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ELASTIC AND MECHANICAL PROPERTIES OF GLASS SPECIMEN BY ULTRASONIC METHOD

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ABSTRACT

Ultrasonic velocity and density measurements in $Na_2CO_3 – ZnO – B_2O_3$ and $Na_2CO_3 – PbO – B_2O_3$ composition glasses have been made at a temperature of 303K. These measured values are used to evaluate elastic modulii such as longitudinal, Young's, bulk and shear, Poisson's ratio, acoustic impedance, micro hardness, Debye temperature and thermal expansion coefficient. The results of these parameters have been discussed in terms of the structural and physical properties of the prepared glasses.

Keywords: glass, ultrasonic velocity, elastic modulii, microhardness, debye temperature.

1. INTRODUCTION

The ultrasonic non-destructive testing has been found to be one of the best techniques to study the microstructure, characterisation, mechanical properties, phase changes as well as to evaluate elastic constants. One can also characterise the materials such as semi conducting glasses, super conducting glasses, glass ceramics, bio-active glasses etc. by this non-destructive testing technique. The propagation of ultrasonic waves in solids such as glass provides valuable information regarding the solid state motion in the material. Interest in glasses has rapidly increased in recent years because of diverse applications in electronic, nuclear, solar energy and acousto-optic devices. The acoustic wave propagation in bulk glasses has been of considerable interest to understand their mechanical properties [1]. The velocity of sound is particularly suitable for characterising glasses as a function of composition because it gives information about the microstructure and dynamics of glasses [2]. The study of elastic properties of glasses has inspired many researchers [3, 4] and significant information about the same has been obtained. The elastic moduli of glasses are influenced by many physical parameters, which may in turn be studied by measuring the ultrasonic velocities [5]. The dependence of ultrasonic velocity on the composition of glass indicates the various changes in the structural configuration between the network former and modifiers [6, 7].

In recent years, Borate based glasses find wide applications in all the fields due to its varied physico-chemical properties. Elastic properties combined with acoustic properties are quite significant because of their applications in certain devices such as delay lines, light modulators and solid state sensors. The present work aims to measure the ultrasonic velocity (both longitudinal and shear) and density for two series of glasses namely Na_2CO_3-ZnO-B_2O_3 (SZB glasses) and Na_2CO_3-PbO-B_2O_3 (SLB glasses). These values have been used to evaluate longitudinal, Young's, bulk and shear moduli, Poisson's ratio, acoustic impedance, micro hardness, Debye temperature and thermal expansion coefficient which will give further insight into the rigidity and structure of glasses.

2. MATERIALS AND METHODS

The chemicals used in the present research work were analytical reagent (AR) and spectroscopic reagent (SR) grade with minium assay 99.9% were obtained from Sd fine chemicals India and E-Merck, Germany as such without further purification. The composition in mol% of (increasing ZnO, PbO content) glass specimen are listed in Table-1.

Table-1. Composition of glasses.

S. No.	Glass specimen	Composition in mol %
	$Na_2CO_3 – ZnO – B_2O_3$	
1.	SZB1	20 – 10 – 70
2.	SZB 2	20 – 12 – 68
3.	SZB 3	20 – 14 – 66
4.	SZB 4	20 – 16 – 64
5.	SZB 5	20 – 18 – 62
6.	SZB 6	20 – 20 – 60
	$Na_2CO_3 – PbO – B_2O_3$	
1.	SLB 1	20 – 10 – 70
2.	SLB 2	20 – 12 – 68
3.	SLB 3	20 – 14 – 66
4.	SLB 4	20 – 16 – 64
5.	SLB 5	20 – 18 – 62
6.	SLB 6	20 – 20 – 60

The required amounts (approximately 20g) in mol% of different chemicals in powder form were weighed using single pan digital balance (Model SHIMADZU AX 200) having an accuracy of 0.1mg. The homogenisation of the appropriate mixture of the component of chemicals was effected by repeating grinding using a mortar. The homogeneous mixture was put in a platinum crucible and placed in an electrical furnace. Melting was carried out under controlled conditions with occasional stirring. The molten sample was cast into a copper mould having the dimension of 12mm diameter and 6 mm length. Then the glass samples were annealed at 400K for two hours to avoid the mechanical strains developed during the quenching process.

