Volumetric and compressibility studies and phase equilibria of aqueous biphasic systems of alcohols using phase diagram

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Abstract

The solubility data of $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ in various concentrations of water and ethanol/1-propanol/2-propanol/2-methyl-2-propanol have been obtained to plot triangular phase diagrams and to determine the liquid–liquid–solid equilibria at 298.15 K. The density and sound velocity measurements were carried out for binary systems (water–salt, water–ethanol/1-propanol/2-propanol/2-methyl-2-propanol) and ternary systems (water–ethanol/1-propanol/2-propanol/2-methyl-2-propanol- $\text{Na}_2\text{S}_2\text{O}_3$) to investigate volumetric and compressibility properties. The obtained data was used to determine the acoustic parameters including adiabatic compressibility (β_s), excess molar volume (V^E), intermolecular free length (L_f), specific acoustic impedance (Z), relative association (R_A), solvation number (S_n) of water–alcohols, water–salt and water–alcohol–salt at 298.15 ± 0.05 K to evaluate equilibrium effects. Based on which, the salting-out of studied alcohols and phase forming ability of $\text{Na}_2\text{S}_2\text{O}_3$ through its bond making and breaking properties, intermolecular interactions were reported. The density, sound velocity and adiabatic compressibility of ternary system suggest phase separation phenomenon is bond breaking and bond making process with hydrogen bonding and hydrophobic interaction. The phase formation ability of systems composed of different alcohols is in order of 2-methyl-2-propanol > 1-propanol > 2-propanol > ethanol.

Keywords Phase diagram · Acoustic properties · Salting out effect · Hydrophobic interactions · Ion–ion interactions

1 Introduction

Phase diagram represents a phase boundary, the conditions when two phases may coexist in equilibrium and the preferred physical state of a matter at different temperature and pressure for binary or ternary mixture. This experimental data is important for studying the various aqueous two-phase systems (ATPs), from which the optimization of the operating condition for superior results in separation and solvent extraction can be possible. In addition, it has various applications in the field of biology, medicine, research and industry [1–3]. Furthermore, the ATPs diagrams offer (salt–aqueous alcohol system) most

valuable information about the structural changes in solvent, salting-in/salting-out effect, to understand the hydration and hydrophobic interaction between ions–solvent systems and nature of hydrogen bonding [4, 5]. The challenge to separate the alcohol is due to its many desirable characteristics in fuel additive (gasoline), replacing ethers like methyl tertiary butyl ether (MTBE), beverages, solvent, plasticizer, precursor to detergent. So it needs to distinct two layers as well as recycling the alcohols. The phase separation is depends upon the dielectric constant, ion–ion, ion–dipole interaction, hydrogen bonding and solubility etc.

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In our previous study liquid–liquid–solid equilibria in the ternary system $\text{Na}_2\text{S}_2\text{O}_3$ + ethanol + water and $\text{Na}_2\text{S}_2\text{O}_3$ + *t*-butanol + water at ambient pressure and at room temperature (303 ± 2 K) [6, 7] have been studied in detail. Now, our aim is to study the molecular interactions such as solute–solute, solute–solvent, solvent–solvent, which are responsible for phase separation. For these phase separation, the interactions of salt with solvent, the behavior of ions produced from salt plays a crucial role. Generally the ions are categorized into two types such as “kosmotropic” or “chaotropic” based on ‘water structure maker’ or ‘water structure breaker’ giving salting out and salting-in effect respectively [8, 9]. Up to now, various researchers were carrying out the study of ATPS by using a phase diagram in which they used some models and equations to correlate the binodal and tie line in liquid–liquid equilibria (LLE) [10–16]. In recent years, several researchers focused on the measurement and investigation of thermodynamics of ATPSs composed of an aqueous solution of a short chain aliphatic alcohol in the presence of an electrolyte [10, 11, 17–21]. However, the detailed study of molecular interactions responsible for phase separation is not reported in detail. Therefore, our aim is to do the study of liquid–liquid and liquid–solid equilibria by using molecular interactions.

Through this paper, we attempt to present, the liquid–liquid–solid phase equilibria of ternary system (water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$) at 298.15 ± 0.05 K. In addition, this paper presents a systematic study of density, ultrasonic velocity and some thermo-acoustic parameters of binary systems such as, water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol, water + $\text{Na}_2\text{S}_2\text{O}_3$, and ternary systems like water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$. The thermo-acoustic parameters like adiabatic compressibility (β_s), apparent molar volume (ϕ_v), intermolecular free length (L_f), specific acoustic impedance (Z), relative association (R_A), solvation number (S_n) and excess molar volume (V^E) estimated from density and speed of sound data. The obtained data further used to explain the molecular interactions such as solute–solute, solute–solvent, solvent–solvent. Moreover, the purpose of this study is to develop the thermo-acoustic model of ATPS system as well as to understand the mechanism of salting out and predict the effect of electrolyte on interactions in a water–alcohol mixture.

2 Materials and method

AR grade ethanol (Changshu Hongsheng Fine Chemical; 99.9%), 1-propanol (Molychem; 99.5%), 2-propanol (Molychem; 99.5%), 2-methyl-2-propanol (Molychem; 99.5%),

Sodium thiosulphate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$, Lobachemie; 99.0%), were used without further purification. Different percent mass fraction compositions of solutions were prepared by using double distilled water. The weight of solutions required for the preparation of compositions taken on Shimadzu balance (AUW220D) with a precision of 0.0001 g.

3 Experimental procedure

The experimental apparatus employed in this work is double-wall glass vessel with air tight lid. The phase separation data of the phase diagram were obtained using water + various aliphatic alcohols (ethanol/1-propanol/2-propanol/2-methyl-2-propanol) mixture (initially 50:50 wt%) to which successive addition of solid $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ (wt%) in a small increment were made with constant stirring. The point of phase separation (salting-out) was determined by the appearance of turbidity in the solution. The solution was allowed to stand for 1 h to confirm the phase separation and further addition of $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ was continued until solid ceases to dissolve (saturated point of salt in aqueous layer). In a similar way, water + alcohol mixtures of different compositions were used (Table 1) and phase separation data (liquid–liquid equilibrium) and solid separation data (liquid–solid equilibrium) were obtained by adding $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ in these mixtures. The concentrations of the constituent in terms of mass fraction $\times 100$ were plotted on a triangular graph (known as a triangular phase diagram) to determine the mentioned concentrations (Table 1). All concentrations in terms of % mass fraction of the hydrated salt solutions were converted to that of anhydrous salt solutions.

