Wonders of Glass

Synthesis, Elasticity and Application

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Allah is the Light of the heavens and the earth. The Parable of His Light is as if there were a Niche and within it a Lamp: the Lamp enclosed in glass: the glass as it were a brilliant star: Lit from a blessed Tree, an Olive, neither of the east nor of the west, whose oil is well-nigh luminous, though fire scarce touched it: Light upon Light! Allah doth guide whom He will to His Light: Allah doth set forth Parables for men: and Allah doth know all things.

(An-Noor, Chapter 24, Verse 35)

She (Balqis) was asked to enter the lofty Palace: but when she saw it, she thought it was a lake of water, and she (tucked up her skirts), uncovering her legs. He said: "This is but a palace paved smooth with slabs of glass." She said: "O my Lord! I have indeed wronged my soul: I do (now) submit (in Islam), with Solomon, to the Lord of the Worlds."

(An-Naml, Chapter 27, Verse 44)

If diamonds are forever, glass is eternal and for everything.
(md-glass.com)

Contents

ABSTRACT

The term 'glass' has a precise scientific meaning: a glass, or a substance in the glassy or vitreous state, is a material, formed by cooling down from the normal liquid state, which has shown no discontinuous change (such as crystallization or separation into more than one phase) at any temperature, but has become more or less rigid through a progressive increase in its viscosity. In common usage, the term 'glass' refers to a class of versatile materials of great practical usefulness, with a number of very characteristic properties which are typically hard and brittle solids, lustrous and often optically transparent. Glass is one type of amorphous solid material which also shows property of softening progressively and continuously when heated.

The term is usually applied to inorganic solids and not to plastics or other organics. Glasses do not have crystalline (non-crystalline) internal structure. Its molecules have a disordered arrangement, but there is enough cohesion to produce rigidity. Majority of glass seen in everyday life is transparent, but glass can also be translucent or opaque. In science, however, the term glass is usually defined in a much wider sense, including every solid that possesses a non-crystalline (i.e. amorphous) structure and that exhibits a glass transition when heated towards the liquid state.

The term 'glass' was developed in the late Roman Empire. It was in the Roman glassmaking center at Trier, now in modern Germany, that the late-Latin term *glesum* originated, probably from a Germanic word for a transparent, lustrous substance. Glasses can be made of quite different classes of materials. Glassy state, which is a universal property of supercooled liquids if they are cooled rapidly enough, is regarded as the fourth state of matter. The physics of glass is the science of the glassy or amorphous state of matter as seen from an atomic or molecular point of view.

The mysterious glass transition phenomenon, which connects the liquid and glassy states, is related widely to daily life, industry, materials preparation and a lot of natural phenomena. However, the exact and comprehensive physical understanding of the glass nature is considered to be one of the most challenging problems in condensed matter physics and material science. Due to their random disordered structure, the characterization of glasses is very difficult, and this leads to problems in understanding the formation, nature, and the structure-properties relationship of glasses.

The mechanics of solids, regarded as continuous media, forms the content of the theory of elasticity. The macroscopic behaviour of a solid is described by a continuum field theory, the theory of elasticity, which describes the way a solid deforms when stresses are applied. Glass itself provides plentiful precise knowledge of fundamental parameters of elastic modulus, which offer a benchmark reference point for understanding and applications of these materials.

In general, the elastic constants of glasses show a correlation with a weighted average of the elastic constants of the constituent elements. This information can be employed in selecting the constituent elements with suitable elasticity for controlling the elastic properties and glass-forming ability of the glasses, and thus the results would enable the design, control and tuning of the formation and properties of any type of glasses.

So far glass structure is still the basic foundation in understanding the behaviour of the material. Elasticity of any solid materials can be studied through ultrasonic investigation which is associated with the velocity of ultrasonic waves and bulk density. Hence the elastic moduli are particularly suitable for characterizing glasses as a function of composition. Elastic properties also provide vital information about the structure of solids and they are directly related to inter-atomic potentials.

Glass is normally lustrous and transparent in appearance and shows great durability when exposed to natural elements. Hence, glass applications are found to be common and varied in many implementations in human civilization and life, such as domestic appliances, construction elements, scientific investigation, medical devices and artistic items. Throughout history, glass has been used to make ornamental and decorative objects. In addition, it has been used for useful objects such as windows, containers, optical lenses and glass fibers. Its flexible character allows it to be shaped into a wide variety of forms and sizes, in addition to which glass's cohesiveness with other substance gives benefits in the form or new transitions. The varied applications are driven by one or several of the properties that make the use of glass so attractive.

This lecture comprehensively reviews the science of glass and the development of the study of the elastic properties of borate, phosphate and tellurite based glass systems, the establishment of correlations between elastic moduli and other physical properties of glass, and also the application and preparation techniques of glass. The goal is to show the key roles of elastic moduli in the study, formation, and understanding of several types of glasses, and to present a comprehensive elastic perspective on the major fundamental issues from its processing to structure to properties in this rapidly evolving field.

INTRODUCTION

What is Glass?

Glass is an inorganic product of fusion which has been cooled to a rigid condition without crystallizing (American Society for Testing Materials, 1945). However, glass can also be produced in other ways; for instance by the direct condensation of vapour or compressing a liquid or through electron beam irradiation (Doremus, 1994). Glass can be defined as any isotropic material, whether inorganic or organic, which lacks of three dimensional (3D) atomic periodicity and has a viscosity greater than about 10^{14} poise (Elliott, 1990). An even more general definition that has been proposed is that a glass is an X-ray amorphous material which exhibits a glass transition.

Pfaender (1996) also mentioned glass, among amorphous, homogeneous and isotropic^{-} materials, as the one material which can be solidified into a non-crystal from the melt. Glassy and vitreous, the words being derived from Indo-European roots and Latin (Doremus 1994), may be used synonymously. The terms glass, or vitreous, or more generally amorphous, have been used interchangeably by many and this practice is followed in this lecture. It is not our aim to review the physics of glass extensively since the definitive descriptions have been well documented and are available elsewhere.

In principle, glass shows two characteristic structural features that are short-range or first neighbour order and continuous framework of strong primary bonds. An amorphous or vitreous substance, even with identical chemical composition, differs from the crystalline state by its higher energy content (Mackenzie, 1982). The short-range order regions of a crystalline solid often continue to exist even after melting. On the other hand, as stated by Gupta

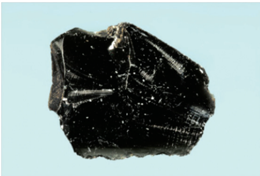
(1996), normally the transition to the liquid state is accompanied by reconstructive structural changes in the first coordination sphere. Glass has numerous properties in common with crystalline solids, such as hardness and elasticity of shape.

The structure and properties of glassy materials is more likely to define a glass as a hard solid in which arrangement of atoms or molecules is irregular in contrast to the highly-ordered arrangement in normal crystalline solids (Shelby, 2005). The high viscosity indicates that the atoms and/or molecules in the melt are not so easily moved relative to one another by applied stress (Elliott, 1994). The solid material with viscosity between 10^{12} to 10^{13} Poise is a glass. The process of crystallization involves structural changes involving the rearrangement of atoms relative to one another.

Glass Prehistory

According to Macfarlane & Martin (2004), no one is certain where, when or how glass originated. It may have appeared first in the Middle East, in regions such as Egypt and Mesopotamia, around 3000 to 2000 B.C. although there are hints of glazing on pottery as early as in 8000 B.C. However natural glass has existed since the beginnings of time, formed when certain types of rocks high in silicates melt as a result of high-temperature phenomena such as volcanic eruptions, lightning strikes on a beach which contains silicate-rich sand or the impact of meteorites, and then cool and solidify rapidly (Elliot, 1983). Stone-age man is believed to have used cutting tools made of obsidian (a natural glass of volcanic origin also known as hyalopsite, Iceland agate or mountain mahogany) (see Figure 1) and tektites (naturally-formed glasses of extraterrestrial or other origin, also referred to as obsidianites, a kind of alumino-silicate (SiO_2–Al_2O_3) glasses containing crystalline particles such as Fe_2O_3.).

Glass was almost certainly discovered by accident. According to the ancient-Roman historian Pliny (AD 23-79), Phoenician traders transporting stone actually discovered glass in the region of Syria around 5000 BC. Pliny tells how the merchants, after landing, rested cooking pots on blocks of nitrate placed by their fire. With the intense heat of the fire, the blocks eventually melted and mixed with the sand of the beach to form a shining and opaque liquid (Macfarlane & Martin, 2004).



Obsidian-super-heated sand or that rapidly cooled

Moldavite formed by meteorite impact (Besednice, Bohemia)

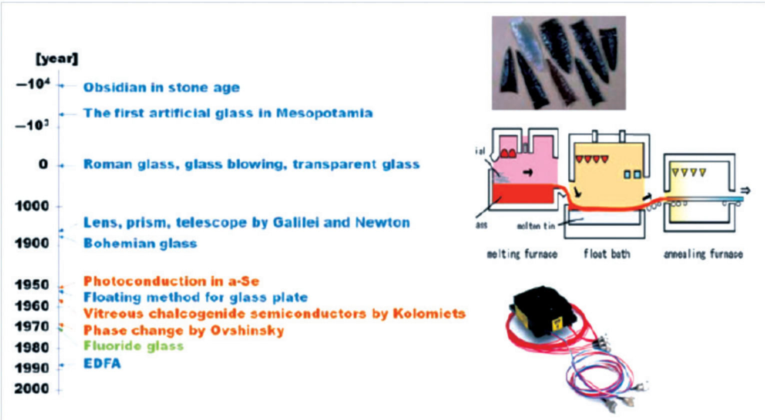


Figure 1 History of glasses, including oxide, chalcogenide, and fluoride. The pictures on the top show obsidian and moldavite, and the below right hand side show, from the *top* to the *bottom*, obsidian arrows, a floating method for producing window glasses, and an Er-doped fiber amplifier (EDFA)

As shown in Figure 1, the glassy material has a history longer than 5000 years. The first use of oxide glass by mankind seemed to have started with natural glasses such as obsidian for decoration, money and the tips of spears, knives and arrowheads in the stone ages, but before long, ingenious humans discovered their own process for making glass (Doremus 1994). Early forms of glass were probably rife with impurities and subject to cracking and other instability, but examples of glass beads, jars and eating materials first appeared in ancient Egyptian culture. Egyptian craftsmen developed a method for producing glass vessels around 1500 B.C., and the first manual of glassmaking appeared on Assyrian stone tablets about 650 B.C. About 5000 years ago, people in Mesopotamia might have accidentally discovered a method of producing artificial glass using sand (SiO_2) and salt (NaCl), which could yield soda-silicate glasses (SiO_2 –Na_2O) in charcoal fires (Macfarlane & Martin, 2004). Due to the unavoidable metallic impurities such as Fe, glasses from that era were thus necessarily colored, which might make the glass ornamental in nature. Syrian craftsmen invented glassblowing, a skill adopted by the Romans, who carried it with them as they swept through western Europe on their conquests (Holloway, 1973).

The rise of Venice to prominence in the 13th century enabled this city to become the center of glassmaking in the western world. As the industrial revolution gathered momentum, new manufacturing technologies enabled the mass production of glass scientific instruments, bottles, window panes, and many other items.

In the Roman age (1st century B.C.–A.D. 5th century), however, transparent wine glasses became available. Later, in the 17th century, Galilei and Newton employed transparent glasses as optical components, e.g., lenses and prisms. Optical instruments such as eyeglasses, telescopes, microscopes, and prism monochromators were also devised. Gradually, wider and flatter glass plates became available, which were employed as stained glasses in churches.

Glass plates could also be coated with silver, producing mirrors, which replaced polished metal mirrors. However, the glass might have been very expensive till the 19th century. Around 1955, Pilkington and co-workers developed the so-called floating method (Figure 1, middle) for commercial production of large glass plates, which came to be widely utilized as windows. And, at the end of the 20th century, researchers in Corning devised a preparation method called outside vapor deposition, which can produce ultimately-transparent and long (~100 km) glass fibers, a kind of photonics glasses, in which the purity (better than ppm) is a determinative factor as that in many crystalline semiconductors. In addition, functional devices such as fiber amplifiers (Figure 1, bottom) have also been produced using glass (Doremus, 1994).

Functional Materials for Mankind

Glass is believed to be one the most versatile substances on Earth, used in many applications and in a wide variety of forms, from plain clear glass to tempered and tinted varieties, and so forth. Earlier, when manufactured by humans, glass was a mixture of silica, soda and lime. Other materials were sometimes added to the mixture to “frost” or cloud the glass or to add colour. The elements of glass were heated to 982° Celsius (Rawson, 1980) and the resulting fused liquid could be poured into molds or blown into various shapes, and when cooled, the glass formed was a strong, minimally conducting substance that did not interact with the materials stored inside. As a result, glass is frequently used in scientific laboratories to minimize inadvertent chemical reactions and to insulate power lines.

Glass is a strange substance, defying easy scientific categorization. It is not a solid, not a gas, and not quite a liquid either. Generally, it is classified as a rigid liquid, maintaining liquid properties while acting like a solid. Heat can return the glass to a liquid and workable form, making it easy to reuse and recycle.

As depicted in Figure 2, glass is a favoured material for a lot of reasons. It resists chemical interactions, it is easy to recycle, it does not leach chemicals like plastics do, and it can withstand extremes of heat and cold, although not at the same time. Tempered or safety glass is used in a wide variety of applications and virtually all consumers use many forms of glass daily.


Optical fiber


Camera lens


Laboratory flask


Halogen lamp

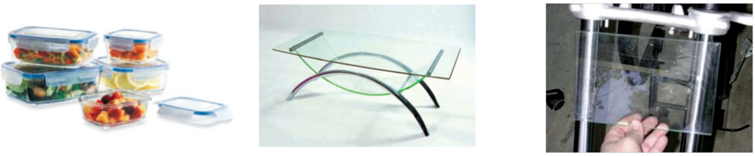

Telecopes


LCD Panel


Green House


Bulb


Fluorescent tube



Dishware Table Flat glass

Figure 2 Some application of glassy materials (Common creative 2011)

Glasses also have special properties which are hard to find in other industrial materials such as engineering materials. This is because glasses have a good combination of transparency and hardness at room temperature along with sufficient strength and excellent corrosion resistance to most normal environments. The most obvious characteristic of ordinary glass is that it is transparent to visible light. This transparency is due to an absence of electronic transition states in the range of visible light and because ordinary glass is homogeneous on all length scales greater than the wavelength of visible light (Shelby, 2005).

Glasses also have the ability to provide a vacuum light, where it is the main material used in the chemical, electrical and electronic industry (see Figure 2). Interest in inorganic oxides and their mixtures of glasses has rapidly increased in recent years because of diverse applications in electronics, nuclear and solar energy technologies and optic devices.

Fascinating Materials - Coloured Glass

Generally glass is a colourless material. Early glass derived its colour from impurities that were present when the glass was formed. For example, ‘black bottle glass’ was a dark brown or green glass, first produced in 17th Century England. This glass was dark due to the effects of the iron impurities in the sand used to make the glass and the sulphur from the smoke of the burning coal used to melt the glass (Shelby, 2005). In addition to natural impurities, glass is coloured by purposely introducing minerals or purified metal salts (pigments), as shown in Table 1.

Table 1 Some pigments used to produce coloured glass

Compounds	**Colors**	**Compounds**	**Colors**
iron oxides	greens, browns	selenium compounds	reds
manganese oxides	deep amber, amethyst, decolorizer	carbon oxides	amber/ brown
cobalt oxide	deep blue	mix of manganese, cobalt, iron	black
gold chloride	ruby red	antimony oxides	white
uranium oxides	yellow green (glows!)	sulfur compounds	amber/ brown
copper compounds	light blue, red	tin compounds	white
lead with antimony	yellow		

Figure 3 Some examples of coloured glass used as decoration items (Common creative 2011)

Color in glass (Figure 3) can also be obtained by addition of electrically charged ions and by precipitation of finely dispersed particles (such as in photochromic glasses). Ordinary soda-lime glass appears colorless while iron(II) oxide (FeO) impurities of up to 0.1 wt% produce a green tint. Further, FeO and Cr_2O_3 additions may be used for the production of green bottles. Sulfur, together with carbon and iron salts, is used to form iron polysulfides and produce amber glass ranging from yellowish to almost black. Further, manganese dioxide can be added in small amounts to remove the green tint given by iron(II) oxide.