The amorphous nature of glass samples was confirmed by X-ray diffraction technique using an X-ray diffractometer (PANalytical, The Netherlands: X-PertPro, 2002). XRD spectrum shows no evidence of unmelted or crystalline particles in a quenched glass. The XRD patterns of SZB1 and SLB1 glasses are shown in Figure-1. A and 1B. The prepared glass samples were polished and the surfaces are made perfectly plane and smoothened by diamond disc and diamond powder.

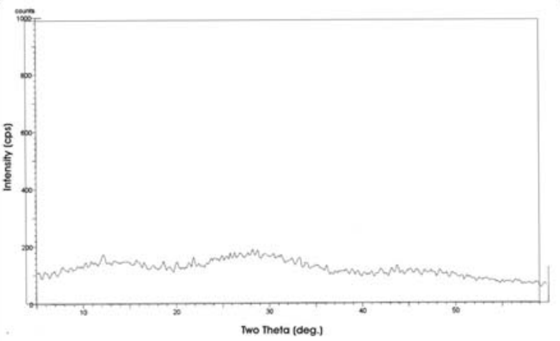

Fig. 1-A X-ray diffractogram for SZB1 glass

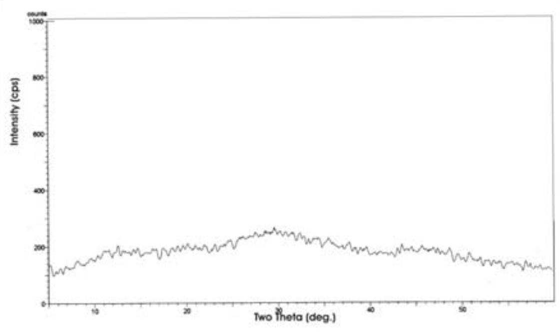

Fig. 1-B X-ray diffractogram for SLB1 glass

The density of the glass samples were measured using Archimedes's Principle. Ultrasonic longitudinal and shear velocities of the specimen were determined by using the conventional pulse-echo method at room temperature by making use of 2.25 MHz X-cut and Y-cut transducers.

3. THEORY AND CALCULATIONS

The elastic constants of the glass specimen were calculated at room temperature using the measured density (ρ), longitudinal velocity (U_l) and shear velocity (U_S) as given below:

Longitudinal Modulus (L)
The ratio between longitudinally applied stress and the longitudinal strain is obtained for longitudinal wave propagation as

$$L = \rho U_l^2 \qquad \ldots (1)$$

Shear Modulus (G)
The shear modulus can be found from shear velocity as,

$$G = \rho U_S^2 \qquad \ldots (2)$$

Bulk Modulus (K)
The ratio between bulk stress and bulk strain is obtained from the ultrasonic velocities as

$$K = L - \left(\frac{4}{3}\right)G \qquad \ldots (3)$$

Young's Modulus (E)
It is defined as the ratio between unidirectional stress and resultant strain and is given as

$$E = (1+\sigma)2G \qquad \ldots (4)$$

Where σ Poisson's ratio.

Poisson's Ratio (σ)
It is the ratio between lateral and longitudinal strain produced when tensile force is applied, as given by the relation,

$$\sigma = \left(\frac{L-2G}{2(L-G)}\right) \ldots (5)$$

Acoustic Impedance (Z)
The transmission and reflection of sound energy in the glass specimen is determined using the acoustical impedance.

$$Z = U_l \rho \qquad \ldots (6)$$

Micro Hardness (H)
It is given by

$$H = (1-2\sigma)\frac{E}{6(1+\sigma)} \qquad \ldots (7)$$

Debye Temperature (θ_D)
The Debye temperature θ_D of the sample is calculated from the relation

$$\theta_D = \frac{h}{K}\left(\frac{9N}{4\pi V_m}\right)^{1/3} U_m \qquad \ldots (8)$$

Where h, K, N and V_m are the Planck's constant, the Boltzmann's constant, the Avagadro's number and the molar volume of the sample, respectively.