The densities of binary systems such as, water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol, water + $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ and for ternary system such, water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ were determined using an Anton Paar DMA-4100 M vibrating tube densitometer with an accuracy of 0.1 kg m^{-3} . Calibration was performed periodically under atmospheric pressure, in accordance with the specification using dry air and deionized water. The densities and sound velocities values of pure water, ethanol, 1-propanol, 2-propanol, 2-methyl-2-propanol were found to be in good agreement 298.15 ± 0.05 K with literature data [22–27] which are given in Table S1 and Fig.S1 [28]. The sound velocity measurements were carried out at 298.15 ± 0.05 K for all mixtures using an ultrasonic interferometer (Mittal Enterprises, New Delhi, India, F-05) operating at 2 MHz frequency. The uncertainty in measured values of sound velocity is found to be ± 0.5 m/s. The density and speed of sound velocity measurements for binary systems such as,

Table 1 Liquid–liquid and liquid–solid equilibria data in terms of mass of water (w_1), ethanol/n-propanol/2-propanol/2-methyl-2-propanol (w_2) and $\text{Na}_2\text{S}_2\text{O}_3$ salt (w_3)

Liquid–liquid equilibria			Solid–liquid equilibria		
$100w_1$	$100w_2$	$100w_3$	$100w_1$	$100w_2$	$100w_3$
<i>Ethanol + $\text{Na}_2\text{S}_2\text{O}_3$ + water</i>					
00.00	100	NP*	0.009	99.97	0.02
10.04	89.95	NP*	10.06	89.92	0.03
20.10	79.89	NP*	20.12	79.83	0.05
30.03	69.96	NP*	30.05	69.74	0.20
40.02	58.03	01.95	39.52	50.21	10.27
49.19	47.05	03.76	45.28	32.81	21.90
56.61	34.46	08.92	49.88	23.03	27.09
61.14	22.39	16.46	52.94	15.00	32.06
62.89	12.55	24.55	56.02	09.31	34.67
89.78	10.22	NP*	57.03	03.96	39.00
100	00.00	NP*	59.37	00.00	40.63
<i>1-Propanol + $\text{Na}_2\text{S}_2\text{O}_3$ + water</i>					
00.00	100	NP*	0.004	99.99	0.008
10.06	89.94	NP*	10.07	89.92	0.014
20.04	79.62	0.33	22.20	69.03	08.77
30.09	69.29	0.62	31.60	52.41	15.77
39.98	59.09	0.92	38.81	40.31	20.88
49.53	48.41	02.06	44.68	30.67	24.65
58.44	37.52	04.03	49.07	21.64	29.29
67.02	27.43	05.55	53.02	14.93	32.05
74.34	17.49	08.17	55.79	08.97	35.24
75.06	07.27	17.66	59.26	04.31	36.43
100	00.00	NP*	59.38	00.00	40.63
<i>2-Propanol + $\text{Na}_2\text{S}_2\text{O}_3$ + water</i>					
00.00	100	NP*	0.004	99.99	0.008
10.05	89.95	NP*	10.05	89.93	0.013
20.15	79.54	0.30	21.06	72.86	05.63
30.00	69.49	0.51	31.27	55.45	13.27
39.99	59.11	0.81	38.72	38.96	22.31
49.57	48.25	02.18	44.32	29.17	26.50
58.07	36.71	05.22	49.12	21.64	29.23
65.03	25.65	09.32	52.28	14.27	33.43
69.75	15.50	14.75	55.02	08.68	36.29
70.44	06.36	23.19	56.27	03.72	40.00
100	00.00	NP*	59.37	00.00	40.63
<i>2-Methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$ + water</i>					
00.00	100	NP*	00.00	99.99	0.006
10.06	89.94	NP*	11.18	99.98	0.012
20.13	79.68	0.18	22.38	68.59	09.03
30.18	69.41	0.41	31.37	55.88	12.74
39.93	58.98	01.10	38.94	42.94	18.12
49.62	48.60	01.77	44.53	30.03	25.43
59.01	38.34	02.64	49.09	21.61	29.29
67.50	27.94	04.55	52.56	14.56	32.88
74.71	17.69	07.59	55.87	09.02	35.11
72.05	06.79	21.15	58.17	04.16	37.66

Table 1 (continued)

Liquid–liquid equilibria			Solid–liquid equilibria		
$100w_1$	$100w_2$	$100w_3$	$100w_1$	$100w_2$	$100w_3$
100	00.00	NP*	59.37	00.00	40.63

NP*, no phase separation

water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol and water + $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ as well as for ternary system of water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ were carried out at 298.15 K.

4 Results and discussion

In the present work, liquid–liquid and liquid–solid equilibria of water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$ systems were carried out in order to achieve a further understanding about the salting out effect. The results obtained for the different alcohols + water were discussed in different subsections such as, construction of phase diagram and liquid–liquid equilibria properties, volumetric and acoustic properties of binary system, volumetric, acoustic, conductometric properties of ternary system etc.

4.1 Construction of phase diagram and liquid–liquid equilibria properties

The triangular phase diagram of water + ethanol + $\text{Na}_2\text{S}_2\text{O}_3$ (Fig. 1), water + 1-propanol + $\text{Na}_2\text{S}_2\text{O}_3$ (Fig. 2), water + 2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$ (Fig. 3) and water + 2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$ (Fig. 4) have been constructed from solubility data of $\text{Na}_2\text{S}_2\text{O}_3$ in different compositions of water–alcohol mixtures. All the data has been plotted in terms of percentage mass fraction of concentrations of each components [water (w_1), alcohol (w_2) and $\text{Na}_2\text{S}_2\text{O}_3$ salts (w_3)] (Table 1). To understand the region of the phase diagram, we used terms like L_A , L_O and S as aqueous layer, organic layer and solid $\text{Na}_2\text{S}_2\text{O}_3$ salt respectively.