World Glass Demand

The world market for glass in 2007, as reported by ReportLinker (2011), was at around 44 million tonnes, equivalent to 4.4 billion square metres of glass with a thickness of 4 mm. This represents a value, at the level of primary manufacture, of about US$20 billion. At present, the world demand, especially for flat glass, is forecast to rise 6.0 percent per year through to 2014, to 8.1 billion square meters. Maintaining the trend seen over the 1999-2009 period, this demand will easily outpace real (i.e., inflation-adjusted) gains in the global economy as depicted in Figure 4.

The market value of fabricated glass (basic flat glass as well as value added products such as laminated, tempered, insulating glazing (for building applications) or automotive glazing and mirrored glass) is forecast to reach almost $90 billion in 2014. Gains will be spurred by continued robust growth in the Asia/ Pacific region, as well as by recovery in the building construction and motor vehicle industries in North America and Western Europe after the recession (AGC, 2011).

Fabricated flat glass demand will benefit from rapid growth in more expensive products such as solar control glass, low-e glass, smart glass, self-cleaning glass and head-up-display (HUD) windshields. In recent years, glass used in solar energy applications has witnessed surging growth in demand, a trend that will accelerate through 2014 due to increasing government support around the world for renewable energy (ReportLinker, 2011).

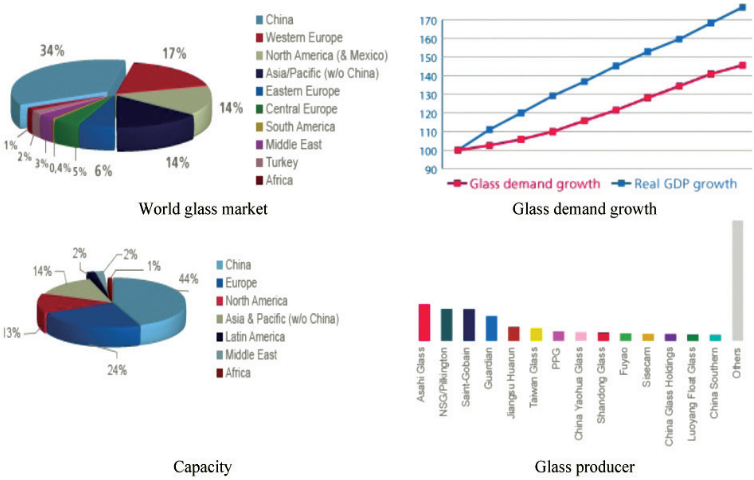


Figure 4 The world demand for flat glass and the glass producers (AGC, 2011)

On a square meter basis, however, solar energy applications account for a very small share of global flat glass demand. Value gains in glass demand will be aided by more rapid gains in laminated glass demand than in lower value tempered glass demand.

As reported by AGC (2011) China is now the biggest market in the world as depicted in Figure 4. Europe, North America and China, between themselves, account for 80% of world glass demand. China's share of world flat glass demand in square meters will rise from 40 percent in 2009 to 43 percent in 2014. The country's share of world fabricated flat glass demand, in value, will stand at a less significant but still impressive 32 percent in 2014. Basic unfabricated float glass continues to account for a disproportionate share of the overall Chinese flat glass market due to the frenetic pace of building construction activity taking place in the country, often necessitating the utilization of the cheapest materials available. Further, other developing Asian countries such as India and Thailand will post particularly impressive gains, given that their base level of demand is currently many times smaller than China's (ReportLinker, 2011).

Growth in demand for flat glass has generally outpaced real GDP growth for the past 20 years. This is true not only for emerging markets, where demand is boosted by the booming automotive and construction sectors, as in China or Russia, but also for mature markets (Japan, western Europe or North America) where higher performance and added value are required. New applications for glass also contribute to this growth. Innovation has extended the range of uses for glass and allowed it to play a greater role in the world in which we live. World demand has been growing by 5 to 7% in recent years, and the trend is expected to be similarly at around 5% in the coming years.

Total installed (or designed) capacity (Figure 4) is about 65 million tonnes annually, which means that 185,000 tonnes of glass is pulled every day. A breakdown of float capacity shows a similar profile to that of demand, China being the leader. Indeed in recent years there has been major increase of float capacity in China. This development has also brought new players into the glass industry.

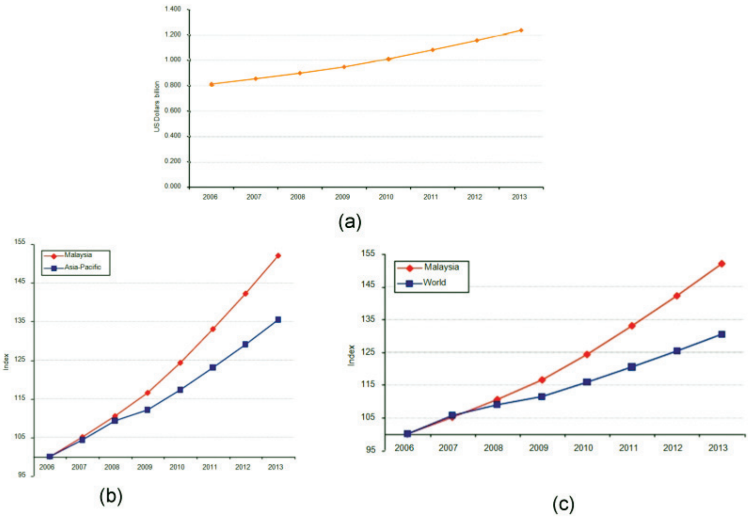


Figure 5 (a) Forecast for glass in Malaysia, and compared with those (b) Asia-Pacific and (b) world (Gobi International, 2010)

Figure 4 also shows the world glass producers. AGC is the first world producer followed by NSG (Japan), Saint-Gobain (France) and Guardian (USA). These are also the only four global players with operations in the Americas, Europe and Asia. AGC has recently expanded capacity in Russia (Klin 2005), Czech Republic (Retenice 2007) and in China (Suzhou 2006). A project is ongoing in Russia (Klin 2) where the largest tank in the world (1.000Tons per day) is under construction and is scheduled to start production in the first quarter 2009 (AGC, 2011).

Statistical market forecast for glass in Malaysia, as provided by Gobi International, 2010 (26 April 2010), shows the consolidated demand for glass and glass products. This includes flat glass, pressed and blown glass and glass containers. The market forecast from 2006 to 2013 is shown in Figure 5(a). Meanwhile the Malaysian market forecast is compared to the Asia-Pacific and world forecast in the index shown in Figure 5(b-c).

Glass Research and Production in Malaysia

The R&D activities in glassy materials are mainly carried out at Institutes of Higher learning (such as Universiti Putra Malaysia (UPM), Universiti Teknologi Malaysia (UTM), Universiti Teknologi MARA (UiTM), Universiti Pendidikan Sultan Idris (UPSI) and government research institutes such as the Minerals and Geoscience Department Malaysia and Natural Resource and Environment Ministry.

The private sector's involvement in R&D in glassy materials is minimal due to the fact that most industries related to advanced materials are not local and hence the R&D activities are usually carried out in the parent company. Table 2 shows a number of glass companies operating in Malaysia.

Table 2 Some of the glass companies operating in Malaysia

Company	Website	Product/Service
Malaysian Sheet Glass Sdn Bhd (Pilkington)	www.msg.com.my	Flat glass and automotive glass industry Sheet, wired, figured, float, tinted and tempered glass
SCHOTT Glass Malaysia	www.schott.com/sgm/english/	Lens, prisms, optical product
Kien Safety Glass Sdn Bhd	www.ksg.com.my	Tempered Glass, Heat Strengthened Glass, Heat Soak Glass, Laminated Glass, Refshine (Reflective Glass), Double Glazing Units (DGU)
Emhart Glass	www.emhartglass.com	Glass container manufacturers

Vest Nucleus Sdn. Bhd.	www.alibaba.com/member/vestnucleus/	Tableware, dinnerware, Glassware Crystal Vases
Poly Glass Fibre, (M) Bhd	www.polyglass.com.my/	Glass wool
Malaya Glass Products Sdn Bhd	www.malayaglass.com	Manufacture of glass bottles and other glass containers
GlassKote (Malaysia) Sdn. Bhd.	www.glasskote.com.my	Colour coating process for glass

In UPM glass research activities began at the Department of Physics, Faculty of Science, in the late 1990s where we successfully managed to prepare and elastically characterize zinc chloride phosphate glasses using the ultrasonic system (Sidek et al., 1995). Table 3 shows the glass research scope, lead researchers and types of glass being studied at the Universiti Putra Malaysia.

Table 3 Glass research activities conducted at Universiti Putra Malaysia

Glass Type	Research Scope	Researchers
Borate Based Glass		
Lithium Chloroborate	Ultrasonic Studies	Sidek et al. (1999)
Lead Borate	Preparation and Elastic Properties	Azman et al. (2002)
Lead Bismuth Borate	Elastic Constant and Thermal Properties	Hamezan et al. (2006)
	Ultrasonic and Thermal Properties	Sidek et al. (2006)
Bismuth Borate Glass	Formation and Elastic Behaviour	Sidek et al. (2008)
Phosphate Based Glass		
Zink Chloride Phosphate	Preparation and Elastic Behaviour	Sidek et al. (1995)
	Elastic and Anelastic Properties	Sidek et al. (1998)
Silver Phosphate	AC Conductivity	Chow et al. (1998)
Lithium Phosphate	Elastic Properties	Low et al. (1999)
Lithium Chlorophosphate	Elastic Properties	Low et al. (1999)
Lead Magnesium Chlorophosphate	Formation and Elastic Behaviour	Sidek et al. (2004)
Lithium Chloride Phosphate	Dielectric Properties	Loh et al. (2005)

Lithium Zink Phosphate	Physical and Elastic Properties	Sidek et al. (2005)
Lead Zink Metaphosphate	Elastic Properties	Sidek et al. (2005)
Lead Bismuth Phosphate	Optical Characterization	Sidek et al. (2005)
	Elastic and Thermal Properties	Hamezan et al. (2005)
Lithium Chloride Phosphate	Dielectric Properties	Loh et al. (2005)
Lithium Zink Phosphate	Physical and Elastic Properties	Sidek et al. (2005)
Lead Zink Metaphosphate	Elastic Properties	Sidek et al. (2005)
Lead Bismuth Phosphate	Optical Characterization	Sidek et al. (2005)
	Elastic and Thermal Properties	Hamezan et al. (2005)
	Ultrasonic and Thermal Properties	Sidek et al. (2006)
Zinc magnesium phosphate	Degradation Studies	Khor et al. (2011)
Tellurite Based Glass		
Silver Borotellurite	Ultrasonic Studies	Halimah et al. (2005)
Borotellurite	Ultrasonic and Physical Properties	Halimah et al. (2005)
	Optical Properties	Halimah et al. (2005)
	Ultrasonic Studies	Halimah et al. (2005)
	Synthesis and Elastic Behaviour	Sidek et al. (2006)

Zinc Tellurite	Infrared and Ultra Violet Spectral Studies	Rosmawati et al. (2007)
	Physical Properties	Rosmawati et al. (2007)
Borotellurite	Qualitative Analysis	Sidek et al. (2007a)
	Elastic Behaviour	Sidek et al. (2007b)
	Structural Analysis	Halimah et al. (2007)
Zinc Tellurite	Physical Properties	Rosmawati et al. (2008)
	Synthesis and Optical Properties	Sidek et al. (2009)
Zinc oxyfluorotellurite	Elastic Properties	Sidek et al. (2009)
Borotellurite	Elastic Properties	Halimah et al. (2010)
Lead Borotellurite	Structural and Optical Properties	Iskandar et al. (2010)
Silver Borotellurite	Elastic Properties	Halimah et al. (2010)
	Optical Properties	Halimah et al. (2010)
Zinc Neodymium Tellurite	Structural and Elastic Properties	Mohamed et al. (2010)
Zinc borotellurite	Optical Properties	Ayuni et al. (2011)
Zinc oxyfluorotellurite	Elastic Properties	Sidek et al. (2011a)
	Ultrasonic Characterization	Sidek et al. (2011b)

Ferum Tellurite	Magnetic Behaviour	Zarifah et al. (2011)
Other types of glass		
TeO_2-PbO-Li_2O-Nd_2O_3	Elastic Properties	Azman et al. (2007)
Nano silicate based glass ceramic	Preparation and properties	Norfaizah et al. (2009)
Amorphous White Silica From Rice Husk	Preparation	Matori et al. (2009)
Zinc soda lime silicate	Elastic moduli	Zaid et al. (2011)

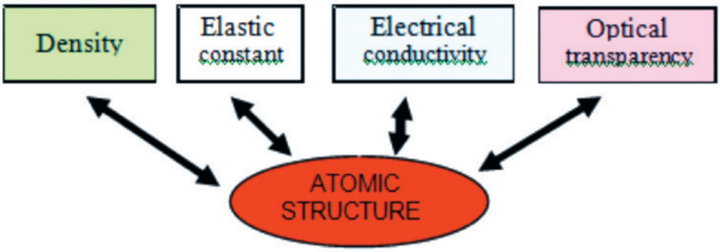


Figure 6 A goal of solid-state science, which intends to give universal understandings of macroscopic properties through simple theories on the basis of known atomic structures

In short our glass research activities are more focussed on the borate, phosphate and tellurite types only. Their physical properties comprising mainly elastic, thermal, optical etc have been studied using a number of relevant research instrumentation. Commonly the goal of solid-state science is to connect atomic structures and other macroscopic properties using simple theories where we try to bridge atomic structures and physical properties as shown in Figure 6. In such ways, relationships among different macroscopic properties can be understood.

However, so far, we cannot as yet identify the glass structure. In addition, macroscopic properties are likely to vary depending upon the quasi-stability of non-crystalline solids. Needless to say, in theoretical analyses, such an assumption as the periodic boundary condition cannot be applied to the disordered structure, and thus, the amorphous materials' science remains far behind the crystalline materials science. This lecture thus, only summarizes marked progress made in the study of a number of glassy materials covering the scope of density and elasticity.

BASICS OF GLASS STRUCTURE AND SYNTHESIS

Random Network Theory

Zachariasen (1932) suggested that a glass could be modelled by a random network of atoms by stating:- (a) Each oxygen atom has coordination number of two, which means that no oxygen atom can be linked to more than two network cations; (b) The number of oxygen atoms surrounding the network cation must be small, spefically 3 or 4; (c) Oxygen polyhedra share corners, not edges or faces; and (d) The network can only be 3D if at least three corners of each oxygen polyhedron are shared. The investigation of the structure of simple glasses through an X-ray diffraction method by Warren in 1942 substantially confirmed Zachariasen's concept – the absence of the periodically and symmetry in a glassy network (Gaskell, 1995) and since then this model (Figure 7) has become widely known as the Random Network Theory (Warren, 1942).

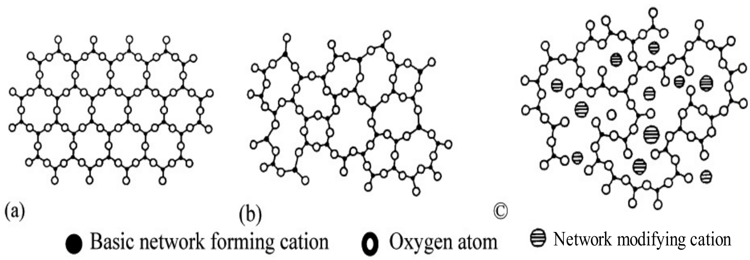


Figure 7 Schematic two-dimensional representation of the microscopic structure of (a) an oxide crystal, (b) binary oxide glass composed of basic glass former and glass former; (b) showing the effect of network modifying cations on the network of the glass former (Phillips, 1980).

The network former, network modifiers, intermediate compounds and doping salt are four compounds that play an important role in determining the properties of glass.

Network Formers are covalently bonded compounds. Some examples of these network formers are oxides of silicon, boron, phosphorus, germanium, sodium, calcium, lithium and arsenic, which are all known to form tetrahedral structural units which share corners in crystalline compounds, and all form glasses. BO forms triangles and can readily produce a glass.

