test was developed in the early 1920s as an alternative method to measure the metals and has one of the widest scales among hardness tests. The unit of hardness given by the test is known as the Vickers Pyramid Number (HV). The hardness number can be converted into units of Pa, but should not be confused with a pressure, which also has units of Pa. The hardness number is determined by the load over the surface area of the indentation and not the area normal to the force, and is therefore not a pressure.

The hardness number is not really a true property of the material and is an empirical value that should be seen in conjunction with the experimental methods and hardness scale used. When doing the hardness tests the distance between indentations must be more than 2.5 indentation diameters apart to avoid interaction between the work-hardened regions.

The yield strength of the material can be approximated as (Nix,.1998):

$$H_V = c\sigma \approx 3\sigma.$$

where c is a constant determined by geometrical factors usually ranging between 2 and 4.

2.4.1 Implementation

It was decided that the indenter shape should be capable of producing geometrically similar impressions, irrespective of size; the impression should have well-defined points of measurement; and the indenter should have high resistance to self-deformation. A diamond in the form of a square-based pyramid satisfied these conditions. It had been established that the ideal size of a Brinell impression was $\frac{3}{8}$ of the ball diameter. As two tangents to the circle at the ends of a chord $3d/8$ long intersect at 136°, it was decided to use this as the included angle between plane faces of the indenter tip. This gives an angle from each face normal to the horizontal plane normal of 22° on each side. The angle was varied experimentally and it was found that the hardness value obtained on a homogeneous piece of material remained constant, irrespective of load.[2] Accordingly, loads of various magnitudes are applied to a flat surface, depending on the hardness of the material to be measured. The HV number is then determined by the ratio F/A, where F is the force applied to the diamond in kilograms-force and A is the surface area of the resulting indentation in square millimeters (Nix,.1998).

The Vickers hardness test uses a hardness of the material to be measured. The Vickers Pyramid Number (HV) is then determined by the ratio F/A where F is the force applied to the diamond and A is the surface area of the resulting indentation. ***A*** can be determined by the formula (Nix,.1998):

$$A = \frac{d^2}{2\ sin(136°/2)},$$

which can be approximated by evaluating the sine term to give

$$A \approx \frac{d^2}{1.854},$$

where *d* is the average length of the diagonal left by the indenter. Hence,

$$H_V = \frac{F}{A} \approx \frac{1.854F}{d^2}.$$

The corresponding unit of HV is then the kilogram-force per square millimeter (kgf/mm^2) or HV number. In the above equation, *F* could be in N and *d* in mm, giving HV in the SI unit of MPa. To calculate Vickers hardness number (VHN) using SI units one needs to convert the force applied from newtons to kilogram-force by dividing by 9.806 65 (standard gravity). This leads to the following equation (Nix,.1998):

$$\mathrm{HV} \approx 0.1891 \frac{F}{d^2} \quad [\mathrm{N/mm^2}],$$

where *F* is in N and *d* is in millimeters. A common error is that the above formula to calculate the HV number does not result in a number with the unit newton per square millimeter (N/mm^2), but results directly in the Vickers hardness number (usually given without units), which is in fact one kilogram-force per square millimeter (1 kgf/mm^2).

A practical method to convert HV to SI units:

To convert HV to MPa, multiply by 9.807. To convert HV to GPa, multiply by 0.009807

Vickers hardness numbers are reported as xxxHVyy, e.g. 440HV30, if duration of force differs from 10 s to 15 s, e.g. 440HV30/20, where:

- 440 is the hardness number,
- HV gives the hardness scale (Vickers),
- 30 indicates the load used in kg.
- 20 indicates the loading time if it differs from 10 s to 15 s

Table 2.1: Examples of HV values for various materials

Material	Value
316L stainless steel	140HV30
347L stainless steel	180HV30
Carbon steel	55–120HV5
Iron	30–80HV5
Martensite	1000HV
Diamond	10000HV

CHAPTER THREE

RESULTS AND DISCUSSIONS

3.1 Introduction

In this chapter, the results of different characterization analyses on toughened commercial Soda-Lime glass samples are presented. First, the density of the glass was discussed. It is then followed by mechanical and optical properties of the glass sample are presented.

3.2 Glass Density

Density is a reliable tool for evaluating the degree of compactness in glassy material. The densities of selected toughened Soda-Lime glasses are listed in Table 3.1.

Table 3.1: Glass codes and Density.

Density Calculation gm/cm^3										**Average Density gm/cm^3**
Glass Code	**Weight in Air**			**Weight in Distilled Water**			**D1 gm/cm^3**	**D2 gm/cm^3**	**D3 gm/cm^3**	
	WA1	**WA2**	**WA3**	**WD1**	**WD2**	**WD3**				
SL300	1.7	1.69	1.69	1.02	1.01	1.01	2.5084	2.4726	2.4834	2.4881
SL500	1.06	1.05	1.05	0.63	0.65	0.65	2.4975	2.5917	2.5727	2.5539
SL700	1.66	1.66	1.65	0.98	0.98	0.98	2.4486	2.4458	2.4515	2.4486

The variation of density with different type is presented in Fig. 3.1. It is clearly indicating an increase and decrease in the density by changing the annealing temperature from 300 to 700 ^{o}C. An increase in net molecular weight accompanies this increment and decrement. This reflects that a close-patched glass structure is obtained with the formation of a stable network structure.