The various areas in all the four phase diagrams can be described as, the area 'AabcdA': a point in this region represents homogeneous mixtures (L) of all three components such as, water, ethanol/1-propanol/2-propanol/2-methyl-2-propanol and $\text{Na}_2\text{S}_2\text{O}_3$, where point 'a' represent the solubility or saturation point of salt in water. The area 'BabB': a point in this region ($L_A + S$) represents $\text{Na}_2\text{S}_2\text{O}_3$ salt in equilibrium with the water rich saturated solution. The area 'BdCB': this region ($L_O + S$) represents $\text{Na}_2\text{S}_2\text{O}_3$ salt in equilibrium with alcohol rich saturated solution. The area 'dcdb' ($L_A + L_O$) represents the alcohol is separated continuously from the aqueous layer by adding salt (two

Fig. 1 Phase diagram of ternary system of water + ethanol + $\text{Na}_2\text{S}_2\text{O}_3$: (open circle) liquid–liquid phase separation; (filled circle) solid–liquid phase separation at 298.15 ± 0.5 K

Fig. 2 Phase diagram of ternary system of water + 1-propanol + $\text{Na}_2\text{S}_2\text{O}_3$: (open triangle) liquid–liquid phase separation; (filled triangle) solid–liquid phase separation at 298.15 ± 0.5 K

conjugated solutions of salt in water–alcohol mixture), the area 'BbdB' ($L_A + L_O + S$): a point in this region represents the saturation of $\text{Na}_2\text{S}_2\text{O}_3$ salt in aqueous layer.

The curve 'bcd' represents the liquid–liquid phase separation curve, which was observed by formation of turbid solution. The solid separation points (line denoted as a solid symbol, i.e. 'abd') was determined from the point where the solubility of $\text{Na}_2\text{S}_2\text{O}_3$ ceases, at this point solid

Fig. 3 Phase diagram of ternary system of water + 2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$: (open square) liquid–liquid phase separation; (filled square) solid–liquid phase separation at 298.15 ± 0.5 K

Fig. 4 Phase diagram of ternary system of water + 2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$: (open inverted triangle) liquid–liquid phase separation; (filled inverted triangle) solid–liquid phase separation at 298.15 ± 0.5 K

$\text{Na}_2\text{S}_2\text{O}_3$, liquid L_A and L_O are coexisting in equilibrium. Further addition of salt could not generate any change in the composition of these liquid layers hence in this region 'BbdB', the system is isothermally invariant ($L_A + L_O + S$). The triangular phase diagram shows that the point 'a' represents the saturation solubility of $\text{Na}_2\text{S}_2\text{O}_3$ in water, where

the composition of $\text{Na}_2\text{S}_2\text{O}_3$ and water 59.37% and 40.63% respectively. The 'd' point is the composition of $\text{Na}_2\text{S}_2\text{O}_3$ at which salting out starts, these points are different for different alcohols, the values obtained from the phase diagrams are given in Table 2. The 'd' point of ethanol is 58.03% alcohol composition with 1.95% $\text{Na}_2\text{S}_2\text{O}_3$ (Fig. 1). Whereas, 'd' point of 1-propanol, 2-propanol and 2-methyl-2-propanol are found to be, ~ 79.61% alcohol composition with ~ 0.27% $\text{Na}_2\text{S}_2\text{O}_3$ (Figs. 2, 3, 4), due to hydrogen bonding interaction and the ion–dipole interactions with alcohols. While ~ 10.22% of ethanol composition was not separated due to strong interaction with water and water has enough space to make bond with salt without salting out the ethanol than the rest of alcohols. From Figs. 1, 3 and 4 it is observed that, the determined phase separation abilities of investigated alcohols from the extent of biphasic areas (dcdbd) of water + ethanol + $\text{Na}_2\text{S}_2\text{O}_3$, water + 1-propanol + $\text{Na}_2\text{S}_2\text{O}_3$, water + 2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$ and water + 2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$ systems were in the order of 2-methyl-2-propanol > 1-propanol > 2-propanol > ethanol. This observed sequence follow the order, which is reported in literature [29, 30]. The effect of the addition of salt in a solution of water–alcohol is very complex, primarily because a large number of different types of interactions come into play between the water–alcohol, water–ion, and water–alcohol–ion. These interactions were explained by using acoustic properties to resolve this mechanism [31–34].

4.2 Volumetric and acoustic properties of binary systems (water + alcohol and water + salt)

The density and speed of sound data of water–alcohol mixture at different mole fractions and for water + $\text{Na}_2\text{S}_2\text{O}_3$ mixture at concentrations from 0.01 to 3 M solutions were determined and given in Tables 2 and 3 respectively. From these experimental data, various acoustical parameters like, adiabatic compressibility (β_s), inter molecular free length (L_f), relative association (R_A), specific acoustical impedance (Z), Solvation number (S_n) and excess molar volume (V^E) were determined using the following equations,

$$\beta_s = (\rho u^2)^{-1} \quad (1)$$

$$L_f = K \sqrt{\beta_s} \quad (2)$$

$$R_A = (\rho/\rho_0)(u_0/u)^{\frac{1}{3}} \quad (3)$$

$$Z = u \times \rho \quad (4)$$

$$S_n = \left(n_1/n_2 \right) ((1 - \beta_s)/\beta_s^0) \quad (5)$$

$$V^E = \frac{(M_1X_1 + M_2X_2)}{\rho_{1,2}} - \frac{M_1X_1}{\rho_1} - \frac{M_2X_2}{\rho_2} \quad (6)$$

where ρ , ρ_0 and u , u_0 are the densities and ultrasonic velocities of solutions and solvents respectively. M is the molecular weight of the solute, β_s^0 and β_s is the adiabatic compressibility of solvent and solution respectively, K the Jacobson constant, n_1 and n_2 are the number of moles of the solvent and solute respectively. V^E is excess molar volume of liquid mixture x_1 and x_2 are mole fraction, M_1 and M_2 molecular weight of liquid mixtures.

From the result, it is observed that the density (ρ) and sound velocity (u) of water + alcohol systems gradually increase with increase in mole fraction of water (Fig. S2–S3), whereas for water– $\text{Na}_2\text{S}_2\text{O}_3$ (Table 3) data increases with increase in concentration of $\text{Na}_2\text{S}_2\text{O}_3$ (Figs. S5, S6). This may be attributed to the aggregation of alcohol in water which results in the decrease in volume and rise in mass. The apparent molar volumes of aqueous solutions of sodium thiosulphate were estimated by using Eq. (1) and the data obtained was given in and Table 3.

$$\varphi_V = \frac{M_2}{\rho} + \left(\frac{(\rho_0 - \rho)}{m\rho\rho_0} \right) \quad (7)$$

In Eq. (1), M_2 represents the molar mass of the salt in kg mol^{-1} and m is the molality in mol kg^{-1} whereas ρ and ρ_0 represents the densities in kg m^{-3} , for salt in aqueous solution and water respectively.