With the four rules as proposed by Zachariasen (1932), there are oxides of types AO_2, A_2O_3 and A_2O_5 which can easily form glasses, where A is designated a cation such as SiO_2, GeO_2, B_2O_3, P_2O_5 and As_2O_3. Normally the glass formers have high melting temperature, such as SiO_2 (1610˚C), B_2O_3 (450˚C), and P_2O_5 (580˚C). Hence, they have high resistance against chemical attack due to their continuous rigidly held oxygen bonds.

Network Modifiers are compounds with a marked ionic feature and include the oxides and chalcogenides of alkali, alkaline earth and silver ions, such as Na_2O, K_2O, LiO_2, CaO, MgO and ZnO. They do not form glass alone, but they will react with the glass former and become incorporate in it, where their presence will induce changes in the glass network (Macfarlane & Martin, 2004). This reaction will cause the rupturing of the oxygen or chalcogenide bond which is connected to two glass cations. In this way, the ionic bonds are created between the positively-charged interstitial modifier cations and negatively-charged covalent chains.

The existence of the modifier not only changes the network structure and bonding, but will also affect the network's rigidity, net charge and distribution of interconnected interstices at the same time. As a result, a drastic effect is reflected over the physical properties, such as melting point, glass transition temperature T_g, density, shear moduli, etc. (Phillips, 1980).

Intermediate Compounds are the oxides having single bound strength, such as the oxide of iron, titanium and aluminium. They cannot form glass on their own but will behave as glass former, when combined with glass formers. They may also occupy the holes in between a network former. They become incorporated in the macromolecular chain with intermediate cation substituting the network former cations.

Doping Salts are only introduced into a vitreous network which already consists of at least a glass former and a modifier. The salt dissolves in the vitreous matrix but the anions (mostly a halogenide or a sulphate) do not incorporate in the existing glass network, but accommodate interstitially in the macromolecular chain. The structure is then defined as an anionic sub-network consisting of two types of ions (a macroanion from the former and discrete ions from the doping salt) combined with cations. It is however difficult to specify the distribution of the anions of the doping salt.

Structure of Binary Borate Glass

Early studies on B_2O_3 glass structure by means of X-ray diffraction method (Warren, 1942) indicated that the pure glass is composed of a random network in which each boron atom is triangularly bonded to three oxygen atoms and each oxygen atom is bonded to two boron atoms. Phillips (1980) considered a pure B_2O_3 glass as a molecular solid composed of $(B_2O_3)_2$ molecules. Nuclear magnetic resonance (NMR) experiments have confirmed that glassy B_2O_3 consists of some planar BO_3 units which are randomly arranged in a three-dimensional network by sharing all three oxygen atoms with adjacent BO_3 units (Varshneya, 1994).

The planar BO_3 unit presumably involves sp^2 hybridization, with the third p orbital being vacant and extending in a direction perpendicular to the BO_3 plane. This vacant orbital accepts electron density from the unpaired electrons of the oxygen atoms, forming a partial double bond as evidenced by a shortening of the B-O bond from a normal single bond value of approximately 1.50Å to about 1.35Å.

An addition of an ionic oxide M_2O (i.e M = Ag, Li, Na, K) into a pure borate (B_2O_3) glass, in order to obtain B_2O_3-xM_2O glass where x is a molar fraction of M_2O, produces the following network modifications (Mackenzie, 1987):- (a) The B-O-B bond may be broken by oxygen anions in order to form non-bridging terminal oxygen atoms (Figure 8c); (b) A filled orbital of an oxygen anion may overlap with an empty p orbital on a boron atom, resulting in a change of hybridization of the boron atom to the sp^3 tetrahedral configuration and as a consequence, a BO_4 tetrahedron with three bridging and one terminal oxygen atoms is formed; and (c) An oxygen atom may contribute electron pairs to two BO_3 units which causes the change in coordination of two borons from sp^2 to sp^3 hybridization and no terminal oxygen atom is observed.

In fact all these possible processes are believed to occur depending on the concentration of the ionic oxide M_2O present in the borate glass system. Osaka et al. (1987) reported that a successive addition of ionic oxides into the pure borate glass results in change of the average coordination of boron atom, where this is normally known as the "borate anomaly". That such an anomaly occurs has been supported by means of NMR, X-ray diffraction and also ultrasonic experiments.

In general, in the range from pure B_2O_3 to 30 mole percent of M_2O, all oxide ions are involved in the process of increasing the coordination number of boron atoms from 3 to 4. When between 30 and 50 mole percent the proportion of tetrahedral and planar triangles remains relatively constant and above 50 mole percent the process reverses and the planar triangle of BO_3 rapidly become favored until at 70 mole percent of M_2O all boron atoms will once again have the coordination number of 3 (Feltz, 1993). An increment of ionic oxide M_2O causes a progressive change of the boron coordination number resulting in the network formation of various structural group units as illustrated in Figure 8. These structural groupings are composed of BO_3 and BO_4 polyhedra as found in crystalline borate. The concentration of these groups depends on the mole percent of M_2O introduced into the borate glass system.

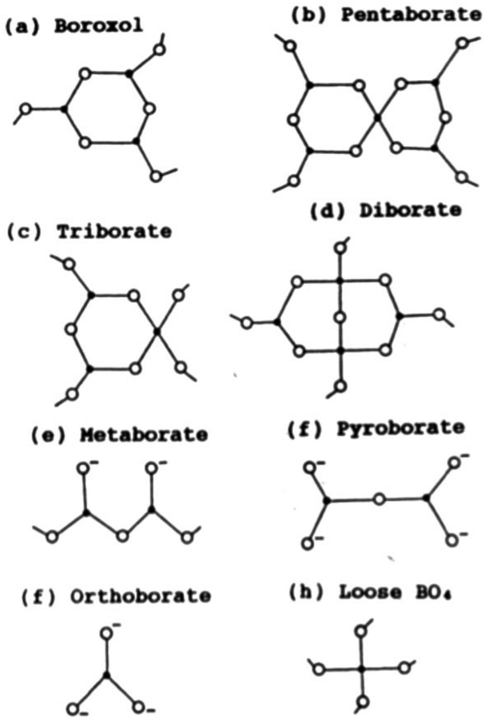


Figure 8 Some structural groupings in borate glasses as indicated from nuclear magnetic resonance experiments (Doremus, 1994). Small solid circles represent boron atoms, open circles oxygen atoms and an open circle with negative sign indicates non-bridging oxygen

Structure of Binary Phosphate Glass

The concepts involved in the structure of phosphate crystals and glasses have been discussed in detail by numerous workers (Gutzow & Schmelzer, 1995). Briefly, at room temperature, the thermodynamically stable P_2O_5 crystal consists of discrete P_4O_{10} molecules, in which each phosphorus atom is surrounded by three bridging and one terminal oxygen atoms. The P-O bond is covalent in nature and the terminal P-O bonds (1.39Å) are significantly shorter than the bridging bonds (1.62Å).

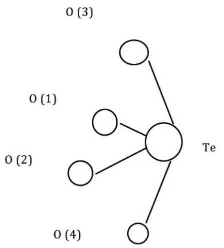
The basic structural unit in pure P_2O_5 and binary phosphate glasses is a tetrahedral PO_4 group, similar to those of binary silicate glasses. This has been confirmed by low-angle X-ray and neutron scattering experiments (Doremus, 1994). In this structural unit, the phosphorus atom is covalently bonded to four oxygen atoms which lie at the corners of a tetrahedron. In the case of calcium metaphosphate glass, the P-O-P bond angle is approximately 140^0. The PO_4 tetrahedral are linked together to form the three dimensional network of the glass structure. The total number of oxygen atoms in a phosphate glass is always greater than twice the number of phosphorus atoms, and therefore for all compositions there is an appreciable number of oxygen atoms which are bonded only to one phosphorus as well as those that are bonded to two phosphorus atoms (Fanderlik, 1983).

The possible microscopic structure of the binary glasses in the composition range between highly P_2O_5 and 50 mole% metal oxide is essentially a random network of the type described by Zachariasen (1932). Within the range of 50 to 60 mole % of metal oxides, mixtures of small rings and chains of varying lengths in relative amounts dependent on the composition are present in a phosphate glass. From 60 to 70 mole% metal oxides, only chains occur. So in brief, increasing concentrations of modifying oxides result in an increasing number of singly bonded oxygen atoms.

Structure of Binary Tellurite Glass

Kozhukharov (1983) presented data containing two crystalline forms of TeO_2, including a yellow orthorhombic form (the mineral tellurite) and a colorless tetragonal form (paratellurite). There are 4 coordinations of Te in both forms, the nearest neighbours being arranged at four of the vertices of a trigonal bipyramid, which suggests a considerable covalent character to the Te-O bonds. Tellurite has a layered structure in which TeO_4 groups form edge-sharing pairs that then form a layer by sharing their remaining vertices. The short Te-Te distance, 3.17 Å (compare with the shortest in paratellurite, 3.47 Å) may account for its color. In paratellurite, very similar TeO_4 groups share all vertices to form a 3D structure with 4:2 coordination in which the O-bond angle is 140^0, distances of the two axial bonds are 2.08 Å, and distances of the two equatorial bonds are 1.9 Å.

Lanqvist (1968) stated that the structure of α-TeO_2 was defined in terms of a three dimensional (3D) network built up from TeO_4 subunits, with each oxygen atom shared by two units, bonded in the equatorial position to one tellurium atom, and in the axial position to another, as illustrated in Figure 9.



Components	Distance (Å)
$TeO_1 - TeO_2$	1.903
$TeO_3 - TeO_4$	2.082
Te - Te	3.740, 3.827, 4.070
$O_1 - O_2$	2.959
$O_{1\text{-}}O_3 - O_{2\text{-}}O_4$	2.686
$O_{1\text{-}}O_4 - O_{2\text{-}}O_3$	2.775
$O_3 - O_4$	4.144

Figure 9 Schematic of the TeO_2 unit and distances between components in the structure of α-TeO_2 (Lanqvist, 1968)

Glass Formation

In order to explain the glass formation, it is easier to understand by referring to the volume-temperature diagram as shown in Figure 10 (Feltz, 1993). At the usual melting temperature, the glasses are highly viscous liquids. When the glass is cooled, their viscosity increases progressively and continuously. This continuous transition from a liquid to a solid condition provides the distinction between glasses and crystalline solids.

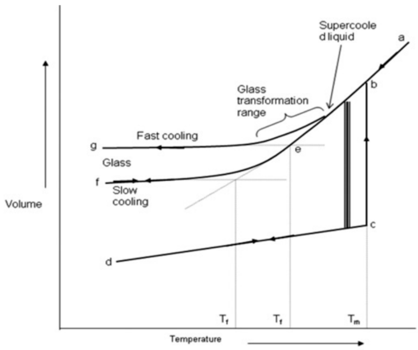


Figure 10 The volume-temperature diagram for a glass-forming liquid (Shelby, 2005)

When the melt or liquid form is cooled, its initial state is represented by the point *a*, and the volume of a given mass decreases steadily along the path *ab*. Point *b* corresponds to the melting point of the corresponding crystal, T_m. When the liquid is cooled very slowly an abrupt change occurs in the specific volume and in other physical properties at the melting point, T_m, where the material crystallizes. Large number of nucleus are present in the mass and have large enough subsequent crystal growth rate. On further cooling, the crystalline material contracts along *cd*.

When the liquid is cooled rapidly there is no abrupt change in specific volume at any temperature, instead the slope of the specific volume-temperature curve changes continuously over a range of temperature. Crystallization does not occur. As the cooling continues, the volume of the now supercooled liquid decreases along the line *be*, which is a smooth continuation of *ab* since the liquid has to rearrange itself into a lower volume as required by the lower energy corresponding to the lowered temperature.

At sufficiently low temperatures, the molecular group is not able to rearrange themselves fast enough to reach the volume characteristic of the temperature. The straight line then starts a smooth departure from *be* and soon becomes a near straight line that often is roughly parallel to *cd* and then ending at point *f*.

The temperature T_g, at which the bend occurs, is called the transformation temperature or glass transition temperature. Only below T_g is it correct to describe a material as a glass. Between T_g and T_m, the material is a supercooled liquid. It can thus be concluded that the formation of glasses is dependent upon the rate of cooling.

Glass Preparation Techniques

There are various methods in producing glass, from the conventional method to modern techniques and from small batch operations producing a few kilograms to large continuous processes producing tonnes per day. The range of glasses made is wider than ever before and now includes chalcogenides, fluorides and metals as well as oxides, while the variety of techniques available for producing them has also expanded notably in recent years.

Although glasses can be made by a wide variety of methods, the vast majority are still produced by melting of batch components at an elevated temperature (Shelby, 2005). This procedure always involves the selection of raw materials, calculation of the relative proportions of each to use in the batch, and weighing and mixing these materials to provide a homogeneous starting material. During the initial heating process, these raw materials undergo a series of chemical and physical changes to produce the melt.

The binary borate, phosphate and tellurite glass series in the form of (X-B_2O_3), (Y-P_2O_5) and (Z-TeO_2), as listed in Table 4, have been successfully synthesized by rapid melt quenching techniques. The ternary glass samples of borate, phosphate and tellurite systems are also included in Table 4. The binary and ternary systems consist of oxides of glass former and glass or network modifiers.

Since the oxidation and reduction reactions in a glass melt are known to depend on the size of the melt, on the sample geometry, on whether the melt is static or stirred, on thermal history and on quenching rate, all glass samples were prepared under similar conditions to minimize the factors (Sidek et al., 2009).

Table 4 Some of the selected prepared binary and ternary glass samples at the Department of Physics, Universiti Putra Malaysia.

Glass Oxide Former	Modifier	Glass Samples	Researchers
Binary Oxide Glass Series			
Borate (B)	Silver (Ag)	Ag_2O-B_2O_3	Sidek et al. (1994)
	Lead (Pb)	PbO-B_2O_3	Azman et al. (2002)
	Bismuth (Bi)	Bi_2O_3-B_2O_3	Sidek et al.(2007)
Phosphate (P)	Lithium (Li)	Li_2O-P_2O_5	Low et al. (1999) Sidek et al.(2003)
	Lead (Pb)	PbO-B_2O_3	Azman et al. (2002) Talib et al. (2003)
	Lead Chloride ($PbCl_2$)	$PbCl_2$-P_2O_5	Talib et al. (2003)
	Lithium Chloride (LiCl)	$LiCl$-P_2O_5	Loh et al. (2005)
Tellurite (Te)	Boron (B)	B_2O_3-TeO_2	Halimah et al.(2005) Sidek et al.(2006)
	Zink (Zn)	ZnO-TeO_2	Rosmawati et al. (2008) Sidek et al.(2009)
	Ferrum (Fe)	Fe_2O_3-TeO_2	Zarifah et al. (2010)

Glass Former	Network Modifier		Glass Samples	Researchers
Ternary Oxide Glass Series				
Borate (B)	Bismuth (Bi)	Lead (Pb)	PbO-Bi_2O_3-B_2O_3	Sidek et al. (2005) Hamezan et al.(2006)
Phosphate (P)	Lithium (Li)	Lithium Chloride (LiCl)	LiCl-Li_2O-P_2O_5	Low et al. (1999) Sidek et al.(2003)
	Magnesium (Mg)	Lead Chloride ($PbCl_2$)	PbCl2-MgO-P2O5	Sidek et al.(2004)
	Zink (Zn)	Lithium (Pb)	Li_2O-ZnO-P_2O_5	Sidek et al.(2005)
	Zink (Zn)	Lead (Pb)	PbO-ZnO-P_2O_5	Sidek et al.(2005)
	Bismuth (Bi)	Lead (Pb)	PbO-Bi_2O_3-P_2O_5	Sidek et al.(2006)
	Calsium (Ca)	Copper (Cu)	Cu_2O-CaO-P_2O_5	Talib et al. (2008)
Tellurite (Te)	Boron (B)	Silver (Ag)	Ag_2O-B_2O_3-TeO_2	Halimah et al. (2005)
	Zink (Zn)	Aluminum Floride (AlF)	AlF-ZnO-TeO_2	Sidek et al.(2009)
	Boron (B)	Lead (Pb)	PbO- B_2O_3-TeO_2	Iskandar et al. (2010)
	Zink (Zn)	Neodymium (Nb)	Nb_2O_5- ZnO- TeO_2	Mohamed et al. (2010)
	Boron (B)	Zink (Zn)	ZnO- B_2O_3-TeO_2	Ayuni et al (2011)

An example of preparation technique for the series of binary borate, $(Ag_2O)_x (B_2O_3)_{1-x}$ glasses is described as follow. The series of binary borate, $(Ag_2O)_x (B_2O_3)_{1-x}$ glasses and bismuth borate $(Bi_2O_3)_x(B_2O_3)_{1-x}$ glasses were synthesized with x mole fraction. The x percentage for silver dioxide (Ag_2O) were 0.09, 0.11, 0.14, 0.20, 0.33 wt.% and x percentage for bismuth oxide (Bi_2O_3) were 0.10, 0.15, 0.20, 0.25 and 0.30 wt.%. The three chemicals used were silver dioxide Ag_2O (purity of 99.99%), bismuth oxide Bi_2O_3 (purity of 99.975%) and boron oxide B_2O_3 (purity of 97.5%). For both borate glasses the mole fractions of each constituent were weighed using an electronic digital weighing machine with an accuracy of ±0.0001g.

