Journal of Molecular Liquids 195 (2014) 1–8

Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq

Review

Physicochemical characterization of aqueous two phase systems containing Triton X-102 and sodium salts in the range of temperature from 288.15 k to 318.15 k

A. Blanco [1], A. Gayol *, D. Gómez-Díaz [1], J.M. Navaza [1]

PF&PT Research Team, Department of Chemical Engineering, ETSE, University of Santiago de Compostela, Galicia, Spain

ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form 8 January 2014
Accepted 12 January 2014
Available online 21 January 2014

Keywords:
ATPS
Density
Speed of sound
Refractive index
Surfactant

ABSTRACT

Present work studies the characterization of binary and ternary mixtures based on the use of a surfactant (Triton X-102) and different salts in aqueous solution. All of these ternary mixtures form two different aqueous liquid phases. This characterization consists in the analysis of several physical properties such as refractive index, density and speed of sound. Derivative properties were calculated: excess molar volume and isentropic compressibility. This work analyzes aqueous binary and ternary mixtures (Triton X-102 + salt + water) in the homogeneous zone analyzing the influence of surfactant and salt concentration. Also several phases at equilibrium were characterized. The influence of temperature upon these physical and derivative properties was also analyzed.

Contents

1. Introduction

The most common aqueous two-phase systems (ATPS) are mainly based on the use of two polymers or a polymer and a salt in aqueous solution. Several studies have concluded that this type of systems can have interesting characteristics to be used in liquid–liquid extraction processes for the separation of specific substances which can be highly influenced by the presence of a specific medium. Organic substances [1] such as enzymes and others with a biological origin can be target compounds for this kind of liquid–liquid system. ATP systems have been mainly used for antioxidant strategy purification [2].

A significant increase in the development of two-phase aqueous systems for different extraction aims has been observed in the last decades. Studies about the thermodynamic equilibrium of these systems [3,4] are the commonest type of work with these systems. However, the amount of work performed in solute separation processes has been significantly lower [5–7] than conventional organic–aqueous systems. Anyway, most of the studies in the literature are focused on the use of a specific polymer: polyethylene glycol (PEG) with different average molecular weights. Then a lack of knowledge exists in the experimental data corresponding to other polymers.

A significant amount of work must be carried out in this field of research mainly in the analysis of mass transfer processes between the two aqueous phases using different contact devices. In this type of research there is a lack of information and only very specific studies analyzed the behavior of these aqueous two-phase systems to carry

---

* Corresponding author. Tel.: +34 88181762; fax: +34 881816702.
E-mail address: anamaria.gayol@usc.es (A. Gayol).
[1] Tel.: +34 88181762; fax: +34 881816702.

0167-7322/$ – see front matter © 2014 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.molliq.2014.01.010

Table 1
Sample description table.

Chemical name	Source	Initial mole fraction purity
Triton X-102	Sigma-Aldrich	≥0.998
Sodium sulfate	Pancreac	≥0.990
Sodium thiosulfate	Pancreac	≥0.990

out liquid–liquid extraction processes at laboratory scale [8,9]. When mass transfer studies are performed in the laboratory or pilot plant scale, several aspects such as hydrodynamics and interfacial area between both phases are important parameters that must be taken into account [10]. Some physical properties are important variables that affect the overall mass transfer rate because the diffusivity is strongly influenced by these properties, mainly due to viscosity [11,12]. In this kind of systems (ATPS), the polymer or polymers used in the formulation can cause important changes in physical properties and then the overall mass transfer rate can be reduced significantly. This work characterizes binary and ternary systems for homogeneous and phases at equilibrium in relation to several physical properties that can contribute useful information about interactions between the solutes and the influence upon mass transfer processes.

Table 2
Density ρ, excess molar volume V^E, speed of sound u, isentropic compressibility κ_s, and refractive index, n_D of Triton X-102 (1) + water (3) from T = (288.15 to 318.15) K.