The apparent molar volume (φ_V) data for the water + salt, decreases with increase in concentration is generally attributed to electrostriction of ion (Table 3).

The speed of sound data of alcohol and sodium thiosulphate in aqueous solutions were used to determine the adiabatic compressibility (β_s) by using Eq. (1) and the data obtained was given in Tables 2 and 3 respectively.

The decrease in adiabatic compressibility (β_s) of aqueous solutions of alcohols and salt decreases with increase in concentration, which indicates that, the water–alcohol and water–salt molecules undergo structural reorganization and they are being compressed (Figs. S4–S7). The values of ρ , u and β_s along with corresponding uncertainties are given in Tables 2 and 3. The water molecules have strong hydrogen bonded structure with numerous cavities, whereas, the alcohol or salt molecules make a hydrogen bond and occupy the interstitial space of water. Further, they aggregate and contribute to the increase in volume, while the β_s values decreases with the increase in concentration of salt due to association of ions results in compact packing. The value of excess molar volume (V^E) becomes negative with concentration for water + alcohols mixture

Table 2 The values of density ($\rho/\text{kg m}^{-3}$), ultrasonic velocity ($u/\text{m s}^{-1}$), adiabatic compressibility ($\beta_s/\text{m}^2 \text{N}^{-1}$), excess molar volume ($V^E/\text{m}^3 \text{mol}^{-1}$), intermolecular free length (L_f/m), specific acoustic impedance ($Z/\text{kg m}^2 \text{s}^{-1}$), relative association ($R_A/\text{mol dm}^3$) of water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol binary mixture at $298.15 \pm 0.05 \text{ K}$

x_2	$\rho (\text{kg m}^{-3})$	$u (\text{m s}^{-1})$	$10^{-10} \beta_s (\text{m}^2 \text{N}^{-1})$	$10^{-4} V^E (\text{m}^3 \text{mol}^{-1})$	$10^{-3} L_f (\text{m})$	$10^6 Z (\text{kg m}^2 \text{s}^{-1})$	$R_A (\text{mol dm}^3)$
<i>Water + ethanol</i>							
1.0000	785.2 ± 0.080	1143.44 ± 0.142	9.5628 ± 2.915	0.0000	2.9030	0.91	0.341
0.7777	814.8 ± 0.086	1225.84 ± 0.134	8.3022 ± 2.339	− 7.1397	2.7049	0.99	0.336
0.6095	840.0 ± 0.083	1282.3 ± 0.129	7.4712 ± 2.029	− 9.7922	2.5659	1.06	0.334
0.4763	864.0 ± 0.081	1348.42 ± 0.121	6.3655 ± 1.624	− 1.0647	2.3685	1.17	0.321
0.3695	887.4 ± 0.079	1406.34 ± 0.116	5.6977 ± 1.396	− 1.0685	2.2408	1.25	0.316
0.2809	910.0 ± 0.077	1477.56 ± 0.110	5.0334 ± 1.177	− 1.0026	2.1061	1.34	0.309
0.2066	931.8 ± 0.075	1544.74 ± 0.105	4.4974 ± 1.008	− 8.9284	1.9908	1.44	0.302
0.1535	950.7 ± 0.073	1601.36 ± 0.101	4.1018 ± 0.888	− 7.0409	1.9013	1.52	0.297
0.0893	966.5 ± 0.072	1613.9 ± 0.101	3.9723 ± 0.853	− 4.5876	1.8710	1.56	0.300
0.0420	980.2 ± 0.071	1570.34 ± 0.103	4.1371 ± 0.909	− 1.9143	1.9094	1.54	0.312
0.0000	997.0 ± 0.071	1497.4 ± 0.109	4.4792 ± 1.026	0.0000	1.9841	1.54	0.333
<i>Water + 1-propanol</i>							
1.0000	799.8 ± 0.083	1207.48 ± 0.104	8.5234 ± 1.928	0.0000	2.7422	0.97	0.331
0.7258	822.8 ± 0.081	1261.86 ± 0.100	7.6327 ± 1.644	− 4.7662	2.5935	1.04	0.327
0.5458	844.2 ± 0.079	1298.32 ± 0.097	7.0273 ± 1.472	− 6.7257	2.4885	1.10	0.326
0.4107	864.6 ± 0.077	1334.8 ± 0.094	6.4916 ± 1.323	− 6.8365	2.3918	1.15	0.324
0.3095	885.2 ± 0.075	1372.56 ± 0.092	5.9964 ± 1.189	− 6.6974	2.2988	1.21	0.323
0.2306	905.9 ± 0.073	1413.48 ± 0.089	5.5251 ± 1.065	− 6.3228	2.2066	1.28	0.321
0.1665	926.5 ± 0.072	1463.2 ± 0.086	5.0414 ± 0.940	− 5.6643	2.1078	1.36	0.37
0.1138	947.6 ± 0.070	1517.3 ± 0.083	4.5839 ± 0.826	− 4.9972	2.0099	1.44	0.312
0.0696	966.8 ± 0.069	1577.62 ± 0.080	4.1558 ± 0.722	− 3.7870	1.9137	1.53	0.307
0.0322	982.4 ± 0.068	1572.44 ± 0.080	4.1168 ± 0.716	− 1.9034	1.9047	1.54	0.313
0.0000	997.0 ± 0.071	1496.6 ± 0.109	4.4791 ± 0.811	0.0000	1.9840	1.50	0.333
<i>Water + 2-propanol</i>							
1.0000	781.2 ± 0.093	1140.06 ± 0.144	9.4209 ± 2.973	0.0000	2.8913	0.92	0.325
0.7284	807.5 ± 0.090	1203.42 ± 0.135	8.5511 ± 2.378	− 4.1750	2.7451	0.97	0.330
0.5448	832.1 ± 0.088	1255.04 ± 0.130	7.6297 ± 2.063	− 7.3463	2.5930	1.04	0.334
0.4108	855.8 ± 0.085	1301.62 ± 0.121	6.8970 ± 1.652	− 8.5776	2.4654	1.11	0.337
0.3099	880.1 ± 0.083	1362.62 ± 0.116	6.1195 ± 1.418	− 9.1367	2.3223	1.20	0.343
0.2305	902.9 ± 0.081	1423.16 ± 0.111	5.4683 ± 1.195	− 8.6107	2.1952	1.28	0.349
0.1664	926.3 ± 0.079	1493.40 ± 0.106	4.8406 ± 1.022	− 7.9804	2.0654	1.38	0.357
0.1138	948.0 ± 0.077	1562.20 ± 0.102	4.3223 ± 0.898	− 6.7276	1.9517	1.48	0.365
0.0699	966.7 ± 0.075	1619.42 ± 0.101	3.9445 ± 0.859	− 4.8227	1.8644	1.57	0.371
0.0325	980.9 ± 0.074	1425.22 ± 0.104	5.0189 ± 0.914	− 2.1132	2.1031	1.40	0.322
0.0000	997.0 ± 0.071	1496.62 ± 0.109	4.4779 ± 1.032	0.0000	1.9841	1.49	0.333
<i>Water + 2-methyl-2-propanol</i>							
1.0000	781.5 ± 0.094	1125.61 ± 0.145	10.0075 ± 3.076	0.0000	2.9697	0.89	0.348
0.6812	804.5 ± 0.091	1179.34 ± 0.138	8.9370 ± 2.603	− 2.2303	2.8064	0.95	0.341
0.4929	827.9 ± 0.089	1226.3 ± 0.133	8.0321 ± 2.252	− 5.7125	2.6605	1.02	0.338
0.3907	852.5 ± 0.086	1280.5 ± 0.127	7.1539 ± 1.923	− 7.6233	2.5109	1.09	0.333
0.2668	875.7 ± 0.084	1326.26 ± 0.123	6.4921 ± 1.687	− 7.9133	2.3919	1.16	0.330
0.1954	899.4 ± 0.082	1382.02 ± 0.118	5.8212 ± 1.453	− 7.8219	2.2650	1.24	0.320
0.1394	921.4 ± 0.080	1438.62 ± 0.113	5.2439 ± 1.260	− 6.8197	2.1497	1.33	0.320
0.0942	945.3 ± 0.078	1514.6 ± 0.108	4.6114 ± 1.055	− 6.2012	2.0159	1.43	0.312
0.0577	966.9 ± 0.076	1594.2 ± 0.102	4.0694 ± 0.888	− 4.8709	1.8937	1.54	0.303
0.0261	982.1 ± 0.075	1588.72 ± 0.103	4.0341 ± 0.881	− 2.2991	1.8855	1.56	0.309
0.0000	997.0 ± 0.071	1496.44 ± 0.109	4.4790 ± 1.030	0.0000	1.9842	1.49	0.333