For each sample preparation, boron oxide B_2O_3 as former was weighed first followed by a modifier such as silver dioxide Ag_2O and bismuth oxide Bi_2O_3. During weighing and subsequent handling of the materials, gloves and mouth dust cover were used as safety precautions. Before the raw materials (in powder form) of each sample were poured into the crucible (of 100 cm^3 capacity), the crucible was cleaned with alcohol. The contents in the crucible were stirred well, using a glass rod, to ensure the homogeneity of the chemicals. The crucible was then covered with a lid before it was put into the furnace for heating.

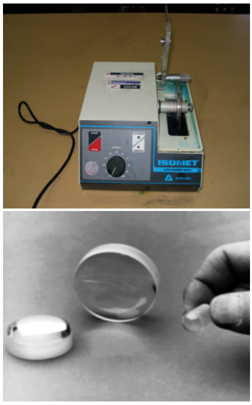
Chemical powders stored in dessicator

High quality of alumina crucibles

High precision balance weighing machine

High temperature electrical furnaces and tongs

Stainless steel cylindrical mould



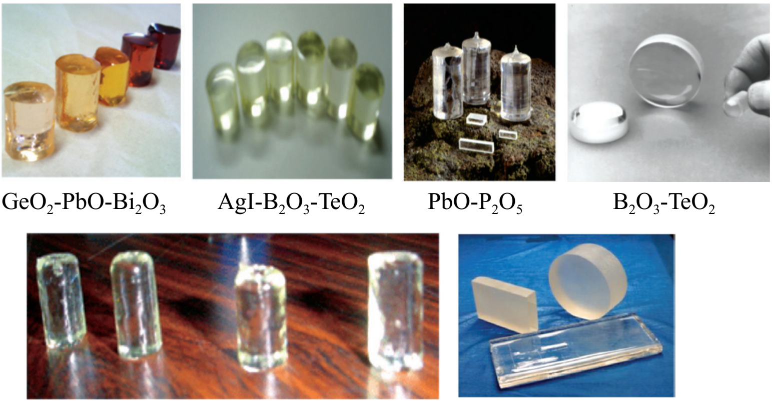
Low speed diamond cutter for cutting the glass sample

Figure 11 Laboratory equipments for glass sample preparation (Common Creative 2011)

Two electrical furnaces (both with an accuracy of 10ºC) were used. The mixtures were kept at 400ºC for 30 minutes in the first furnace to evaporate the moisture content inside the mixtures. This was done to dry the chemical to allow the water vapor to evaporate and also to allow the chemical reaction to start. Then the crucible was transferred to the second furnace which was set at temperature 1100ºC for 60 minutes. It is advisable to wear cotton gloves as a protection from the hot furnace. The melting process happens at this stage. Sometimes, the molten glass is not homogeneous as it might contain a certain amount of bubbles. The bubbles of the melts could be removed by agitating or shaking the crucible every 15 minutes when heated inside the furnace. By using a pair of modified tongs, the crucible was shaken very carefully to avoid the melting glass from spilling out. The air bubbles in the mixtures were thus reduced progressively and a bubble free melt obtained before pouring the molten liquid into the stainless steel cylindrical shaped split mould. The stainless steel split mould was a cylindrical shaped mould (20mm in length and 10mm internal diameter). A steel ring was used to hold the split mould together. The split mould was polished well before being used for casting. As sandpaper has various grades, grade 100 was used first, followed by sandpaper of grade 180, 240, 360, 600, 800 and 1000. This is to ensure that the surface of the mould was smooth. After polishing, the mould was cleaned using acetone to ensure that there was no dirt on the surface. The mould was put on a flat solid steel block, which was used as a base for the mould.

Before the melt was poured into the mould, the mould was preheated at 400ºC in the first furnace to reduce thermal shock of the samples during the casting process. Glasses with high thermal stress are unstable and may shatter to pieces. The pouring process was also done as fast as possible to avoid solidification of the melt before reaching the split mould. After a few minutes, the glass sample was removed from the mould.

The glass samples were then transferred to the first furnace and annealed at 400ºC for one hour immediately after the casting process. It was done to relieve the stress and to prevent the sample from cracking. The first furnace was switched off after one hour and the glass was left inside for another one hour before it was taken out.



GeO_2-PbO-Bi_2O_3 AgI-B_2O_3-TeO_2 PbO-P_2O_5 B_2O_3-TeO_2

PbO-B_2O_3 Ag_2O-B_2O_3

Figure 12 Examples of some glass samples prepared by melt quenching technique (Common Creative 2011)

Sample cutting and polishing were carried out because of the ultrasonic properties measurement where both samples must have parallel and smooth surfaces. Another purpose is to remove the cavities or holes on the samples, which will influence the accuracy of the measurement.

A diamond cutter that has a speed controller ranging from 0 to 10 units was used to cut the glass samples. The diamond cutter blade used for this purpose must have suitable thickness. When the cutting process is carried out, vibration occurs which can cause the glass samples to easily crack. To avoid this the samples must be covered with a piece of tissue paper at the place where the sample is clamped by the holder. Since the glass samples which were being cut were brittle, the speed of the diamond cutter had to be adjusted to the range of 1 to 3 units.

The thickness of the glass samples for the ultrasonic properties measurement were around 0.5cm to 1.0 cm. Sand paper of grades 100, 200, 300, 600, 800 and 1000 were used to polish the glass samples, following which the thickness of each glass sample was measured using electronic digital calliper with an accuracy of ±0.01 mm. A uniform value of thickness indicates the surface of the glass samples are flat and parallel. Figure 12 shows some glass samples prepared using the melt quenching technique.

PHYSICAL AND ELASTIC PROPERTIES OF GLASS

Elasticity and Ultrasonic Wave Velocity

The elastic properties of glass are important because the uses of most glass products critically depend on the solid-like behavior of glass (Devaud & Boiteux (1999). At temperatures well below the glass transition range, glass can reasonably be considered a linear elastic solid, obeying Hooke's law when the applied stress magnitudes are low relative to the fracture strength. This means that, upon application of a stress (force per unit area), glass undergoes instantaneous deformation such that the ratio of the stress to the resulting strain (change in length per unit length) is a constant called the "modulus of elasticity" (measured in Pascals).

This modulus increases as the lengthening at a certain applied stress diminishes. Steel, glass and rubber are elastic while putty or modelling clay are not elastic and steel and glass are both more elastic than rubber. However, each of these materials is elastic to varying degrees. Given the modulus of elasticity, possible deformations can be calculated for any material and loading (Bergman & Kantor, 1984). A higher value of the modulus indicates a more brittle material (i.e. glass, ceramics). A very low value represents a ductile material (i.e. rubber). Young's modulus can be used to predict the elongation or compression of an object as long as the stress is less than the yield strength of the material (El-Moneim et al. 1998).

Ultrasonic non-destructive characterization of materials is a versatile tool for the inspection of their microstructure and their mechanical properties. This is possible because of the close association of the ultrasonic waves with the elastic and the inelastic properties of the materials (El-Mallawany & Saunders, 1988). Also, this technique offers the possibility of using different frequency ranges and many modes of vibration of the ultrasonic waves to probe into any structural level.

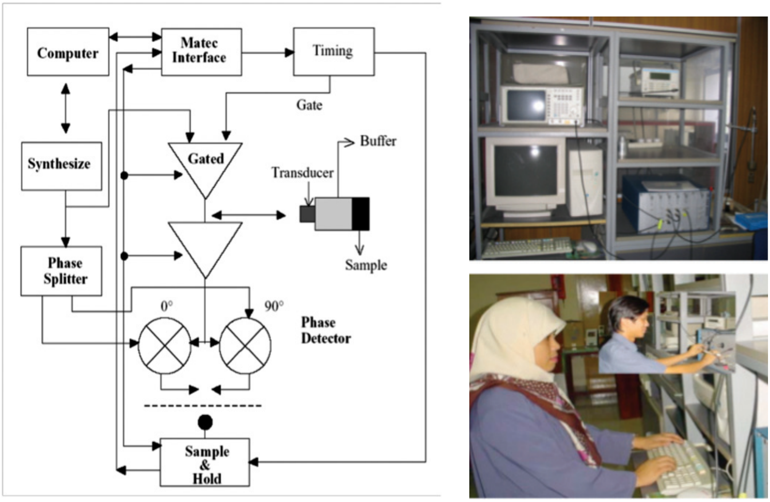
The Ultrasonic technique, similar to other techniques, plays a significant role in understanding the structural characteristics of the glass network. The measurement of ultrasonic parameters such as velocity and attenuation as a function of composition, temperature, and frequency is of great interest in glass (Sidek et al. 2008; Rosmawati et al. 2008). These ultrasonic parameters, besides density and molar volume, are sensitive and informative about the changes occuring in the structure of the glass network .

Ultrasonic Testing Techniques

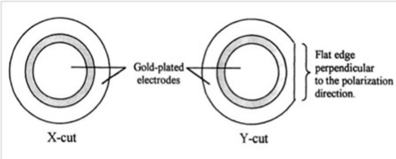
There are many types of ultrasonic testing techniques such as test frequency and wave mode selection, pulse-echo inspection, through-transmission inspection, pitch-catch and delta technique, ultrasonic data displays and scanning, continuous-wave inspection and critical-angle technique (Saddeek, 2004).

Most ultrasonic instruments operate in pulse-echo mode, using the same transducer for transmitting and receiving ultrasonic energy (Brown, 1997)**.** Ultrasonic measurement based on the Non-

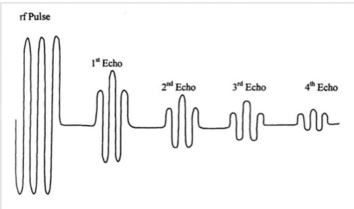
Destructive Testing (NDT) technique was used in analyzing the physical properties of the glass samples (Truell, 1969). Throughout our research project, the DSP MBS-8000 system (Digital signal processing ultrasonic system, a product of Matec Instrument Inc.), shown in Figure 13, was used to determine the ultrasonic velocities in the glasses and hence the elastic properties of the glasses could be measured (Sidek et al. 2004). The principle behind the operation of obtaining the velocities is based on the pulse echo overlap technique via the Digital Signal Processing (DSP). The radio frequency (rf) of the pulse generator in the modulator/receiver Matec 8000 is triggered by a high resolution frequency source (Matec 110) which is generated to produce a synchronized wave signal. The carrier frequency is set to resonant frequency of the transducer and a series of short duration high voltage rf pulses are produced.



Pulse echo system – Matec MBS 8000



Gold-plated quartz transducer



Pulse echo pattern display on the computer screen

Longitudinal modulus $L = \rho V_l^2$

Shear modulus $G = \rho V_s^2$

Bulk modulus $K = \rho\left(V_l^2 - \frac{4}{3}V_s^2\right)$

Poisson's ratio $\sigma = \frac{\left(V_l^2 - 2V_s^2\right)}{2\left(V_l^2 - V_s^2\right)}$

Young's modulus $E = \frac{\rho V_s^2\left(3V_l^2 - 4V_s^2\right)}{V_l^2 - V_s^2}$

Debye Temperature $\theta_t \approx \theta_D = \frac{h}{k}\left(\frac{9Np\rho}{4\pi M}\right)^{\frac{1}{3}} V_m$

$$V_m = \left(\frac{2}{V_s^3} + \frac{1}{V_l^3}\right)^{-\frac{1}{3}}$$

Equation used to estimate the elastic moduli of each glass sample

Figure 13 Ultrasonic data acquisition system MBS8000 (Common Creative 2011)

Figure 13 also shows the pulse echo pattern displayed on the computer monitor screen. Only the best two consecutive echoes were chosen and the computer was used to execute the chosen echoes and get the result of the velocities. Two types of transducers (5 MHz) were used. The X-cut and Y-cut transducers were both used to generate longitudinal wave and transverse waves, respectively. Burnt honey was used as the bonding agent to ensure good bonding between the transducer and the samples. The bonding agent is also capable of minimizing the loss of acoustic energy due to unwanted reflection.

The measured longitudinal and shear velocity of all the samples were used to estimate the elastic constants, Bulk modulus, Young's modulus and Poisson's ratio, depicted in Figure 13. A computer programme was created to calculate the elastic properties of glass.

Host Glass Forming Network

Borate glass is one of the most characteristic glasses having unique super-structures of intermediate range order such as boroxol ring, tetraborate, etc, as presented earlier. The conversion between threefold coordinated boron and fourfold coordinated boron, with the addition of modifier oxides, is found in short-range order and is one of the main factors bringing about the variety of such structures (El-Adawy & Moustafa, 1999). The glass properties are also known to show unique dependencies on the types of added modifier oxide used and their concentrations (Ahmed &Hogarth, 1983). The ability of boron to exist in three and four oxygen coordinated environments and the high strength of covalent B-O bonds enable borate to form stable glasses.

Phosphate glasses exhibit very important physical properties such as low melting temperature, high thermal expansion coefficient, low glass transition temperature, low softening temperature, low optical dispersions, relatively high thermal expansion coefficients and high ultraviolet (UV) transmission (Higazy & Bridge, 1985; Mierzejewski et al., 1988; Low et al., 1999). Despite their solubility, these properties make them useful candidates for fast ion conducting materials and other important applications, such as, laser hosts, glass-to-metal seals and low temperature enamels for metals and for optical elements.

Tellurite glasses are at present the subject of intensive investigations because of their technological and scientific importance (El-Mallawany, 1998). During the past decade, tellurite glasses have been widely studied due to their chemical stability, high homogeneity and relatively high electrical conductivity. Interest in the physical properties of tellurite glasses is especially due to their potential applications in the areas of optoelectronics such as laser technology and fiber optics (Eraiah, 2006).

In search of the best glass host for our research, we finally found the tellurite glasses to be of technical interest on account of their low melting points and absence of hygroscopic properties, which limits the application of phosphate and borate glasses. Further, they have high densities and low transformation temperatures (El-Mallawany, 1998). Their relatively low temperature of crystallization and melting makes these types of glass active candidates for CD memory devices and other optoelectronics systems.

Glass Samples Preparation

A chemical analysis is necessary to determine glass composition by using various research facilities. Figure 14 shows the SEM photos of the chemical powder (TeO_2, ZnO and AlF_3) and TeO_2, binary TeO_2-ZnO and ternary TeO_2-ZnO-AlF_3 glasses.