C_1/%	x_1	ρ	V^E	u	κ_s	n_D
		$\mathrm{g \cdot cm^{-3}}$	$\mathrm{cm^3 \cdot mol^{-1}}$	m·s$-^{1}$	$\mathrm{TPa^{-1}}$	
T = 318.15 *K*						
0.0	0.000	0.9902	0.0	1536.6	427.7	1.3298
4.4	0.001	0.9947	54.2	1541.0	423.3	1.3374
10.2	0.003	0.9994	115.8	1546.0	418.6	1.3454
19.4	0.006	1.0077	183.4	1555.0	410.4	1.3588
31.5	0.012	1.0186	220.2	1567.5	399.5	1.3778
39.6	0.016	1.0260	211.2	1575.3	392.7	1.3893
60.4	0.036	1.0448	78.3	1583.0	381.9	1.4215
69.1	0.053	1.0502	14.2	1576.2	383.2	1.4386
80.7	0.095	1.0556	−64.6	1549.2	394.7	1.4549
90.3	0.191	1.0561	−68.8	1513.6	413.3	1.4680
100.0	1.000	1.0532	0.0	1466.7	441.3	1.4798
T = 308.15 *K*						
0.0	0.000	0.9940	0.0	1520.3	435.2	1.3313
4.4	0.001	0.9988	56.8	1527.8	428.9	1.3387
10.2	0.003	1.0038	121.4	1536.3	422.0	1.3468
19.4	0.006	1.0126	192.0	1551.7	410.1	1.3607
31.5	0.012	1.0243	229.6	1573.8	394.1	1.3799
39.6	0.016	1.0321	220.6	1587.8	384.2	1.3919
60.4	0.036	1.0533	62.8	1611.4	365.5	1.4254
69.1	0.053	1.0582	8.1	1607.0	365.9	1.4419
80.7	0.095	1.0637	−72.1	1582.3	375.4	1.4585
90.3	0.191	1.0641	−73.9	1546.7	392.8	1.4716
100.0	1.000	1.0609	0.0	1500.7	418.5	1.4836
T = 298.15 *K*						
0.0	0.000	0.9970	0.0	1496.8	447.6	1.3326
4.4	0.001	1.0021	60.3	1507.9	438.8	1.3401
10.2	0.003	1.0075	128.7	1520.3	429.4	1.3483
19.4	0.006	1.0169	203.4	1543.1	412.9	1.3625
31.5	0.012	1.0295	242.8	1576.3	390.9	1.3819
39.6	0.016	1.0379	232.6	1597.1	377.6	1.3944
60.4	0.036	1.0606	64.8	1638.4	351.2	1.4284
69.1	0.053	1.0661	4.0	1637.6	349.7	1.4451
80.7	0.095	1.0719	−78.5	1616.4	357.0	1.4621
90.3	0.191	1.0721	−77.9	1581.6	372.8	1.4754
100.0	1.000	1.0688	0.0	1536.0	396.5	1.4874
T = 288.15 *K*						
0.0	0.000	0.999	0.0	1466.4	465.4	1.3335
4.4	0.001	1.005	64.7	1480.8	453.9	1.3411
10.2	0.003	1.010	138.0	1497.2	441.5	1.3496
19.4	0.006	1.021	218.2	1528.4	419.4	1.3640
31.5	0.012	1.034	260.3	1574.1	390.2	1.3838
39.6	0.016	1.043	248.8	1604.0	372.5	1.3966
60.4	0.036	1.068	70.5	1665.2	337.7	1.4314
69.1	0.053	1.074	0.0	1669.6	333.9	1.4481
80.7	0.095	1.080	−83.0	1653.1	338.8	1.4656
90.3	0.191	1.080	−80.9	1617.0	354.0	1.4791
100.0	1.000	1.077	0.0	1572.8	375.4	1.4912

2. Experimental section

2.1. Materials

Reagents employed in present work (Triton X-102, sodium sulfate and sodium thiosulfate) are included in Table 1. Bi-distilled water was used to prepare aqueous binary and tertiary mixtures. All solutions were prepared by mass using an analytical balance (Kern 770) with a precision of 10^{-4} g. The uncertainty in the mole fraction for prepared sample solutions was found to be ±0.0007.