 x_2 —mole fraction of alcohols respectivelyStandard uncertainties u are $u(\rho) = 0.1 \text{ kg m}^{-3}$ with $u(T) = 0.05 \text{ K}$, $u(u) = 0.5 \text{ m s}^{-1}$ with $u(T) = 0.05 \text{ K}$

and water + $\text{Na}_2\text{S}_2\text{O}_3$ solutions are shown in Figs. 5 and S8. The values of V^E are negative for the entire composition in both cases, which indicates that, a more efficient packing or attractive interaction occurred in the water–alcohol and water– $\text{Na}_2\text{S}_2\text{O}_3$ solutions. The nature of graph of water + alcohol system is U-shaped, which ascribed to the equilibria of State effect and steric factor arising from the change of orientation of water molecules with change in its mole fraction [35]. In water + ethanol system shows maximum negative V^E value suggested strong molecular interaction between them compare to the rest of alcohols. The decrease in intermolecular free length (L_f) values in both the cases is observed and it is proportional to the adiabatic compressibility, which shows strong ion–solvent and solute–solvent interactions. The L_f values evident that the degree of H-bonding of salt–water is stronger than water–alcohol. Specific acoustic impedance (Z) is a quantitative property, which is depending on the molecular packing of the system. The increase in the Z value suggests the presence of a strong interaction through hydrogen bonding in both systems [36]. Relative association (R_A) depends either on, solvation of ions or breaking of solvent molecules associated with electrolyte. It is observed that the R_A values of water–alcohol and water–salt increases (Tables 3, 4) due to the strong association between molecules. Solvation number (S_n) determined by using passynski method [31], the obtained values explain the interaction of solvent with solute molecules. This process involves reorganizing solvent and solute into hydration sphere. The maximum S_n value observed at low concentration of salt due to electrostriction of ion while as molarity increases S_n value dropped due to association of ion results in ion–ion interactions. The calculated acoustic values of water–salt system are higher than water–alcohol system as the hydration sphere of ion is stronger than that of alcohol.

4.3 Volumetric, acoustic and conductometric properties of ternary system (water + alcohol + $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$)

It is difficult to understand and discuss the interactions (bond breaking and bond making processes) in ternary water + alcohols + salt system. The volumetric and acoustic properties such as, ρ , u , β_s , ϕ_V , V^E , L_f , Z , R_A and S_n were estimated from density and sound velocity data. For this study, the mixture of 50% water + 50% alcohols composition (which shows maximum separation) has been selected as solvent and $\text{Na}_2\text{S}_2\text{O}_3$ as an electrolyte which acts as solute. The points which are selected to determine the density and sound velocity are before phase separation and last point is the phase separation point of water + alcohol + $\text{Na}_2\text{S}_2\text{O}_3$ systems and the data obtained are given in Table 4. The density (ρ) increases with addition

of small amount of sodium thiosulphate salt in solution up to phase separation point whereas; it suddenly dropped at phase separation point as shown in Fig. S9. Similarly, the speed of sound data (u) decreases and β_s values increases with concentration of salt as shown in Figs. 6 and 7. The obtained density data was further used to estimate the apparent molar volume of ternary systems and from this data it is observed that, the ion–solvent interactions are dominant over ion–ion (solute–solute) interactions at lower concentration while at higher concentration ion–ion interactions are dominant over ion–solvent interactions which results in ion association or ion-pair formation (Fig. S10). From the obtained data it is also observed that, the easy separation of alcohols containing more hydrophobic groups from solution due to increase in ion-pair formation. The negative V^E values of $\text{Na}_2\text{S}_2\text{O}_3$ in ternary system are also correlated to the association of ions in water–alcohol mixture. In addition, L_f values and R_A values are slowly increasing which sense a breaking of water–alcohol bond and formation of water–electrolyte sheath with increases $\text{Na}_2\text{S}_2\text{O}_3$. S_n describes bond formation, hydrogen bonding, and Van der Waals forces between solvent and solute. The S_n value of ethanol is positive while 1-propanol, 2-propanol and 2-methyl-2-propanol values are negative. S_n value increases with increase $\text{Na}_2\text{S}_2\text{O}_3$ and at phase separation point it is higher (Table 4). S_n characterizes the solute–solvent interactions are maximum in water + ethanol + salt than rest studied alcohols due to hydrogen bonding ability of ethanol towards water and therefore this behavior shows that water–salt interactions increases and water–alcohol interaction decreases slowly with salt concentration.