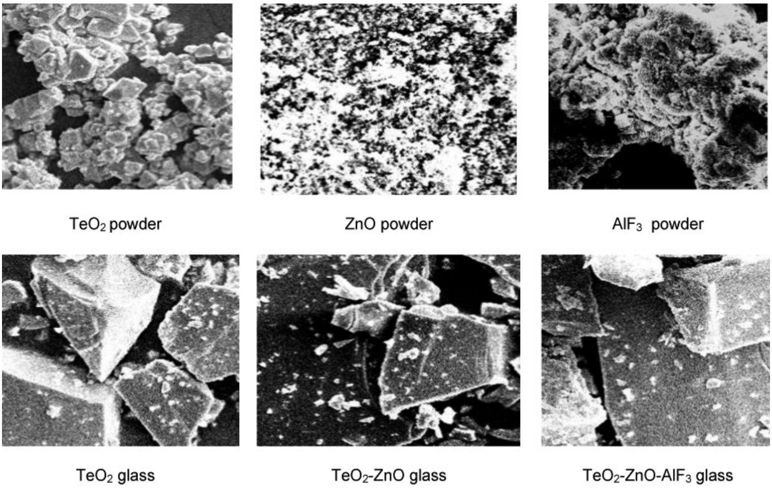
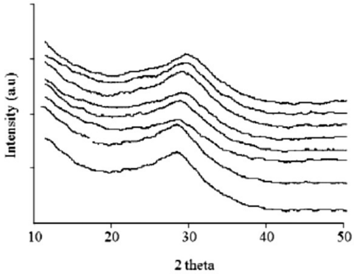


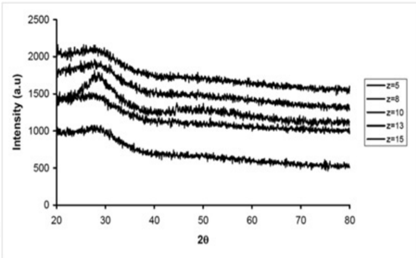
Figure 14 SEM photo of powder and glass samples (Rosmawati et al 2005)

X-Ray and Amorphous State

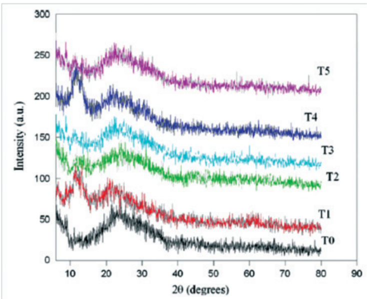
To check the amorphous state, X-ray diffraction (XRD) is usually carried out for each glass sample by using a computer-controlled X'pert Pro Panalytical set. Figure 15 shows the XRD patterns of the binary ZnO-TeO2 (Sidek et al. 2010) and other glass samples studied by others (Halimah et al. 2010, Pavani et al. 2011). All the glass samples were found to show no discrete or continuous sharp peaks but had a broad halo at around 26-30^o, which reflected the characteristic of amorphous glass structure. This indicates the absence of long range atomic arrangement and the periodicity of the three dimensional network in the quenched material.



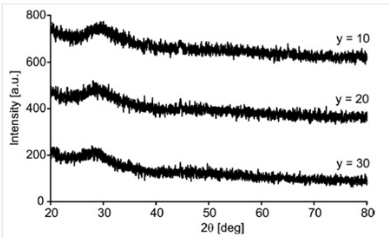
Binary zinc tellurite glass series (Sidek et al. 2009)



{[(TeO2)70 (B2O3)30]90[Ag2O]10}100-z{AgI} z glasses (Halimah et al. 2010)



. Boro-zinc tellurite glass system (Pavani et al. 2011)



[(TeO2)65 (B2O3)35]1–*y*[Ag2O]*y* glasses (Halimah et al. 2010)

Figure 15 The XRD patterns of binary zinc tellurite and quaternary silver borotellurite glasses

Figure 16 show the XRD patterns of (the chemical compositions) tellurite (TeO_2), zinc oxide (ZnO) and aluminium fluoride (AlF_3) and zinc tellurite glass samples. All the glasses were found to show no discrete or continuous sharp peaks but a broad halo at around $2\Theta \cong 26^0 - 30^0$, which reflected the characteristic of an amorphous glass structure. This indicates the absence of long range atomic arrangement and the periodicity of the three dimensional network in the quenched material.

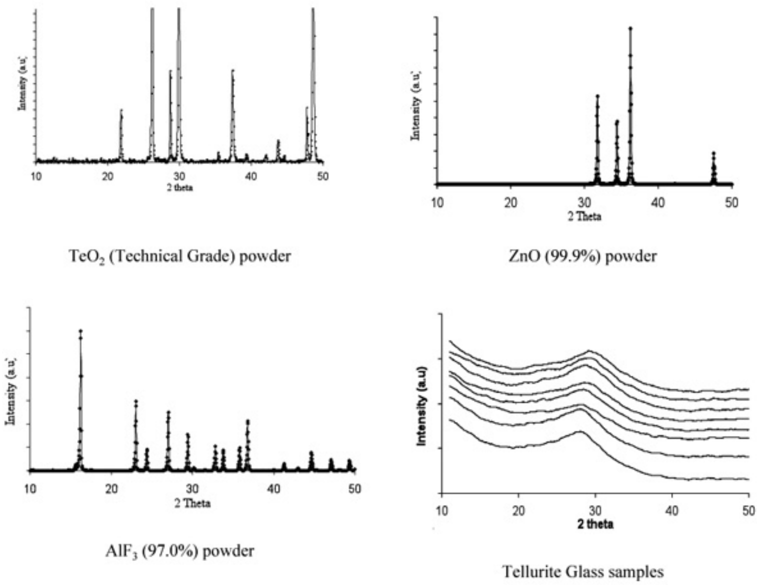
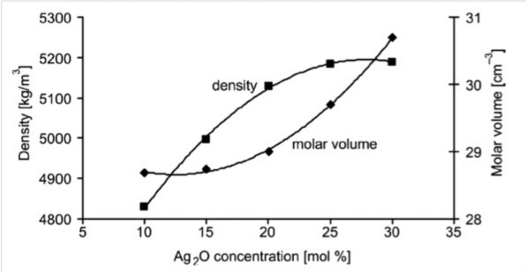


Figure 16 The XRD pattern of powders and zinc tellurite glass samples (Rosmawati et al. 2008)

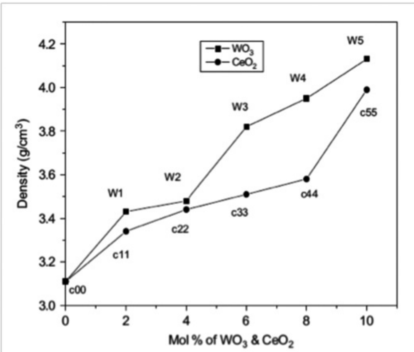
Variation in Density and Molar Volume

The density of a glass is an important property capable of evaluating the compactness and casting light on the short range structure of the glass. The density and molar volume dependencies of [(TeO2)65(B2O3)35]1–*y*[Ag2O]*y* glasses on Ag2O content (Halimah et al. 2010) are shown in Figure 17. They both increase as the molar percentage of Ag2O increases. The atomic weight of TeO2–B2O3 is 229.2 g and the atomic weight of Ag2O is 231.7 g, the replacement of the borotellurite atom with the silver atom is explained by the increase in the density resulting from the increase in the content of Ag2O. The variation in density with WO3 and CeO2 contents of CeO2-PbO-B2O3 and WO3–CeO2–PbO-B2O3 glasses is also shown in Figure 17. The increase in density reveals the change in the structure of glasses with the increase in oxide content(Singh & Singh 2011).

Generally, the density and the molar volume show opposite behaviours, but this was not the case in this work. The increase in the molar volume, resulting from the presence of non-bridging oxygen atoms (NBO) caused bond breaking, and thereby led to an increase in the number of spaces in the network. The observed increase in the molar volume may be due to an increase in the bond length or an increase in the interatomic spacing between the atoms. The values of the molar volume of the ternary tellurite glass system lie in the same range as those reported by El-Mallawany (1998) for the tellurite glasses.



[(TeO2)65(B2O3)35]1–*y*[Ag2O]*y* glasses
(Halimah et al. 2010)



Pure and WO3 dopedCeO2–PbO–B2O3 glasses
(Singh & Singh 2011)

Figure 17 Density and molar volume of selected glass samples

Table 5 shows that the density of soda lime silicate (SLS) added with ZnO glass samples increases with increasing weight percentage of ZnO due to several factors (Zaid et al. 2011). SLS glasses contain a lot of non-bridging oxygen with a highly open glass network. The addition of ZnO will increase their mass and volume. However, the increase in mass is larger than the increase in volume. An increase of density of the glasses probably results in changes of crosslink density with the addition of ZnO. The ZnO added into a glass fills up the interstitial sites of the glass structure and the expansion of all Na2O, CaO and SiO2 will cause increase in density values, up to, 3.313 gcm^{-3}. This is related to the larger atomic mass of the ZnO (81.389 $gmol^{-1}$).

It is expected that the density and the molar volume show opposite behaviour to each other. Insertion of ZnO causes a decrease in the value of molar volume and this can be attributed to the introduction of Zn2+ ions as network modifiers or formers into the glass network.

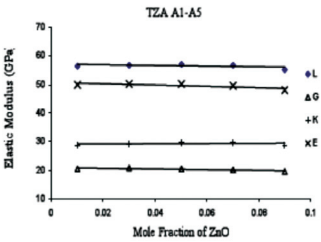
Table 5 Variation of density and sound velocities (both longitudinal and transverse) for (ZnO)*x*(SLS)*1-x* and pure SLS glasses (Zaid et al., 2011)

Designation	Composition (wt. %)		ρ (g cm^{-3})	V_L (m s^{-1})	V_T (m s^{-1})
	SLS	ZnO			
SLS	100	0	2.520	4956	3202
S1	95	5	2.600	4836	3115
S2	90	10	2.679	4667	3048
S3	80	20	2.869	4640	2667
S4	70	30	3.098	4084	2013
S5	60	40	3.313	3541	1704

As shown in **Table 6** the density of (TeO2)90(AlF3)10-x(ZnO) x glass samples increases with an increase in ZnO modifier in the composition range from 1 to 9 mol.% ZnO. The densities of the TeO2-AlF3-ZnO samples increased as the ZnO was added to substitute the AlF3 content where the same trend was exhibited in the binary zinc tellurite (Sidek et al. 2009).

Table 6 Measured density (ρ), molar volume (V), longitudinal ultrasonic velocity (vl), shear ultrasonic velocity (vs), elastic moduli, Poisson's ratio (σ), and fractal dimension ($d = 4G/K$) and (E/G) ratio of (TeO2)90(AlF3)10-x(ZnO)x glasses (Sidek et al. 2009).

Sample no.	Glass Composition (mol. %)	ρ (gm cm^{-3})	V (cm^3)	v_l (m s^{-1})	v_s (m s^{-1})
1	90-9-1	4779	31.81	3435	2075
2	90-7-3	4846	31.36	3424	2068
3	90-5-5	4963	30.61	3393	2038
4	90-3-7	5018	30.26	3364	2013
5	90-1-9	5023	30.22	3316	1979



Elastic modulus of zinc oxyfluorotellurite glasses

Sample no.	L (GPa)	G (GPa)	K (GPa)	E (GPa)	Micro hardness (GPa)	σ	$d = 4G/K$	E/G
1	56.39	20.58	28.95	49.91	3.941	0.213	2.843	2.425
2	56.81	20.72	29.18	50.27	3.967	0.213	2.841	2.426
3	57.14	20.61	29.65	50.21	3.878	0.218	2.781	2.436
4	56.79	20.33	29.67	49.59	3.781	0.221	2.741	2.439
5	55.23	19.67	29.00	48.13	3.628	0.223	2.713	2.447

The decrease in molar volumes (V) with an increase in densities as presented here is due to the rearrangement of the lattice and a decrease in the porosity of the glass. The decrease in molar volumes for this ternary glass system, which ranges from 31.81 cm3/mol to 30.22 cm3/mol, is attributed to a decrease in the bond length or inter-atomic spacing between the atoms where the radius of Te^{2+} (0.097 nm) > Zn^{2+} (0.074 nm) > Al^{3+} (0.0535 nm). The decrease in molar volume is attributed to the increase in the degree of crystallinity, where the volume of the oxide glass sample is higher than that of the corresponding crystalline oxide (Nishara & Rajendran, 2006). The much higher reduction in the molar volume for the sample containing flourine is also attributed to the decrease in viscocity due to the breaking of the Te-O-Te bond to form two Te-F bonds, which increases the efficiency of the crystallization process.

Sound Wave Velocity and Elastic Moduli

The variation of both longitudinal and shear wave velocities that propagated in the present bulk samples depend on the structural changes in the glass network. As shown in Table 6 that both longitudinal and shear ultrasonic velocities decreased as more ZnO was added into the TeO2- AlF3 glass system.

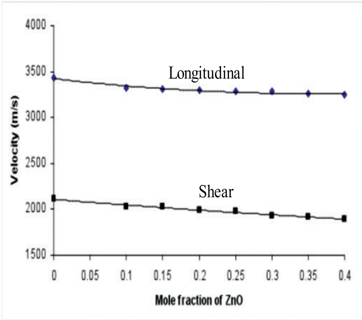
The longitudinal velocity for TeO2-AlF3-ZnO glass samples decreased from 3435 m/s to 3315 m/s as the ZnO content increased from 0.01 mole fraction to 0.09 mole fraction. As small quantities of ZnO glass modifier is added into the TeO2-AlF3 glassy network, a breaking of Te-O-Te takes place. The conversion of this linkage results in breaking up the network leading to the formation of Te-axOeq-Te bridges with the apparition of non-bridging oxygen (NBO) (Nishara & Rajendran, 2006).

It is inferred that a decrease in the Te coordination number (N) has resulted with the increase in the modifier content. Further, a decrease in the coordination number resulted in a slight decrease in the mean Te-O bond length (R). Thus, it is inferred that the observed continuous decrease in sound velocity in the present glasses is due to the change in coordination number with the substitution of ZnO.

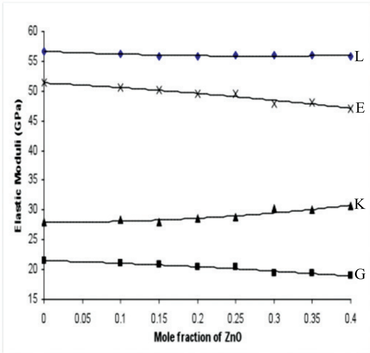
The composition dependence of longitudinal and shear wave velocities is shown in Figure 16 together with the measured values of ultrasonic velocity with the variation of ZnO content. The decrease in ultrasonic velocity of the studied glass reveals that, adding ZnO content to the tellurite network causes a difficult movement for the ultrasonic wave inside the network of the glass structure and hence the tendency for the ultrasonic velocity to decrease as the mole percentage of ZnO decreases (Afifi and Marzouk, 2003).

For most materials, ultrasonic wave velocities will increase as the density increases. A similar behavior has been found by El-Mallawany (1993) for the same glass systems but in this study, the unique thing is that it shows the opposite phenomena, where the ultrasonic velocities decrease as the density increases. This happens because the Zn^{2+} ion in ZnO reduces the degree of crosslinking and gives rise to the non-bridging oxygen bond (single bonded oxygen ion) (Sidek *et al.* 2004) causing the glass network to be therefore weakened or disrupted.

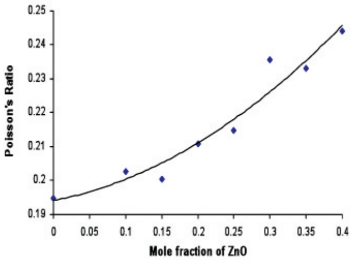
Elastic properties are important parameters for understanding the structural characteristics of a glass network. The measurement of ultrasonic parameters such as velocity and attenuation as a function of composition, temperature and frequency is of great interest in glass. The variation of ultrasonic parameters, besides density and molar volumes, are closely related to the changes occurring in the structure of the glass network (El-Mallawany *et al*., 1994; Sidkey *et al*., 1997). Such properties are associated with the inter-atomic forces and potentials in the lattice structure (Saddeek and Abd El-Latif, 2004). In general, the strength of amorphous materials increases with their elastic moduli and therefore, it is possible to assess the strength indirectly from their elastic properties (Saddeek, 2005).



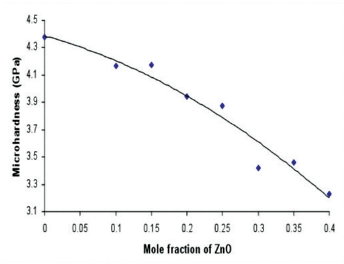
Ultrasonic velocities



Elastic moduli



Poisson's ratio



Micro-hardness

Figure 18 Elastic properties of ZnO-TeO_2 glasses (Sidek et al. 2010)

Furthermore, the decrease of ultrasonic velocity (Figure 18) linearly with the increase of ZnO indicated that ZnO plays a dominant role in the velocity. An addition of more ZnO in glass interstices causes more ions to open up in the network. Thus, weakening of the glass structure or reduction in the rigidity of the network takes places. As a consequence, both velocities v_l and v_s decrease with the addition of heavy metal oxides (HMO) (Sadeek and Abd Latif, 2004).