The mean sound velocity U_m is given by

$$U_m = \left[\frac{1}{3}\left(\frac{2}{U_m^3} + \frac{1}{U_l^3}\right)\right]^{1/3} \quad \ldots (9)$$

Thermal Expansion Coefficient (α_P)

Thermal expansion coefficient can be obtained [8] as

$$\alpha_P = 23.2\,(U_l - 0.57457) \qquad \ldots (10)$$

4. RESULTS AND DISCUSSIONS

The experimental values of density (ρ), longitudinal ultrasonic velocity (U_l) and shear ultrasonic velocity (U_S) of the different glass specimen with respect to the change in the mol% of ZnO and PbO are listed in Table-2. The calculated longitudinal modulus (L), shear modulus (G), bulk modulus (K) and Young's modulus (E) are also reported in Table-2. The Poisson's ratio (σ), acoustic impedance (Z) and micro hardness (H) Debye temperature (θ_D) and thermal expansion coefficient (α_P).which are reported in Table-3.

Table-2. Values of density (ρ), longitudinal velocity (Ul), shear velocity (Us) and elastic moduli of SZB and SLB glass systems.

Name of the sample	Density ρ/(× 10^3 kg. m^{-3})	Ultrasonic Velocity U/(m.s^{-1})		Elastic modulii			
		Longitudinal (U_l)	Shear (U_s)	Longitudinal L/(× 10^9 N.m^{-2})	Shear G/(× 10^9 N.m^{-2})	Bulk K/(× 10^9 N.m^{-2})	Young's E/(× 10^9 N.m^{-2})
SZB1	2.5329	5320.0	3009.2	71.68	22.93	41.18	58.00
SZB2	2.6566	5270.0	2990.0	73.78	23.75	42.19	59.97
SZB3	2.6689	5245.0	2988.2	73.42	23.83	41.72	60.03
SZB4	2.7009	5168.0	2934.2	72.13	23.25	41.20	58.68
SZB5	2.7189	5574.0	2955.1	84.47	23.74	52.89	61.93
SZB6	2.7258	5592.0	3266.2	85.23	23.98	53.33	62.54
SLB1	3.0388	5124.0	2724.6	79.78	22.55	49.78	58.76
SLB2	3.2068	4940.0	2662.0	78.25	22.72	48.03	58.98
SLB3	3.3034	4808.0	2642.4	76.36	23.06	45.69	59.19
SLB4	3.4838	4620.0	2530.9	74.35	22.31	44.67	57.36
SLB5	3.5770	4527.0	2476.1	73.30	21.93	44.13	56.42
SLB6	3.7349	4443.0	2406.2	73.72	21.62	44.96	55.88

Table-3. Values of Poisson's ratio (σ), acoustic impedance (Z), and micro hardness (H), Debye temperature (θ_D), and thermal expansion coefficient (α_P) of SZB and SLB glass systems.

Name of the sample	Poisson's ratio (σ)	Acoustic impedance Z/(× 10^7 kg.m^{-2} s^{-1})	Micro hardness H/(× 10^9 N.m^{-2})	Debye temperature θ_D/(K)	Thermal expansion coefficient α_P/(K^{-1})
SZB1	0.2648	1.3475	3.5951	287.56	123410.67
SZB2	0.2626	1.4000	3.7586	289.91	122250.67
SZB3	0.2597	1.3998	3.8171	289.80	121670.67
SZB4	0.2621	1.3958	3.6869	285.83	119884.27
SZB5	0.3045	1.5155	3.0937	289.40	129303.47
SZB6	0.3042	1.5242	3.9597	290.42	129721.07
SLB1	0.3029	1.5570	2.9630	263.15	118863.47
SLB2	0.2981	1.5841	3.0578	258.72	114594.67
SLB3	0.2836	1.5882	3.3262	256.29	111532.27
SLB4	0.2856	1.6095	3.1886	247.47	107170.67
SLB5	0.2865	1.6193	3.1210	241.91	105013.07
SLB6	0.2925	1.4594	2.7903	236.43	103064.27