The toughening process, typically used for soda lime glass, can affect the density of the glass. During the tempering process, the glass is rapidly heated and then cooled, creating internal stresses that increase the strength of the glass. This process can cause some changes in the density of the glass, though these changes are generally minimal (Fischer,2007).

In most cases, the density of toughened soda lime glass remains relatively consistent with the density of untreated soda lime glass. However, there may be slight variations depending on factors such as the specific composition of the glass, the tempering process parameters, and any additional treatments applied.

In practice, the density of toughened soda lime glass can vary within a small range around the typical density of soda lime glass, which is approximately 2.5 grams per cubic centimeter (g/cm³). The changes in density resulting from the toughening process are usually negligible and do not significantly affect the overall properties or performance of the glass (Balamurugan, 2022).

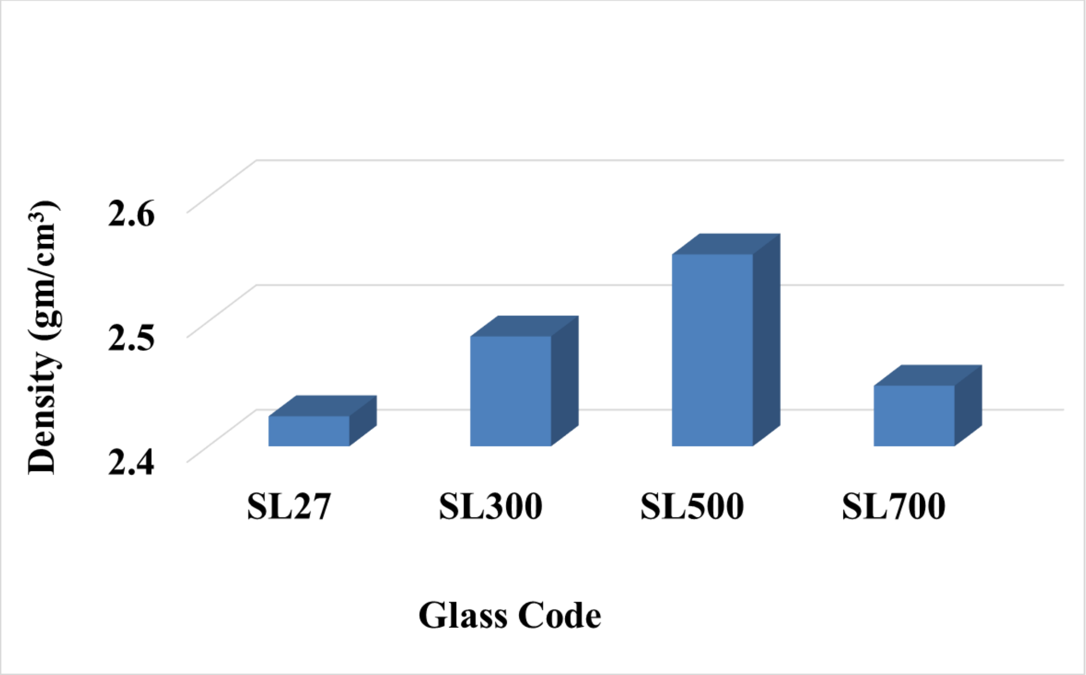

Fig. 3.1: Density of different toughened soda lime glass.

3.3 Hardness of the Glass

The toughening process significantly impacts the hardness of glass, making it substantially stronger and more resistant to impact and scratching compared to untreated glass. Here's how the toughening process affects the hardness of glass:

1. **Increased Strength**: Toughening, also known as tempering, involves rapid heating and cooling of the glass, which induces compressive stresses on the

surface and tensile stresses in the interior of the glass. This process effectively increases the overall strength of the glass, making it more resistant to breakage under impact.

2. **Enhanced Scratch Resistance**: Toughened glass is harder and more resistant to scratching compared to untreated glass. The compressive stresses induced during toughening make the glass more resistant to surface damage, such as scratches, which can occur during handling or use.
3. **Uniform Hardness**: The toughening process typically results in uniform hardness throughout the glass, unlike untreated glass, which may have variations in hardness due to differences in composition or manufacturing processes.
4. **Safety**: When toughened glass does break, it shatters into small, relatively harmless pieces instead of sharp, dangerous shards. This is due to the internal stresses created during toughening, which cause the glass to break into granular, blunt pieces, reducing the risk of injury.