It was inferred from a study on binary zinc tellurite glasses performed by Hoppe *et al.* (2004) that the average coordination number of TeO_2 decreases from 4 to 3 as the ZnO content increases. Therefore, the structural unit TeO_4 tbps, will be converted into the structural unit TeO_3 tp, which in its turn is accompanied by the creation of non-bridging oxygens (NBOs), that is, the rigidity of the glass decreases (Hoppe *et al.*, 2004)

By considering the character of such oxides in this glass system, which act as modifier, it will modify the glass structure, thus making the glass get softer (Sidek *et al.*, 1996). In fact, when the wave is propagated through the sample, a harder material will produce higher velocity whereas a softer material will produce lower velocity (Carini *et al.*, 1984). Although the glass is softer, it does not mean that the glass is less dense (Azman, 2000).

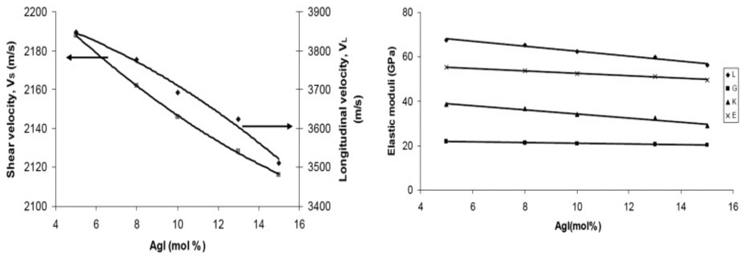


Figure 19 Ultrasonic velocity and elastic moduli of {[(TeO2)70(B2O3)30]90 [Ag2O]10}100-z {AgI}z glasses (Halimah et al. 2010)

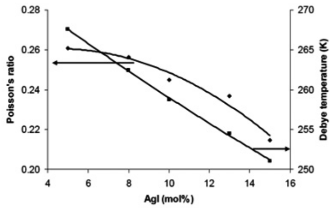
Figure 19 depicts the variations in longitudinal and shear velocities of silver iodide borotellurite with AgI content. Both velocities decrease as AgI content increases. This decreasing trend is due to weakening of the glass structure as I ion enters into the glass network and resides at the interstices. The decrease in velocities with addition of AgI is ascribed to the change in the coordination number. When AgI is added to the glasses framework, distorted TeO4 units, followed by creation of regular TeO3 sites, will be formed, besides the transformation of BO4 into BO3. This ionic character bond results in a monotonic decrease in velocity.

Figure 19 also shows the variation of elastic moduli of quaternary tellurite with the increase in AgI content. Elastic moduli are more sensitive to structural changes, where the observed monotonic decrease in moduli shows loose packing structure of the glass network to take place giving rise to continuous reduction in rigidity and hence velocities. Physically, this implies that progressive softening of the glass network has taken place by introducing AgI into the system. The accommodation of the anion to form halide doped glasses, induces an expansion of the matrix and, consequently, bridging oxygen atoms are broken with formation of BO3 triangles with non-bridging oxygen atoms; the degree of connectivity of the network is reduced and the elastic constants become smallest in these glasses.

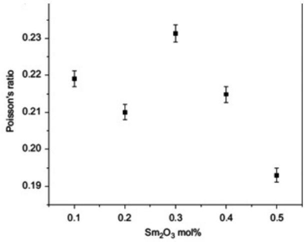
Poisson's Ratio

The ratio of the transverse compression to the longitudinal extension is called Poisson's ratio, σ, so named after Siméon Poisson. Poisson's ratio is an important material property used in elastic analysis of material. When a material is compressed in one direction, it usually tends to expand in the other two directions perpendicular to the direction of compression.

Poisson's ratio is affected by the changes in the cross-link density of the glass network, and structures with high cross-link density have Poisson's ratio in the order of 0.1–0.2, while structures with low cross-link density have Poisson's ratio in the order of 0.3–0.5.



$\{[(TeO_2)_{70}(B_2O_3)_{30}]_{90}[Ag_2O]_{10}\}_{100-z}\{AgI\}_z$ glasses
(Halimah et al. 2010)



xSm2O3–(40_x) PbO–60P2O5
(Eraiah et al.2010)

Figure 20 Variation of Poisson's ratio and Debye temperature of selected glass samples

The decreasing trend of Poisson's ratio with AgI, as shown in Figure 20, indicates that the glass network weakens. It can be seen that Poisson's ratio decreases from 0.261 to 0.215 with increase of AgI. These values are within the same range as that of tellurite glasses, as reported by El-Mallawany (1998).

Generally, as the glass structure weakens the Poisson's ratio value increases but for this quaternary tellurite glass system the Poisson's ratio decreases. This anomalous behaviour may be due to the changes in the cross-link density of the glass network. Rajendran *et al.* (2000) has reported Poisson's ratio in the order of 0.1-0.2 for high cross-link density, while a low cross-link density glass network has Poisson's ratio of between 0.3 and 0.5. The Poisson's ratio variation of xSm2O3–(40_x) PbO–60P2O5 (Eraiah et al.2010) should be exactly the reverse of the elastic moduli variation (El-Adawy & Moustafa, 1999).

Compilation of Physical Properties of Selected Materials

Table 7 shows a comparison of the density of selected materials between crystalline and amorphous phases. The ratio between crystalline (C) and amorphous (A) yield values are unique for each material.

Table 7 The density (gcm^{-3}) comparison between crystalline and amorphous phases for selected materials (Bass, 1995).

Material	Crystal	Amorphous	Ratio (C/A)	Material	Crystal	Amorphous	Ratio (C/A)
SiO_2	2.65 (alpha-quartz)	2.20 (silicate)	1.20	H2O, ice	0.9175		
TeO_2	6.02	5.11	1.18	Obsidian		2.33	
P_2O_5	2.69	2.52	1.07	Borosilicate		2.23	
B_2O_3	2.55	1.84	1.38	Au, Gold	19.283		
GeO_2	4.25	3.65	1.16	Ag, Silver	10.500		
Soda lime	2.6	2.4	1.08	Cu, Copper	8.932		
Lead	7.3 (galena)	4.0 (crystal glass)	1.82	E-glass		2.62	
C, Carbon	3.512 (diamond)	2.23 (graphite)	1.57	S-glass		2.50	
				C-glass		2.56	

Table 8 The density (gcm^{-3}) and elastic moduli of selected binary glassy materials.

		Elastic Moduli (GPa)					
Materials	**Density**	**L**	**G**	**K**	**E**	**σ**	**References**
$15Sm_2O_3$-$85P_2O_5$	3.280	66.42	23.63	34.91	57.84	0.224	Sidek et al. (1988)
$15La_2O3$-$85P_2O_5$	3.413	67.63	23.05	36.90	57.23	0.241	Sidek et al. (1988)
15Nd2O3-$85P_2O_5$	3.233	70.50	24.80	37.40	60.90	0.229	Senin et al. (1993)
15Bi2O3-$85P_2O_5$	4.418	56.8	19.2	31.2	47.9	0.244	Sidek et al. (2011)
20Ho2O3-80P2O5	3.327	73.1	24.7	40.1			Senin et al. (1996)
20Nd2O3-80P2O5	3.358	67.4	24.1	35.3	58.8	0.22	Sidek et al. (1993)
20Sm2O3-80P2O5	3.326	63.1	23.4	31.9	56.5	0.20	Sidek et al. (1993)
20Ce2O3-80P2O5	3.254	74.4	25.0	41.1	62.3	0.23	Sidek et al. (1993)
14Ag2O-$86B_2O_3$	2.850	44.15	13.37	26.32			Saunders et al. (1987)
20PbO-80B2O3	3.801	45.4	14.70	25.90	43.0	0.262	Azman et al. (2002)

40PbO-B2O3	4.852	76.09	25.15	42.54	63.04	0.253	Sidek et al. (2003)
40Bi2O3-B2O3	5.262	74.67	27.70	37.75	66.75	0.205	Sidek et al. (2003)
30PbO-70B2O3	4.019	71.40	22.80	41.00	57.60	0.265	Azman et al. (2002)
30PbO-70P2O5	4.135	47.30	15.70	24.00	39.20	0.252	Azman et al. (2002)
26Tb2O3-74P2O5	3.578	76.2	25.4	42.00	64.0	0.246	Senin et al. (1994)
26Ce2O3-74P2O5	3.234	72.5	24.00	40.60	60.00	0.233	Saunders et al. (2001)
26Pr2O3-74P2O5	3.338	74.3	24.3	41.9	61.1	0.257	Senin et al. (2000)
33Ag2O-67B2O3	4.030	72.18	19.17	46.61			Saunders et al. (1987)
30ZnO-70TeO2	5.211	56.06	19.39	30.21	47.92	0.236	Rosmawati et al. (2008)
33ZnCl2-67TeO2	4.63	50.8	15.10	30.6	39.0	0.289	El-Mallawany et al. (1998)
30V2O5-70TeO2	4.564	44.1	11.5	28.8	30.5	0.289	El-Mallawany et al. (1998)
30B2O3-70TeO2	4.89	63.62	23.33	32.51	56.48	0.21	Halimah et al. (2007)
30B2O3-70TeO2	4.78					0.21	Sidek et al.(2006)

TeO_2 (pure glass)	5.101	56.40	19.90				Sidek et al. (1989)
TeO_2 (pure glass)	5.105	59.1	20.6	31.7	50.7	0.233	El-Mallawany et al. (1998)
TeO_2 (pure crystal)	6.02	56.0	27.2				Arlt & Schweppe (1968)
P_2O_5 (pure glass)	2.52		12.1				Bridge et al. (1984)
SiO_2 (pure glass)	2.203		30.7				Borgadus et al. (1965)

Table 8 shows the density and elastic moduli and Poisson's ratio (σ) of selected binary materials, mainly for borate, phosphate and tellurite based glasses.

Table 9 The density (gcm^{-3}) elastic moduli of selected ternary glassy materials.

Material	Density	Elastic Moduli (GPa) L	G	K	E	σ	References
10Ag2O-32B2O3-58TeO2	4.914	59.78	18.94	34.51	48.05	0.268	Halimah et al. (2005)
10Ag2O-27B2O3-63TeO2	4.989	61.41	19.97	34.78	50.30	0.259	
15Ag2O-30B2O3-55TeO2	4.923	59.65	18.89	34.62	47.92	0.268	
15Ag2O-26B2O3-59TeO2	5.011	61.20	19.88	34.69	50.08	0.259	
20Ag2O-28B2O3-52TeO2	4.965	58.47	18.27	34.11	46.51	0.276	
20Ag2O-24B2O3-56TeO2	5.182	61.60	19.37	35.77	47.83	0.271	
25Ag2O-27B2O3-48TeO2	5.082	58.19	17.31	35.12	44.60	0.288	
25Ag2O-23B2O3-52TeO2	5.280	59.88	18.39	35.35	44.43	0.278	
30Ag2O-25B2O3-45TeO2	5.248	56.08	16.76	44.60	43.14	0.287	
30Ag2O-21B2O3-49TeO2	5.425	60.11	17.36	36.95	39.56	0.297	

1Bi2O3-9PbO-90B2O3	3.972	64.0	21.9	34.70	54.40	0.24	Hamezan et al. (2004)
2Bi2O3-18PbO-80B2O3	5.095	77.4	26.30	42.30	65.30	0.24	
3Bi2O3-22PbO-75B2O3	5.508	75.1	26.6	39.60	55.40	0.19	
4Bi2O3-36PbO-60B2O3	5.663	66.6	21.0	38.60	53.20	0.27	
5Bi2O3-45PbO-50B2O3	6.392	68.0	20.4	40.80	52.50	0.29	
54TeO2-10PbO-36B2O3	4.763	56.99	20.61	29.51	50.15	0.217	Faizal et al. (2004)
51TeO2-15PbO-34B2O3	4.794	56.93	20.30	29.86	49.66	0.223	
48TeO2-20PbO-32B2O3	4.836	57.13	20.11	30.32	49.40	0.229	
45TeO2-25PbO-30B2O3	4.866	56.65	19.99	29.99	49.07	0.227	
42TeO2-30PbO-28B2O3	4.930	57.02	19.74	30.71	48.68	0.235	
40P2O5-18PbCl2-42MgO	3.739	57.5	24.7	24.6	55.5	0.124	Sidek et al. (2004)
40P2O5-21PbCl2-39MgO	3.849	54.7	18.6	29.6	46.2	0.242	
40P2O5-23PbCl2-37MgO	3.878	53.3	19.1	27.8	46.6	0.221	
40P2O5-24PbCl2-36MgO	4.045	55.0	18.2	30.7	45.6	0.252	
40P2O5-26PbCl2-34MgO	3.971	53.3	17.8	29.6	44.4	0.250	
40P2O5-27PbCl2-33MgO	4.077	53.1	15.4	32.5	40.0	0.295	

Table 9 shows the density and elastic moduli and Poisson's ratio (σ) of selected ternary materials, mainly for borate, phosphate and tellurite based glasses.

APPLICATIONS OF GLASS

Commercial Glass

There are many different types of glass for commercial use. In principle, commercial production requires very large scale melting and is linked to the unique forming methods required for each type of product. Commercial glass differs in terms of their chemical composition, the method used to produce them or their processing behaviour. Generally, they are categorised according to their chemical compositions.

A differentiation is made between vitreous silica, soda-lime glass, lead glass and borosilicate glass. These three types of glass make up around 95 percent of the cullet glass used in the production process. The remaining 5 percent of glass is special-purpose glass. Table 10 shows the glass types and their applications (see Figure 21).

Table 10 Glasses and applications

Glass	Application
Soda-lime-silica	Glazing, packaging
Borosilicate	High temperatures (cookware, laboratory glassware), pharmacy
Aluminosilicate	Fibres for reinforcement
Lead glasses	Lead-crystal tableware ('crystal' glass), protecting panels
Silica	Optical fibres
Chalcogenide	IR optics
Vitroceramics	Cooking tools, optics
Bioglasses	Medical

Glass is a favoured material for a lot of reasons, mainly due to its unique properties as depicted in Table 11. Generally glass resists chemical interactions, it is easy to recycle, it does not leach chemicals like plastics do, and it can withstand extremes of heat and cold, although not at the same time (Rawson, 1980). Glass is also an ideal material for manufacturing as well as considered as a sustainable and healthy material.

Table 11 Properties of glass from the consumer's perspective

Consumer's Favorite	Ideal Manufacturing	A Sustainable and Healthy Material
• Natural • Pure • Highly Aesthetic • Inert • Optimal taste and smell protection of the filled product • humidity and heat resistant	• Inexpensive • Freedom of design (versatile shapes, multiple colors, multiple cap and closure options) • Sterile • Aseptic • Antistatic • High chemical resistance • Pressure resistant • innovation friendly	• 100% recyclable • Reusable • Pure • Inert • Ultimate protection of filled goods • Long shelf life • Hermetic sealing properties • Environmentally safe • made from natural and abundant raw materials

Soda-lime glass contains 71 to 75 percent silicium dioxide (SiO_2), 12 to 16 percent sodium oxide (Na_2O), 10 to 15 percent calcium oxide (CaO) and small quantities of other substances such as dyes. Soda-lime glass is the glass produced in by far the largest quantities of all mass produced glass types. As the name indicates, the main constituents in addition to sand are soda and lime (Shelby, 2005).

The chemical and physical properties of soda-lime glasses make them suitable for a visible light and hence related applications. The nominally colorless types transmit a very high percentage of visible light and hence have been used for windows since at least the time of the Romans.

Soda-lime glass containers are virtually inert, and so cannot contaminate the contents inside. Their resistance to chemical attack from aqueous solutions is good enough to withstand repeated boiling (as in the case of preserving jars) without any significant changes in the glass surface. One of the main disadvantages of soda-lime is their relatively high thermal expansion (Pfaender, 1996). Silica does not expand very greatly when heated but the addition of soda has dramatic effect in increasing the expansion rate and, in general, the higher the soda content of a glass, the poorer will be its resistance to sudden changes of temperature (thermal shock). Thus, care is needed when soda-lime containers are filled with hot liquids, to prevent breakage due to rapid thermal expansion.

Soda-lime glass is used to make bottles, food jars, simple drinking glasses and flat glass products. Soda-lime glass is light permeable and has a smooth, fine-pored surface, making it easy to clean. Soda-lime glass expands very quickly under the influence of heat so care should always be taken when putting hot water into a soda-lime glass container.