The density, speed of sound and isentropic compressibility of ternary systems after phase separation (upper layer and lower layer) including saturation point of studied alcohols with $\text{Na}_2\text{S}_2\text{O}_3$ were given in Table S2. From the obtained result, it is observed that, the density and sound velocity of upper layer i.e. alcohol rich layer decreases and compressibility increases while density and sound velocity of lower layer i.e. water rich layer increases and compressibility decreases. This can be illustrated that the salt slowly breaks the hydrogen bonding between alcohol and water due to electrostatic interactions of ions produced from the sodium thiosulphate with water. The increase in hydrophobic moieties on the alcohols as we goes from ethanol to tertiary butanol results in ion-pair formation ability due to reducing hydrogen bonding capacity of water towards alcohol. The obtained results are further supported with the degree of dissociation (α) values determined for ternary system containing different (water–alcohol) solvents from conductivity data given in Table 5. From the conductivity data, it is observed that, with addition of salt in solvent, initially conductance increases with increase

Table 3 The values of density (ρ /kg m⁻³), ultrasonic velocity (u /m s⁻¹), adiabatic compressibility (β_s /m² N⁻¹), apparent molar volume (ϕ_v /m³ mol⁻¹), excess molar volume (V^E /m³ mol⁻¹), intermolecular free length (L_f /m), specific acoustic impedance (Z /kg m² s⁻¹), relative association (R_A /mol dm³), solvation number (S_n) of water + Na₂S₂O₃ with different molar concentration at 298.15 ± 0.05 K

M	x_1	x_3	ρ (kg m ⁻³)	u (m s ⁻¹)	$10^{-10} \beta_s$ (m ² N ⁻¹)	ϕ_v (m ³ mol ⁻¹)	$10^{-4} V^E$ (m ³ mol ⁻¹)	$10^{-3} L_f$ (m)	$10^6 Z$ (kg m ² s ⁻¹)	R_A (mol dm ³)	S_n
0.0092	0.9998	0.0002	998.7 ± 0.1008	1501.08 ± 0.1009	4.4438 ± 1.002	0.1581	-0.0031	1.9789	1.05	0.3345	31.8014
0.0459	0.9992	0.0008	1003.6 ± 0.1003	1505.00 ± 0.1007	4.3991 ± 0.989	0.1574	-0.0891	1.9689	1.51	0.3370	18.4903
0.0917	0.9984	0.0016	1010.1 ± 0.0996	1512.54 ± 0.1001	4.3274 ± 0.968	0.1564	-0.2019	1.9528	1.53	0.3409	19.0225
0.3669	0.9936	0.0064	1047.1 ± 0.0961	1557.96 ± 0.0972	3.9346 ± 0.853	0.1509	-0.8169	1.8621	1.63	0.3640	18.3832
0.7338	0.9874	0.0126	1094.4 ± 0.0920	1615.92 ± 0.0937	3.4993 ± 0.731	0.1444	-1.5418	1.7561	1.77	0.3946	17.0470
0.9173	0.9747	0.0253	1117.4 ± 0.0901	1646.78 ± 0.0920	3.3001 ± 0.676	0.1414	-1.8699	1.7053	1.84	0.4105	02.0105
1.6680	0.9549	0.0451	1178.3 ± 0.0854	1812.88 ± 0.0836	2.5823 ± 0.485	0.1341	-2.6764	1.5085	2.14	0.4766	08.9282
2.9364	0.9232	0.0768	1285.8 ± 0.0783	1904.78 ± 0.0795	2.1436 ± 0.380	0.1229	-3.9067	1.3744	2.45	0.5464	06.2502

M is the molarities of salt, x_1 and x_3 —mole fraction of water and Na₂S₂O₃ respectively
Standard uncertainties u are $u(\rho) = 0.1$ kg m⁻³ with $u(T) = 0.05$ K, $u(u) = 0.5$ m s⁻¹ with $u(T) = 0.05$ K

Fig. 5 Comparison of excess molar volume (V^E) for the alcohol+water system at 298.15 ± 0.05 K: (open circle) ethanol; (open triangle) 1-propanol; (open square) 2-propanol; (open inverted triangle) 2-methyl-2-propanol

in concentration of salt due to the dissociation of Na⁺ and S₂O₃ ions in solvent. Whereas after phase separation conductance dropped due to ion-pair formation as well as decreasing hydrogen bonding ability of water. The degree of dissociation of salt in each solvent system can be considered as efficient criteria to represent the dissociation of salt [37]. The degree of dissociation of Na₂S₂O₃ is in solvent, the order of water + 2-methyl-2-propanol (0.7766) > water + 1-propanol (0.66710) > water + 2-propanol (0.5993) > water + ethanol (0.5579). The dissociation of salt in each system is different due to different strength of hydrogen bonding between water–alcohol and the decrease in degree of dissociation with increase electron donating group due to association of alcohol and ion-pair formation in aqueous solutions.