Overall, the toughening process significantly improves the hardness and durability of glass, making it suitable for various applications where safety and resistance to breakage are important, such as architectural glazing, automotive windows, and consumer electronics. The Vickers hardness test, Vickers hardness number, and Tensile strength are listed in Table 2. the toughening temperature is a critical parameter that significantly influences various mechanical properties of glass, including strength, toughness, surface compression, residual stresses, fracture behavior, and annealing characteristics. Careful control of toughening parameters is essential for achieving desired mechanical performance and ensuring the reliability and safety of toughened glass products. Toughening processes like tempering induce compressive stresses on the surface of the glass while leaving the core in tension. This compression-tension balance enhances the overall strength of the glass, including its tensile strength. Tempered glass typically has much higher tensile strength compared to untreated glass of the same composition and thickness; as presented in figure 3.2, the tensile strength is increased with the increase of toughening temperature up to 500 °C, and then it is decreased at high toughened temperature 700 °C (Shahdad, 2017).

Table 3.2: Effect of Toughened Temperature on mechanical properties.

Toughened Temperature (°C)	Mean Diagonal Length on Indentation (mm)	Vickers Hardness Number (HV)(KgF/mm2)	Surface Area Hardness (H) (GPa)	Tensile Strength (σu) (MPa)
27	0.192	502.45	4.927	1675
300	0.1855	538.8	5.284	1796
500	0.173	618.7	6.067	2062.3
700	0.1935	495.5	4.859	1651.7

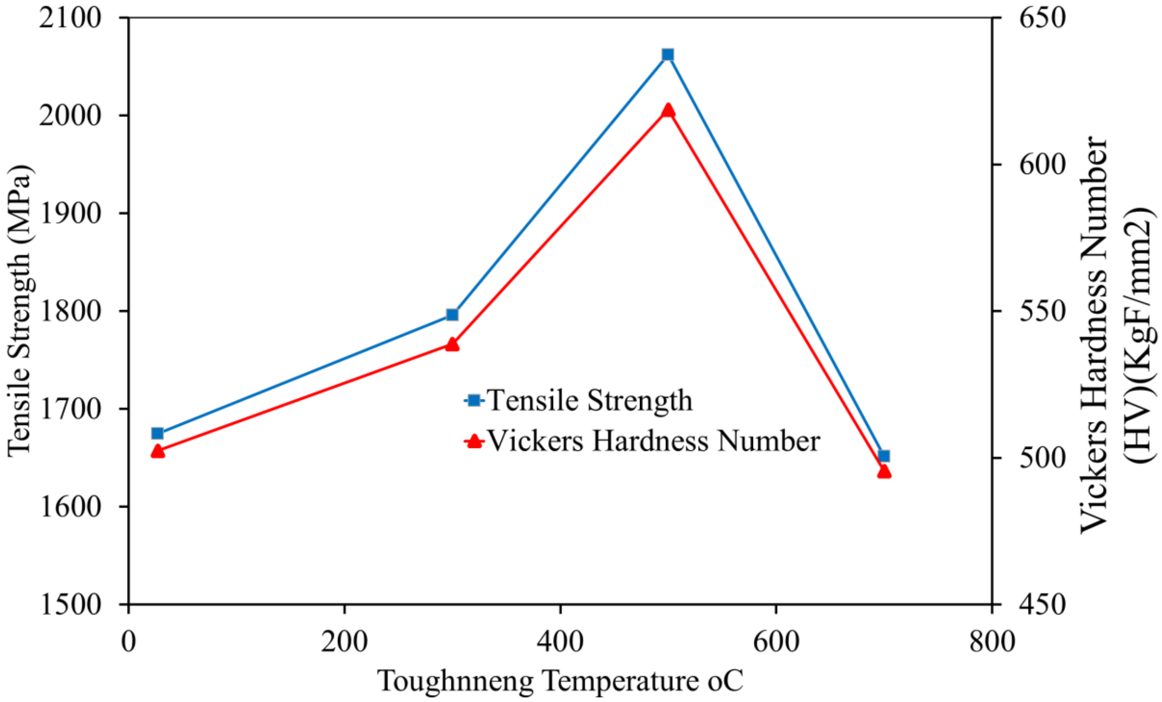

Figure 3.3: Variation of tensile strength and Vickers hardness number under different toughening temperatures.

CHAPTER FOUR

CONCLUSIONS

4.1Conclusions

In this project, we concluded that the toughening temperature significantly influences the mechanical and physical properties of glass, including its strength, toughness, surface compression, residual stresses, fracture behavior, density, and annealing characteristics. Careful control of the toughening parameters is essential to achieve the desired mechanical performance and ensure the reliability and safety of toughened glass products. Toughened glass is less prone to crack propagation compared to untreated glass. The compressive stresses on the surface of the glass help inhibit the growth of cracks, thereby increasing the tensile strength and making it more resistant to fracture under tensile loads. The toughening process often results in a more uniform distribution of tensile strength throughout the glass. This means that toughened glass exhibits consistent tensile strength properties across its entire surface, reducing the likelihood of weak spots or vulnerabilities that could lead to failure under tensile stress. The increased tensile strength of toughened glass enhances its reliability and safety in various applications. It can withstand higher tensile loads and is less likely to fail catastrophically under tension, which is crucial for structural elements like glass facades, fences, and automotive windows.

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