Some of physical features of soda-lime glass include;

- Can be chemically tempered to increase mechanical strength
- Can be heat strengthened or heat tempered to increase thermal shock resistance and mechanical strength
- Can be bent, laminated, machined, optically coated, chemically etched, sandblasted or colored
- Good flatness and surface quality due to float process
- Economically priced

Figure 21 Some commercial glasses for specific application (Creative Common, 2011)

Lead crystal glass contains 54 to 65 percent sand, 18 to 38 percent lead oxide, 13 to 15 percent alkali oxide and the rest consists of further oxides. Glasses which contain less than 18 percent lead oxide are also called crystal glass (Rawson, 1980).). The inclusion of at least 24% lead oxide in the composition is required by law for crystal to be called full lead crystal. The lead lends brilliance and weight to the product. Crystal without lead is still crystal, i.e. clear glass, however, it is more commonly perceived as “glass”. The lead also makes the crystal softer and more conducive to cutting. This is why the lead crystal is cut and for the most part, the unleaded crystal is not cut. Crystal glass has a high level of light refraction and is perfect for decorative engraving. It has a far higher density than soda-lime glass. In our everyday lives, we use lead glass to make drinking glasses, vases, bowls, ashtrays or decorative ornaments.

Borosilicate glasses, as the name implies, are composed mainly of silica (70-80%) and boric oxide (7-13%) with smaller amounts of the alkalis (sodium and potassium oxides) and aluminum oxide (Rawson, 1980). They are characterized by the relatively low alkali content and consequently have good chemical durability and thermal shock resistance. Thus they are permanently suitable for process plants in the chemical industry, for laboratory apparatus, for ampoules and other pharmaceutical containers, for various high intensity lighting applications and as glass fibers for textile and plastic reinforcement. In the home they are familiar in the form of ovenware and other heat-resisting ware, possibly better known under the trade name of the first glass of this type to be placed on the consumer market - Pyrex.

Special glass is used for special technical and scientific applications. Its composition can vary and it includes numerous chemical elements. Examples of special glass are lenses, glass products used by the electrical and electronics industries and glass ceramics.

Present Glass Development

R&D has lead to much development in glass applications, continuously improving performances and devices. Today, flat glass comes in many highly specialized forms intended for different products and applications. Flat glass produced by way of the float process is often further processed to give it certain qualities or specificities. In this way, the industry can meet the various requirements and needs of the construction, automotive and solar-energy industries:

Annealed glass is the basic flat glass product that is the first result of the float process. It is the common glass that tends to break into large, jagged shards. It is used in some end products -

often in double-glazed windows, for example. It is also the starting material that is turned into more advanced products through further processing such as laminating, toughening, coating, etc.

Mirrored Glass - To produce mirrored glass, a metal coating is applied to one side of the glass. The coating is generally made of silver, aluminium, gold or chrome. For simple mirrored glass, a fully reflective metal coating is applied and then sealed with a protective layer. To produce “one-way” mirrors, a much thinner metal coating is used, with no additional sealing or otherwise opaque layer. Mirrored glass is gaining a more prominent place in architecture, for important functional reasons as well as for the aesthetic effect.

Extra-clear glass is not the result of processing of annealed glass but instead a specific type of melted glass. Extra-clear glass differs from other types of glass by its basic raw material composition. In particular, this glass is made with a very low iron-content in order to minimize its sun reflection properties (Fanderlik, 1983). It therefore lets as much light as possible through the glass. It is most particularly of use for solar-energy applications where it is important that the glass cover lets light through to reach the thermal tubes or photovoltaic cells. Anti-reflective properties can be further increased by applying a special coating on the low-iron glass. It can also be used in windows or facades as it offers excellent clarity, which allows occupants to appreciate true colours and to enjoy unimpaired views.

Toughened glass is treated to be far more resistant to breakage than simple annealed glass, and to break in a more predictable way when it does break, thus providing a major safety advantage in almost all of its applications. Toughened glass is made from annealed glass treated with a thermal tempering process (Doremus,1994). A sheet of annealed glass is heated to above its “annealing point” of 600 °C;

its surfaces are then rapidly cooled while the inner portion of the glass remains hotter. The different cooling rates between the surface and the inside of the glass produces different physical properties, resulting in compressive stresses in the surface balanced by tensile stresses in the body of the glass.

These counteracting stresses give toughened glass its increased mechanical resistance to breakage, and are also, when it does break, what cause it to produce regular, small, typically square fragments rather than long, dangerous shards that are far more likely to lead to injuries. Toughened glass also has an increased resistance to breakage as a result of stresses caused by different temperatures within a pane.

Toughened glass has extremely broad application in products both for buildings and for automobiles and transport, as well as other areas. Car windshields and windows, glass portions of building façades, glass sliding doors and partitions in houses and offices, glass furniture such as table tops, and many other products typically use toughened glass. Products made from toughened glass often also incorporate other technologies, especially in the building and automotive and transport sectors.

Laminated glass is made of two or more layers of glass with one or more “interlayers” of polymeric material bonded between the glass layers. Laminated glass is produced using one of two methods:

1. Poly Vinyl Butyral (PVB) laminated glass is produced using heat and pressure to sandwich a thin layer of PVB between layers of glass. On occasion, other polymers such as Ethyl Vinyl Acetate (EVA) or Polyurethane (PU) are used. This is the most common method.

2. For special applications, Cast in Place (CIP) laminated glass is made by pouring a resin into the space between two sheets of glass that are held parallel and very close to each other.

Laminated glass offers many advantages. Safety and security are the best-known of these -- rather than shattering on impact, laminated glass is held together by the interlayer, reducing the safety hazard associated with shattered glass fragments, as well as, to some degree, the security risks associated with easy penetration (Pfaender, 1996). However, the interlayer also provides a way to apply several other technologies and benefits, such as colouring, sound dampening, resistance to fire, ultraviolet filtering, and other technologies that can be embedded in or with the interlayer.

Laminated glass is used extensively in building and housing products and in the automotive and transport industries. Most building façades and most car windscreens, for example, are made with laminated glass, usually with other technologies also incorporated.

Surface coatings can be applied to glass to modify its appearance and give it many of the advanced characteristics and functions available in today's flat glass products, such as low maintenance, special reflection/transmission/ absorption properties, scratch resistance, corrosion resistance, etc. Coatings are usually applied by controlled exposure of the glass surface to vapours, which bind to the glass forming a permanent coating. The coating process can be applied while the glass is still in the float line with the glass still warm, producing what is known as "hard-coated" glass. Alternatively, in the "off-line" or "vacuum" coating process, the vapour is applied to the cold glass surface in a vacuum vessel.

Patterned glass is flat glass whose surfaces display a regular pattern. The most common method for producing patterned glass is to pass heated glass (usually just after it exits the furnace where it is made) between rollers whose surfaces contain the negative relief of the desired pattern(s).

Patterned glass is mostly used in internal decoration and internal architecture. Today, it is typically used for functional reasons, where light but not transparency is desired, and the patterns are accordingly subtle. However, it has also at times been fashionable as a design feature in itself, in such cases often displaying more prominent patterns.

Other Glass Applications

Flat glass is used in many other applications than the main building, transport and solar-energy ones described earlier. These applications are very visible in every-day life and illustrate how glass is a vector of comfort, style, well-being, security and safety.

Thin glass has numerous applications, typically specialized and in moderate volumes, often technical. It is used for example in microscope slides, which are usually 1 mm thick, and for the corresponding cover glasses that are only a fraction of a millimetre thick. Float glass processes can produce extra-thin glass down to 0.4 mm. Thin glass is used to perform specific functions in a wide array of equipment and appliances, various kinds of mirrors such as electrochromic mirrors and cosmetic mirrors, touchscreens and filters, glass masters and data storage glass discs, display, and telecom equipment.

Appliances - Flat glass is used extensively for household appliances, office equipment, and similar applications. Oven doors are made of tempered glass and engineered to resist very high temperatures. Stove-tops and control panels are made from drilled, silk-screen printed and tempered glass in order to provide high thermal and mechanical safety as well as to create an aesthetic look. Fridges are equipped with silk-screened, tempered, edged and clipped glass for their shelves, so as to be capable of resisting shocks as well as being spill-proof. Washing and dryer machines and dishwashers equally have tempered glass for their drums and panels. Anti-reflective glass is used to reduce the glare that reflects off televisions, computer screens, glass cases and other electronic displays. Photocopiers, scanner, and fax machines all use highly transparent glass sheets to support document imaging.

Figure 22 Other application of glassy materials
(Creative Common, 2011)

Furniture - Glass offers unique aesthetic possibilities to furniture designers, and is very durable and low-maintenance, as it is not harmed by moisture and is highly resistant to wear and scratching. Almost every piece of furniture in a house can be made from, or incorporate, glass: coffee tables, dining tables, book cases and shelves, TV units, media storage, office furniture, lightning, aquaria, and other accessories. Glass furniture is particularly ideal where the available light needs to be maximised, because it reflects and transmits light rather than absorbing it. It also adds a bright, vibrant effect, thereby increasing the light in a room, subjectively as well as in real terms.

Greenhouses - Glass is used for the roof, and often also for the walls, of greenhouses. The glass in greenhouses functions as a selective transmitter of solar energy. The effect it has is to trap energy within the greenhouse, warming plants, air, soil, water and other things inside the greenhouse. As infrared frequencies are blocked by glass, this thermal energy generated by plants is also conserved within the greenhouse, adding to the warming effect.

Urban furniture - Glass is more prominent in the urban landscape than one might think: bus and tram stop shelters, phone booths, advertising stands, kiosks, street lighting, traffic lights, and shelter over walkways all include large glass components. Glass is easy to clean and highly resistant to different weather conditions; damaged parts are easily replaceable and the glass can be engineered to be vandalism-resistant.

Radiation protection - There are three radiation protection principles: time, distance and shielding. Glass is a good provider of shielding against some types of radiation. X-ray facilities often use leaded glass screens to protect the operators, and radiation-protection glass is also used in PET-scan (positron emission tomography) apparatuses. There is also special nuclear radiation protection glass, which is used to make viewing windows in nuclear power installations. Within the nuclear sector, glass takes the form of large blocks used for radiation shielding windows, with individual blocks sometimes weighing over 4 tonnes. Lead and non-lead containing glasses can be stabilized against radiation-induced browning through the addition of cerium oxide.

Glass in solar energy applications plays an active role in ensuring efficient and effective solar energy conversion. Glass is designed to optimise solar energy conversion while providing long term protection against external conditions. Extra clear glass, with low iron oxide content is typically used in solar applications.

Either float or patterned, low iron glass may be coated with an anti-reflecting coating to further increase performance. Glass may also be toughened to increase strength and durability. Coatings on glass can also play a functional role in solar energy conversion. For example, transparent conductive coating can be used as an electrical contact in some photovoltaic technologies allowing the light through to the photovoltaic material while conducting the general electricity out of the modules.

Glass in Solar thermal collectors are intended to collect heat - as opposed to photovoltaic panels which convert sunlight into electrical power. The collected solar heat can be used to supply hot water or heat exchangers, for domestic or industrial applications. There are various kinds of solar thermal collectors but most require a flat glass cover, or glazing, which serves not only to protect the panel while letting sunlight through but also to prevent cooling of the panel from exposure to cold air.

Glass in Photovoltaic Applications - Photovoltaic technologies are used to convert solar energy directly into electricity. There are many different technologies available to suit various requirements, from domestic systems to utility scale. Photovoltaic panels come in various shapes and colors offering flexibility for design integration and building integrated applications (BIPV). The most common photovoltaic technology is based on crystalline silicon solar cells. In this application glass acts as a protective outer layer, while transmitting the solar light to the photovoltaic cells interconnected underneath.

Other photovoltaic technologies include thin film photovoltaics where solar cells are deposited as a sequence of thin films on glass. In these technologies, transparent conductive coated glass can be used as the front glass upon which the films are grown. The conductive coating not only allows light through to the photoactive films, but also conducts the generated electricity out of the modules.

Glass and mirrors in Concentrated Solar Power Systems - Concentrated Solar Power (CSP) systems are used to produce electricity from the sun at utility scale. These systems are mainly used in regions with high levels of solar irradiance. CSP systems use lenses or mirrors to concentrate a large amount of sunlight onto a central receiver, thereby producing electricity either by concentrating the sunlight onto a high performance photovoltaic cell or by heating a transfer fluid to supply heat to a conventional thermodynamic power plant. For CSP systems, extra clear glass and mirrored glass are used to redirect accurately the maximum amounts of light towards the focal point.

Future Prospects in Glass Applications

Metallic glass can be fabricated in bulk form with superior strength, elasticity and magnetic properties. A glass is any material that can be cooled from a liquid to a solid without crystallizing. Most metals do crystallize as they cool, arranging their atoms into a highly regular spatial pattern called a lattice. However if crystallization does not occur, and the atoms settle into a nearly random arrangement, the final form is a metallic glass.

Window glass possesses this same random atomic arrangement, although it is not metallic. Unlike window panes, metallic glasses are not transparent, yet their unusual atomic structure gives them distinctive mechanical and magnetic properties. Unlike window glass, metallic glass is not brittle. Many traditional metals are relatively easy to deform, or bend permanently out of shape, because their crystal lattices are riddled with defects. A metallic glass, in contrast, will spring back to its original shape much more readily.

A new metallic glass that will remain solid and not crystallize at higher temperatures, will be useful for engine parts. The new metallic glass may also have military applications as armour-piercing projectiles. Unlike most crystalline metal projectiles, which flatten into a mushroom shape upon impact it is believed that the sides of a metallic glass head will shaer away on impact, essentially sharpening the point and providing more effective penetration. In the 1950s, metallurgists learned how to slow the crystallization by mixing certain metals, such as nickel and zirconium. When thin layers of such alloys were cooled at 1 million degrees Celsius per second, they formed a metallic glass. Due to the rapid cooling requirement, this material could only be made as a thin ribbon, a wire or a powder.

More recently, however, scientists have created about a dozen metallic glasses in bulk form--bars, for example--by mixing four or five elements that possess atoms of varying sizes which makes it tougher for the mixture to form crystal lattices. One of these new metallic glass alloys is being used commercially to make powerful golf club heads.

Gorilla Glass – New special glasses for the future have been developed by Corning® USA. Visually stunning, lightweight, and highly damage-resistant, Corning® Gorilla® Glass is changing the way the world thinks about glass. It helps protect the world's coolest smartphones, tablets, PCs, and TVs from everyday wear and tear (Corning, 2011).

Smart glass, EGlass, or switchable glass, also called smart windows or switchable windows in its application to windows or skylights, refers to electrically switchable glass or glazing which changes light transmission properties when voltage is applied. Certain types of smart glass can allow users to control the amount of light and heat passing through: with the press of a button, it changes from transparent to translucent, partially blocking light while maintaining a clear view of what lies behind the window. Another type of smart glass can provide privacy at the turn of a switch.

Smart glass technologies include electrochromic devices, suspended particle devices, Micro-Blinds and liquid crystal devices.

The use of smart glass can save costs for heating, air-conditioning and lighting and avoid the cost of installing and maintaining motorized light screens or blinds or curtains. Opaque, liquid crystal or electrochromic smart glass blocks most UV, thereby reducing fabric fading; for SPD-type smart glass, this is achieved when used in conjunction with low-e low emissivity coatings.

Critical aspects of smart glass include installation costs, the use of electricity, durability, as well as functional features such as the speed of control, possibilities for dimming, and the degree of transparency of the glass. No space consuming or dirt collecting shades, curtains or blinds are needed. The applications of the smart window, e.g. in aircrafts, automobiles and architectures are also possible.

CONCLUSION

Glass is one of the most versatile materials on earth and therefore perhaps also one of the most fascinating, since it can be shaped and moulded into a variety of forms, long and graceful, ruffled or swirling, with soft or brilliant splashes of colour. Glass is bold, beautiful, elegant, clean and clear. The ability to etch, cut or engrave glass allows the maker even more expression. Glass is widely used in construction, electronics, optics, packaging, lighting, transportation, not to mention cooking and decoration. Their uniqueness in physical, optical, thermal, mechanical and chemical properties offer an almost unlimited range of applications.

Extensive series of investigations using borate, phosphate and tellurite based glasses have been carried out to study the effect of certain oxides into those glass formers in terms of physical properties such as density, molar volumes and elasticity. Ultrasonic systems have been employed to characterize their elastic properties. Thus far, silicate based glasses are seem to be well employed by engineers in optoelectonic devices' development and application, but it has been shown to have some disadvantages. As an alternative, more researchers now prefer tellurite based glass to be used as a host matrix in laser applications. We also do agree that tellurite is the best glass host due to its low melting temperature and absence of hygroscopic properties as compared to borate and phosphate based glasses.