For SZB and SLB glasses, B_2O_3 is a well known network glass former, the network of pure B_2O_3 glass consists of three coordinated trigonal (B_3) boron atoms [9]. All boron atoms in the SZB and SLB glass systems are three-coordinated with oxygen. This is due to fact that the Ba^{2+} and Pb^{2+} ions transfer boron atoms from a three-coordinated state (BO_3 state) to more stable four-coordinated one [10].

For SZB glasses, the density shows a continuous increase (Table 2) with increase in mol% of ZnO. The structure of the glass depends on the nature of the ions entering in the network and hence the density of glass [3]. It is seen from the Tab 2 that both longitudinal velocity (U_l) and shear velocity (U_S) increase almost linearly with the concentration of ZnO, but the rate of increase of U_l is greater than that of U_S. U_l decreases upto 16 mol% of ZnO and increases thereafter. The increase in ultrasonic velocity has been attributed to an increase in packing density because of the transformation of coordination of Boron ions. Due to this packing density, the rigidity of the glass system increases and hence the ultrasonic velocities and elastic constants. The longitudinal, shear, bulk and Young's moduli (Table-2) represent an increasing trend over the entire range of composition of ZnO.

These increasing modes indicate that ZnO tries to form a ring structure in the form of a regular ZnO_4 tetrahedral coordination [11]. Further, the increase in micro hardness (H), strengthen the softening points, as the network modifier (NWM) content is increased, while the increase in Poisson's ratio shows that the atoms experience higher transverse contracting strain and hence become more tightly packed. And also the varying mol% of ZnO in SZB glass system does not affect the structure of glass, and hence ZnO acts as a network modifier (NWM) in such glasses. The continuous increase of micro hardness as well as Poisson's ratio reveals that absence of non-bridging oxygen ion (NBO) which causes the formation of glassy network. In other words, more Zn^{2+} ions begin to close up the interstices of cages with the network [12]. Further the increase of acoustic impedance and thermal expansion coefficient (Table-3) are due to increase in rigidity of the structure of the glass. From Table-3 it can be observed that the increase in Debye temperature with ZnO is possibly due to the charged centre coming closer than the distance required statistically to achieve a more effective Columbian interaction. Such an interaction can give rise to high energy vibrational modes The increasing trend of Debye temperature values confirms the occurrence of strong ring formation in SZB glasses.

The replacement of ZnO by PbO in next series, drastically changes their elastic properties. The density of the glass specimens increases with increase of mol% of PbO. From Table-2 it is observed that both longitudinal and shear velocities show decreasing tendency with increase of mol% of PbO. The continuous decrease in ultrasonic velocity is due to the formation of non-bridging oxygen (NBO) which makes the glass less soften [13]. The longitudinal (L), shear (G) bulk (K) and Young's moduli (Table-2) vary in the same way as that of velocities of longitudinal and shear waves. The decrease in elastic moduli in general indicates a reduction in network rigidity. The ring formation of PbO with Boron is reduced and Boron ions possibly try to modify the ring-like structure into smaller ring formation causing a decrease in bulk modulus which leads to the softening of the glasses. Addition of PbO to $Na_2CO_3 - B_2O_3$ combination reduces the values of Poisson's ratio, resulting in the modification of the network structure. This can be further confirmed by measured micro hardness values which show a decreasing tendency (Table-3).

Further, the decreasing values of acoustic impedance and thermal expansion coefficient as shown in Table-3 are due to the reduction in rigidity of the glass structure. The decreasing trend of the Debye temperature shown in Table-3 strongly confirms the weakening of the glass network in the system.

CONCLUSIONS

- It is concluded that the evaluated acoustical elastic and mechanical parameters of the glass specimen (SZB, SLB) throw light on the rigidity and compactness in structural network.
- The SZB glass posses higher rigidity, strength and compactness in structural network over the SLB glass.

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