The before phase separation of water–alcohol–salt into water–alcohol, and water–salt phases, various interactions are present. These interactions are due to H-bonding, hydrophobic interactions, electrostatic interactions etc. The addition of salt in 50% water–50% alcohol mixture, results in ion–water interactions dominating over water–alcohol interactions which weaken the H-bonding between water and alcohol. This is confirmed from the acoustic data and increase in conductance of solution before phase separation. From comparative study of different alcohol it is observed that, the alcohol carrying more hydrophobic moieties are separated easily due to dominant hydrophobic interactions over water–alcohol interactions. The order of separation is found to be in correlation with the hydrophobicity of alcohol. It has been shown that the two-phase formation ability of systems composed of different alcohols is in order of

Table 4 The values of density ($\rho/\text{kg m}^{-3}$), ultrasonic velocity ($u/\text{m s}^{-1}$), adiabatic compressibility ($\beta_s/\text{m}^2 \text{N}^{-1}$), apparent molar volume ($\phi_V/\text{m}^3 \text{mol}^{-1}$), excess molar volume ($V^E/\text{m}^3 \text{mol}^{-1}$), intermolecular free length (L_f/m), specific acoustic impedance ($Z/\text{kg m}^2 \text{s}^{-1}$), relative association ($R_A/\text{mol dm}^3$), solvation number (S_n) of ternary water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3$ system at $298.15 \pm 0.05 \text{ K}$

$(x_1 + x_2)$	x_3	ρ (kg m^{-3})	u (m s^{-1})	$10^{-10} \beta_s$ ($\text{m}^2 \text{N}^{-1}$)	ϕ_V ($\text{m}^3 \text{mol}^{-1}$)	$10^{-4} V^E$ ($\text{m}^3 \text{mol}^{-1}$)	$10^{-3} L_f$ (m)	$10^6 Z$ ($\text{kg m}^2 \text{s}^{-1}$)	R_A (mol dm^3)	S_n
<i>Ethanol + water + $\text{Na}_2\text{S}_2\text{O}_3$</i>										
1.0000	0.0000	910.1	1497.56	5.0329 ± 0.101	0.0000	0.0000	2.1060	1.3447	0.3333	0.0000
0.9981	0.0019	915.8	1492.24	4.9036 ± 0.096	-0.6394	-2.8685	2.0788	1.3666	0.3321	13.2526
0.9961	0.0039	917.4	1484.46	4.9465 ± 0.099	-0.4328	-2.5486	2.0879	1.3618	0.3344	4.3696
0.9940	0.0060	920.9	1482.04	4.9438 ± 0.099	-0.4116	-3.5728	2.0873	1.3648	0.3363	2.9166
0.9922	0.0078	923.7	1476.5	4.9659 ± 0.099	-0.3650	-4.3508	2.0919	1.3638	0.3386	1.6985
0.9905	0.0095	929.5	1472.96	4.9587 ± 0.099	-0.3718	-7.4219	2.0904	1.3691	0.3415	1.5412
0.9887	0.0113	934.4	1469.96	4.9528 ± 0.099	-0.3978	-9.6693	2.0892	1.3735	0.3440	1.3872
0.9870	0.0130	936.5	1464.5	4.9786 ± 0.099	-0.3649	-9.9391	2.0946	1.3715	0.3461	0.8159
0.9851	0.0149	940.2	1460.04	4.9894 ± 0.097	-0.3600	-0.1129	2.0969	1.3727	0.3485	0.5725
0.9833	0.0167	942.8	1453.78	5.0186 ± 0.100	-0.3423	-0.1181	2.1030	1.3706	0.3510	0.1672
0.9816	0.0184	940.7	1465.58	4.9491 ± 0.986	-0.2655	-8.9928	2.0884	1.3787	0.3474	0.8874
<i>1-Propanol + water + $\text{Na}_2\text{S}_2\text{O}_3$</i>										
1.0000	0.0000	905.9	1413.48	5.5251 ± 0.033	0.0000	-0.6667	2.2066	1.2805	0.3333	0.0000
0.9991	0.0009	906.5	1411.18	5.5394 ± 0.033	-0.0080	-0.5596	2.2095	1.2792	0.3341	-2.7428
0.9979	0.0021	908.8	1410.22	5.5329 ± 0.033	-0.2026	-1.9160	2.2082	1.2816	0.3352	-0.6754
0.9970	0.0030	909.3	1409.42	5.5362 ± 0.033	-0.1927	-1.7785	2.2088	1.2816	0.3355	-0.6771
0.9969	0.0031	910.2	1408.44	5.5384 ± 0.033	-0.1838	-2.5174	2.2093	1.2820	0.3361	-0.7716
0.9950	0.0050	911.5	1407.72	5.5361 ± 0.033	-0.1705	-2.3878	2.2088	1.2831	0.3368	-0.3976
0.9943	0.0057	913.5	1406.06	5.5371 ± 0.033	-0.1678	-3.8131	2.2090	1.2844	0.3379	-0.3817
0.9931	0.0069	914.3	1405.66	5.5354 ± 0.033	-0.1561	-3.7006	2.2087	1.2852	0.3383	-0.2695
0.9922	0.0078	915.4	1404.58	5.5372 ± 0.033	-0.1558	-4.0766	2.2090	1.2858	0.3390	-0.2800
0.9909	0.0091	917.4	1404.08	5.5291 ± 0.033	-0.1675	-5.0574	2.2074	1.2881	0.3398	-0.0798
0.9897	0.0103	916.2	1407.46	5.5098 ± 0.033	-0.0965	-3.0726	2.2036	1.2895	0.3386	0.2662
<i>2-Propanol + water + $\text{Na}_2\text{S}_2\text{O}_3$</i>										
1.0000	0.0000	903.1	1427.52	5.4337 ± 0.055	0.0000	0.0000	2.1883	1.2892	0.3333	0.0000
0.9989	0.0011	905.3	1424.8	5.4412 ± 0.055	-0.0746	-0.8294	2.1898	1.2899	0.33478	-1.2413
0.9978	0.0022	907.6	1423.42	5.4380 ± 0.055	-0.1706	-2.1192	2.1891	1.2919	0.33596	-0.3484
0.9966	0.0034	908.4	1422.98	5.4365 ± 0.055	-0.1639	-1.9891	2.1888	1.2926	0.33636	-0.1542
0.9956	0.0044	910.7	1422.56	5.4260 ± 0.055	-0.1591	-3.3178	2.1867	1.2955	0.33731	0.3188
0.9945	0.0055	911.3	1422.3	5.4244 ± 0.055	-0.1418	-3.0187	2.1864	1.2961	0.33759	0.3082
0.9934	0.0066	914.1	1419.98	5.4255 ± 0.055	-0.1366	-4.7916	2.1866	1.2980	0.33918	0.2273
0.9924	0.0076	915.4	1416.9	5.4414 ± 0.055	-0.1250	-5.2001	2.1898	1.2970	0.34041	-0.1827
0.9912	0.0088	916.6	1413.96	5.4569 ± 0.055	-0.1124	-5.4106	2.1929	1.2960	0.34156	-0.4795
0.9902	0.0098	918.5	1408.58	5.4872 ± 0.055	-0.1087	-6.4019	2.1990	1.2938	0.34358	-0.9949
0.9891	0.0109	915.4	1411.3	5.4846 ± 0.055	-0.0761	-2.6150	2.1985	1.2919	0.34176	-0.8488