Glass is also a strange substance, defying easy scientific categorization. Glass is a favoured material for a lot of reasons. It resists chemical interactions, it is easy to recycle, it does not leach chemicals like plastics do, and it can withstand extremes of heat and cold, although not at the same time. Tempered or safety glass is used in a wide variety of applications, and virtually all consumers use many forms of glass daily.

Certainly glass is one of the most important and fascinating materials since ancient times, although in a physical sense the description 'glass' might be misleading. At present the explanation 'glass' is more commonly used as a synonym for a state of aggregation between fluid and solid. This particular property of glass makes it a universal material which can be used for countless applications.

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BIOGRAPHY

Sidek Ab Aziz was born in Tanjung Karang, Selangor, Malaysia on 12 August 1961. He obtained his early education at Sekolah Kebangsaan Sawah Sempadan, Tanjung Karang. He then completed his secondary school education at Sekolah Dato' Harun, Tanjung Karang and also at the Royal Military College (RMC), Sungai Besi. Later he accomplished his Matriculation course at Sekolah Alam Shah, Kuala Lumpur.

Dr. Sidek graduated with B.Sc. (Hons) in Physics and was conferred the *Tengku Intan Zaharah Gold Medal* award as the most outstanding undergraduate physics student from the Universiti Kebangsaan Malaysia in 1984.

He then pursued his MPhil. which was converted to a PhD program due to his outstanding performance, at the University of Bath, United Kingdom. Whilst at the university, he gained considerable experience and knowledge especially on Solid State Physics as well as low temperature and high pressure ultrasonic techniques.

He received his Doctorate in 1989, and was appointed as a lecturer at Universiti Pertanian Malaysia (now known as Universiti Putra Malaysia). He then instinctively equipped his laboratory with basic ultrasonic research facilities to study and continue his research on the ultrasonic properties of natural latex, palm oils, as well as various species of tropical wood and concrete filled with natural rubber. Subsequently, with his expertise gained at Bath, Sidek and his team initiated the synthesis of some borate, phosphate and tellurite glasses for ultrasonic, thermal, optic and electrical characterization.

The Glass and Ultrasonic Research Laboratory at UPM that started off with very basic facilities picked up momentum and is now ranked amongst the very active laboratories in this region specialising in glass research. In the last 22 years, his research group has been successful in securing more than RM 1.8 million in research grants. In 1997, Dr Sidek was awarded the prestigious *Malaysian Young Scientist Award. In addition, he also* received a cash incentive of RM10,000 from the Ministry of Science, Technology and the Environmental, Malaysia for his outstanding contributions in the field of research and development.

Dr Sidek has enjoyed, without any regrets, working and contributing to the needs of the Department of Physics at the Faculty of Science, UPM for the last over 22 years. He feels honoured to be part of the intellectual team producing physicists or scientists that can further contribute to mankind. As an academician and former Physics Club advisor, caring and responding to students' needs, has always been his prime concern. Improving the teaching approach and finding ways to enhance the quality of the students have been part of his struggle in enhancing R&D in his area of expertise. Dr Sidek uses the latest in IT, including multimedia presentation techniques and implementing Student Centered Learning (SCL) in his lectures with the lecture notes and other resources published on the net via the Learning Management System (LMS).

Being one of the champions in the incorporation of generic skills in students, he implemented the Student Centered Learning (SCL) approach with his team, fully supported by the Centre for Academic Development (CADe). Even though, throughout his career, his teaching assessment scores have always been above the faculty and UPM standard, he has always taken students' comments and suggestions to heart, to ensure continual perfection.

Over the past years, he has lectured 20 subjects, both at the diploma and undergraduate levels, as well as three subjects at the postgraduate level, in the area of physics and material sciences. He also lectured two subjects on the use of information technology as well as computer programming for postgraduate students at the Graduate School of Management, and Faculty of Computer Science and Information Technology, UPM.

Apart from teaching, he supervised 3 PhD students, two of whom have successfully graduated. Ten out of his 15 Master students also graduated subsequently. Currently he is also jointly supervising 2 PhD and 6 Master students. In addition, he has examined 8 PhD/ Master students internally under the research program and was appointed as an external examiner to 10 PhD and Master of Science students, also under the research program of various universities. In addition, Sidek has trained more than 120 undergraduate students in his laboratory at UPM.

Sidek's skills in computer programming were enhanced with the advent of internet technology in Malaysia in the late eighties, through a win-win collaboration with his peers from other faculties. Joint supervision of 16 undergraduate students on system development, multimedia and internet environment at the Faculty of Computer Science and Information Technology, whilst acting as the Deputy Director at the Computer Centre, yielded him additional IT experience. Dr Sidek's use of ICT in his research as well as for teaching led him to develop the e-Punch system used by the staff of the Faculty of Science, and also the e-SPRINT (an alternative learning management system). eSPRINT is an online instructional delivery system which provides sustainable and scalable software for lecturers to create, manage and deploy online courses. The success of this lead ICT product is seen in its being accepted by UPM and being implemented on campus since the year 2000. Due to his renowned teaching and learning contributions, Sidek received the prestigious, UPM Vice Chancellor Fellowship Award (Excellence in Teaching) in 2004.

Currently, his research activities are mainly focussed on physical studies of advanced materials, specifically with borate, phosphate and tellurite based glasses doped with various oxide substances. Diverse experimental techniques such as ultrasonic, thermal, electrical and dielectric have been carried out to characterize these amorphous materials.

Sidek also remains an active member of several professional scientific groups i.e. the Malaysian Solid State Science and Technology Society (MASS), Malaysian Non-Destructive Testing Society and the Glass Society (United Kingdom). In terms of his career advancement he is all set to keep himself fully active in the area of research. His childhood ambition to be a writer and publisher had been achieved through numerous editorial works, monographs, and internet publishing. Since 1998, he served as an editorial team member for Tribun Putra, the only campus newspaper in Malaysia. Most of his R&D work have been published and are well documented, and admirably acclaimed by the scientific community. Sidek has authored more than 180 publications in refereed and citation index journals and conference proceedings since 1989. He has also represented his university at several national and international meetings. He is equally actively involved in presenting papers and chairing technical sessions at conferences and seminars.

Sidek also likes to share his scientific findings as well as his knowledge in information technology through seminars, workshops and courses with the campus community and outsiders. He still keeps a keen eye on the development of undergraduate and graduate students by giving necessary advice and motivation through the Physics Club. Thus, not surprisingly, in 2002, the final year students anonymously elected him as the best and most sporting physics lecturer during their annual dinner function.

In addition to his active participation in Research and Development, Sidek has also been engaged in administrative duties at UPM for the last 20 years. He has contributed his services as Deputy Director of research institutes, centers etc., mainly the Computer Centre, Institute of Multimedia and Research Management Centre. Professor Sidek has been the Director at the Centre for Academic Development (CADe), UPM (2006-2008) and the Dean Faculty of Science (2008-2011). He aspires to be a relevant, creative, and effective individual. Sidek works with utmost zeal and efficiency and ensures that the work undertaken by him is successfully concluded with commendation.

UPM has awarded him with a number of *Excellent Service* awards in the academic staff category in recognition of his teaching, research and extension works. In 2006, Sidek was honoured by the government of Malaysia with the *Malaysian Exemplary Male Worker Award* (Executive Category) in conjunction with National Worker's Day celebrations.

His secret to success has always been in line with his motto "*Strive for Excellence*" and he strongly believes in the saying, "*Today should be better than yesterday, and tomorrow should be better than today*".

ACKNOWLEDGEMENT

Praise be to Allah the Almighty, for thee (alone) we worship and thee (alone) we ask for help. And praise be upon Muhammad s.a.w whose guidance has led us to the true path that God favoured.

I sincerely thank Universiti Putra Malaysia, the Science Faculty and the Sponsors of the research grants for the opportunities provided to explore and excel in my area of research interest.

Sincere gratitude also go to all my colleagues (and teachers), mentors, and friends in the Department of Physics, Faculty of Science, UPM. No matter the level of your contributions and role played, each and every one of you has contributed to my success in one way or another.

I also must thank all my undergraduate and postgraduate students in particular for being part of my research team. Some students worked with me to develop research and applicative studies, and their contributions have been of utmost importance.

Special thanks to all the global glass researchers and anonymous contributors of research works, including the online photographers who willingly shared their wonderful pictures and sketches via the Creative Commons licenses for the benefit of mankind.

To my mother – Hjh Banun Hj Shamsuddin, my late father – Haji Ab Aziz Senin, brothers and sisters, their love and support keep me going; and last but not least, to my beloved wife - Siti Jauyah Sibo and my sons - Amir and Adzrif and daughter - Aizzah, thank you for your sacrifices, love, endless support, encouragement and understanding.

May Allah Bless You All.

LIST OF INAUGURAL LECTURES

1. Prof. Dr. Sulaiman M. Yassin
   The Challenge to Communication Research in Extension
   22 July 1989

2. Prof. Ir. Abang Abdullah Abang Ali
   Indigenous Materials and Technology for Low Cost Housing
   30 August 1990

3. Prof. Dr. Abdul Rahman Abdul Razak
   Plant Parasitic Nematodes, Lesser Known Pests of Agricultural Crops
   30 January 1993

4. Prof. Dr. Mohamed Suleiman
   Numerical Solution of Ordinary Differential Equations: A Historical Perspective
   11 December 1993

5. Prof. Dr. Mohd. Ariff Hussein
   Changing Roles of Agricultural Economics
   5 March 1994

6. Prof. Dr. Mohd. Ismail Ahmad
   Marketing Management: Prospects and Challenges for Agriculture
   6 April 1994

7. Prof. Dr. Mohamed Mahyuddin Mohd. Dahan
   The Changing Demand for Livestock Products
   20 April 1994

8. Prof. Dr. Ruth Kiew
   Plant Taxonomy, Biodiversity and Conservation
   11 May 1994

9. Prof. Ir. Dr. Mohd. Zohadie Bardaie
   Engineering Technological Developments Propelling Agriculture into the 21st Century
   28 May 1994

10. Prof. Dr. Shamsuddin Jusop
    Rock, Mineral and Soil
    18 June 1994

11. Prof. Dr. Abdul Salam Abdullah
    Natural Toxicants Affecting Animal Health and Production
    29 June 1994

12. Prof. Dr. Mohd. Yusof Hussein
    Pest Control: A Challenge in Applied Ecology
    9 July 1994

13. Prof. Dr. Kapt. Mohd. Ibrahim Haji Mohamed
    Managing Challenges in Fisheries Development through Science and Technology
    23 July 1994

14. Prof. Dr. Hj. Amat Juhari Moain
    Sejarah Keagungan Bahasa Melayu
    6 Ogos 1994

15. Prof. Dr. Law Ah Theem
    Oil Pollution in the Malaysian Seas
    24 September 1994

16. Prof. Dr. Md. Nordin Hj. Lajis
    Fine Chemicals from Biological Resources: The Wealth from Nature
    21 January 1995

17. Prof. Dr. Sheikh Omar Abdul Rahman
    Health, Disease and Death in Creatures Great and Small
    25 February 1995

18. Prof. Dr. Mohamed Shariff Mohamed Din
    Fish Health: An Odyssey through the Asia - Pacific Region
    25 March 1995

19. Prof. Dr. Tengku Azmi Tengku Ibrahim
    Chromosome Distribution and Production Performance of Water Buffaloes
    6 May 1995

20. Prof. Dr. Abdul Hamid Mahmood
    Bahasa Melayu sebagai Bahasa Ilmu- Cabaran dan Harapan
    10 Jun 1995

21. Prof. Dr. Rahim Md. Sail
Extension Education for Industrialising Malaysia: Trends, Priorities and Emerging Issues
22 July 1995

22. Prof. Dr. Nik Muhammad Nik Abd. Majid
The Diminishing Tropical Rain Forest: Causes, Symptoms and Cure
19 August 1995

23. Prof. Dr. Ang Kok Jee
The Evolution of an Environmentally Friendly Hatchery Technology for Udang Galah, the King of Freshwater Prawns and a Glimpse into the Future of Aquaculture in the 21st Century
14 October 1995

24. Prof. Dr. Sharifuddin Haji Abdul Hamid
Management of Highly Weathered Acid Soils for Sustainable Crop Production
28 October 1995

25. Prof. Dr. Yu Swee Yean
Fish Processing and Preservation: Recent Advances and Future Directions
9 December 1995

26. Prof. Dr. Rosli Mohamad
Pesticide Usage: Concern and Options
10 February 1996

27. Prof. Dr. Mohamed Ismail Abdul Karim
Microbial Fermentation and Utilization of Agricultural Bioresources and Wastes in Malaysia
2 March 1996

28. Prof. Dr. Wan Sulaiman Wan Harun
Soil Physics: From Glass Beads to Precision Agriculture
16 March 1996

29. Prof. Dr. Abdul Aziz Abdul Rahman
Sustained Growth and Sustainable Development: Is there a Trade-Off 1 or Malaysia
13 April 1996

30. Prof. Dr. Chew Tek Ann
    Sharecropping in Perfectly Competitive Markets: A Contradiction in Terms
    27 April 1996

31. Prof. Dr. Mohd. Yusuf Sulaiman
    Back to the Future with the Sun
    18 May 1996

32. Prof. Dr. Abu Bakar Salleh
    Enzyme Technology: The Basis for Biotechnological Development
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33. Prof. Dr. Kamel Ariffin Mohd. Atan
    The Fascinating Numbers
    29 June 1996

34. Prof. Dr. Ho Yin Wan
    Fungi: Friends or Foes
    27 July 1996

35. Prof. Dr. Tan Soon Guan
    Genetic Diversity of Some Southeast Asian Animals: Of Buffaloes and Goats and Fishes Too
    10 August 1996

36. Prof. Dr. Nazaruddin Mohd. Jali
    Will Rural Sociology Remain Relevant in the 21st Century?
    21 September 1996

37. Prof. Dr. Abdul Rani Bahaman
    Leptospirosis-A Model for Epidemiology, Diagnosis and Control of Infectious Diseases
    16 November 1996

38. Prof. Dr. Marziah Mahmood
    Plant Biotechnology - Strategies for Commercialization
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39. Prof. Dr. Ishak Hj. Omar
    Market Relationships in the Malaysian Fish Trade: Theory and Application
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40. Prof. Dr. Suhaila Mohamad
Food and Its Healing Power
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41. Prof. Dr. Malay Raj Mukerjee
A Distributed Collaborative Environment for Distance Learning Applications
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42. Prof. Dr. Wong Kai Choo
Advancing the Fruit Industry in Malaysia: A Need to Shift Research Emphasis
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43. Prof. Dr. Aini Ideris
Avian Respiratory and Immunosuppressive Diseases- A Fatal Attraction
10 July 1999

44. Prof. Dr. Sariah Meon
Biological Control of Plant Pathogens: Harnessing the Richness of Microbial Diversity
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45. Prof. Dr. Azizah Hashim
The Endomycorrhiza: A Futile Investment?
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46. Prof. Dr. Noraini Abdul Samad
Molecular Plant Virology: The Way Forward
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47. Prof. Dr. Muhamad Awang
Do We Have Enough Clean Air to Breathe?
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48. Prof. Dr. Lee Chnoong Kheng
Green Environment, Clean Power
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49. Prof. Dr. Mohd. Ghazali Mohayidin
Managing Change in the Agriculture Sector: The Need for Innovative Educational Initiatives
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50. Prof. Dr. Fatimah Mohd. Arshad
Analisis Pemasaran Pertanian di Malaysia: Keperluan Agenda Pembaharuan
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51. Prof. Dr. Nik Mustapha R. Abdullah
Fisheries Co-Management: An Institutional Innovation Towards Sustainable Fisheries Industry
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52. Prof. Dr. Gulam Rusul Rahmat Ali
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53. Prof. Dr. Zaharah A. Rahman
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Productivity Driven Growth: Problems & Possibilities
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Immunodiagnosis and Vaccination for Brugian Filariasis: Direct Rewards from Research Investments
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64. Prof. Dr. Han Chun Kwong
Blueprint for Transformation or Business as Usual? A Structurational Perspective of the Knowledge-Based Economy in Malaysia
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Are there "Magic Bullets" for Cancer Therapy?
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155. Prof. Dr. Mohd Azmi Mohd Lila
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Does Genetic Polymorphisms Affect Health?
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