Table 4 (continued)

$(x_1 + x_2)$	x_3	ρ (kg m ⁻³)	u (m s ⁻¹)	$10^{-10} \beta_s$ (m ² N ⁻¹)	ϕ_V (m ³ mol ⁻¹)	$10^{-4} V^E$ (m ³ mol ⁻¹)	$10^{-3} L_r$ (m)	$10^6 Z$ (kg m ² s ⁻¹)	R_A (mol dm ³)	S_n
2-Methyl-2-propanol + water + Na ₂ S ₂ O ₃										
1.0000	0.0000	899.4	1382.02	5.8213 ± 0.055	0.0000	0.0000	2.2650	1.2430	0.3333	0.0000
0.9989	0.0011	900.6	1381.62	5.8169 ± 0.055	-0.1249	-0.5090	2.2641	1.2443	0.3339	0.7117
0.9982	0.0018	901.4	1379.70	5.8279 ± 0.055	-0.1172	-0.8273	2.2663	1.2437	0.3346	-0.6359
0.9973	0.0027	901.9	1376.42	5.8525 ± 0.055	-0.1099	-0.6779	2.2710	1.2414	0.3356	-1.9969
0.9967	0.0033	902.8	1375.18	5.8572 ± 0.055	-0.1055	-1.1685	2.2720	1.2415	0.3363	-1.8446
0.9953	0.0047	904	1373.70	5.8620 ± 0.056	-0.1003	-1.4396	2.2729	1.2418	0.3371	-1.4881
0.9948	0.0052	904.8	1371.62	5.8746 ± 0.056	-0.0993	-1.8875	2.2753	1.2410	0.3379	-1.7368
0.9938	0.0062	905.4	1368.90	5.8941 ± 0.056	-0.0976	-1.8279	2.2791	1.2394	0.3388	-2.0164
0.9933	0.0067	906.1	1366.56	5.9097 ± 0.056	-0.0952	-2.1872	2.2821	1.2382	0.3396	-2.2526
0.9923	0.0077	906.9	1364.88	5.9190 ± 0.056	-0.0909	-2.2604	2.2839	1.2378	0.3403	-2.1560
0.9915	0.0085	905.7	1366.20	5.9154 ± 0.056	-0.0274	-0.2611	2.2832	1.2374	0.3396	-1.8795

($x_1 + x_2$) and x_3 —mole fraction of solvent (50% water + 50% alcohol) and Na₂S₂O₃ respectively
Bold values indicate the point of phase separation
Standard uncertainties u are $u(\rho) = 0.1$ kg m⁻³ with $u(T) = 0.05$ K, $u(u) = 0.5$ m s⁻¹ with $u(T) = 0.05$ K

Fig. 6 Effect of Na₂S₂O₃ on velocity (u) of water + alcohol system at 298.15 ± 0.05 K: (open circle) ethanol; (open triangle) 1-propanol; (open square) 2-propanol; (open inverted triangle) 2-methyl-2-propanol

Fig. 7 Effect of Na₂S₂O₃ on adiabatic compressibility (β_s) of water + alcohol + system at 298.15 ± 0.05 K: (open circle) ethanol; (open triangle) 1-propanol; (open square) 2-propanol; (open inverted triangle) 2-methyl-2-propanol

2-methyl-2-propanol > 1-propanol > 2-propanol > ethanol. The density, sound velocity and adiabatic compressibility results suggest that, phase separation phenomenon is bond breaking and bond making process as well as hydrophobic interaction and hydrophobic hydration.

One way to clarify, the mechanism of salting-out or salting-in effect in aqueous alcohol solutions with the addition of salt is studies based on liquid–liquid–solid equilibria, volumetric, acoustic and conductometric properties of water–alcohol, water–salt and water–alcohol–salt systems.

Table 5 The value of concentration (N), Observed conductance (Ω^{-1}), Specific conductance ($k \Omega^{-1} \text{cm}^{-1}$), Equivalence conductance ($\lambda_v \Omega^{-1} \text{cm}^{-1} \text{eq}^{-1}$), Equivalence conductance at infinity ($\lambda_{\infty} \Omega^{-1} \text{cm}^{-1} \text{eq}^{-1}$), Degree of dissociation (α), of $\text{Na}_2\text{S}_2\text{O}_3$ in studied systems

system	N	Ω^{-1}	$k (\Omega^{-1} \text{cm}^{-1})$	$\lambda_v (\Omega^{-1} \text{cm}^{-1} \text{eq}^{-1})$	$\lambda_{\infty} (\Omega^{-1} \text{cm}^{-1} \text{eq}^{-1})$	α
Water + ethanol	0.3777	0.01124	0.01335	30.0530	53.8643	0.5579
Water + 1-propanol	0.1024	0.00357	0.00361	35.1955	52.7593	0.66710
Water + 2-propanol	0.1522	0.00348	0.00351	23.0987	38.5371	0.5993
Water + 2-methyl-2-propanol	0.0515	0.001268	0.00128	24.85276	32.0001	0.7766

This provides useful information of the interactions that exist in these systems and is of great importance to obtain information about the solvation and association behavior of ions in water–alcohol systems.

5 Conclusion

The phase diagrams for the water + ethanol/1-propanol/2-propanol/2-methyl-2-propanol + $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ systems were constructed from the solubility data. The salting-out effect can be ascribed to ion–ion, ion–dipole, dipole–dipole interactions. Acoustic properties of water–alcohol, water–salt and water–alcohol–salt system provides useful information on the interactions that exist in these systems and is of great importance to obtain information about the solvation and association behavior of ion in these systems. Rise in the density and sound velocity results in a decrease in adiabatic compressibility, which signifies greater structural interaction of water with alcohol and salt in system. The negative value of V^E , decrease in L_F , Z , and R_A suggested a strong interaction of water with salt and alcohol individually through H-bonding and denser packing in binary system. However, the relation is quite changed with the ternary system composed of water + alcohol + salt. Where, water–alcohol hydration sphere has been broken due to kosmotropic salt by forming salt–water hydration sphere. In addition, phase forming ability of alcohol can be explained by the dissociation constant of sodium thiosulphate. It has been shown that the two-phase formation ability of systems composed of different alcohols is in order of 2-methyl-2-propanol > 1-propanol > 2-propanol > ethanol.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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