2.2. Experimental apparatus and procedure

The solubility curves corresponding to the aqueous two-phase systems studied in this work were determined using the cloud point method at T = 298.15 K. A known amount of salt was added to Triton X-102 aqueous solutions under stirring until turbidity is observed.

A drop wise addition of water is held until a single phase region was reached. All samples were weighed with an analytical balance Kern 770. Ternary compositions were determined by the weight of

Table 3
Density ρ, speed of sound u, isentropic compressibility κ_s, and refractive index n_D, of Na_2SO_4 (2) + water (3) from T = (288.15 to 318.15) K.

C_2/%	$\rho/\mathrm{g \cdot cm^{-3}}$	$u/\mathrm{m \cdot s^{-1}}$	$\kappa_s/\mathrm{TPa^{-1}}$	n_D
T = 318.15 *K*				
0.0	0.9902	1536.6	427.7	1.3298
1.9	1.0072	1556.0	410.1	1.3332
4.9	1.0336	1586.2	384.5	1.3377
5.4	1.0377	1589.5	381.4	1.3377
10.9	1.0887	1647.0	338.6	1.3457
13.9	1.1168	1678.1	318.0	1.3332
17.4	1.1514	1718.5	294.1	1.3497
22.6	1.1512	1718.7	294.1	1.3727
T = 308.15 *K*				
0.0	0.9940	1520.3	435.3	1.3313
1.9	1.0112	1541.1	416.4	1.3346
4.9	1.0379	1572.5	389.7	1.3386
5.4	1.0420	1576.4	386.2	1.3392
10.9	1.0935	1637.5	341.1	1.3473
13.9	1.1218	1670.4	319.5	1.3392
17.4	1.1566	1713.7	294.4	1.3511
22.6	1.1567	1713.8	294.3	1.3749
T = 298.15 *K*				
0.0	0.9970	1496.9	447.6	1.3326
1.9	1.0145	1519.1	427.2	1.3359
4.9	1.0416	1552.8	398.2	1.3399
5.4	1.0458	1557.2	394.4	1.3406
10.9	1.0978	1622.2	346.2	1.3469
13.9	1.1264	1657.9	323.0	1.3406
17.4	1.1615	1704.4	296.4	1.3528
22.6	1.1616	1704.6	296.3	1.3399
T = 288.15 *K*				
0.0	0.9991	1466.4	465.5	1.3335
1.9	1.0169	1489.5	443.2	1.3370
4.9	1.0445	1526.1	411.1	1.3411
5.4	1.0488	1531.0	406.8	1.3418
10.9	1.1016	1600.6	354.3	1.3487
13.9	1.1305	1639.2	329.2	1.3418
17.4	1.1660	1689.8	300.4	1.3543
22.6	1.1661	1689.8	300.3	1.3411

Table 4
Density ρ, speed of sound u, isentropic compressibility κ_s, and refractive index n_D, of $Na_2S_2O_3$ (2) + water (3) from T = (288.15 to 318.15) K.

C_2/%	ρ/g·cm^{-3}	u/m·s^{-1}	κ_s/TPa^{-1}	n_D
T = 318.15 K				
0.0	0.9902	1536.6	427.7	1.3298
4.6	1.0276	1577.2	391.2	1.3378
9.8	1.0698	1622.2	355.2	1.3501
15.3	1.1170	1675.2	319.0	1.3610
19.3	1.1561	1720.5	292.2	1.3720
25.3	1.2100	1785.7	259.2	1.3855
29.8	1.2531	1839.2	235.9	1.3949
31.7	1.2748	1865.9	225.3	1.3994
T = 308.15 K				
0.0	0.9940	1520.3	435.3	1.3313
4.6	1.0319	1563.0	396.7	1.3393
9.8	1.0745	1611.0	358.6	1.3511
15.3	1.1222	1667.6	320.4	1.3621
19.3	1.1616	1715.9	292.4	1.3744
25.3	1.2158	1786.2	257.8	1.3880
29.8	1.2592	1843.4	233.7	1.3957
31.7	1.2810	1872.3	222.7	1.4004
T = 298.15 K				
0.0	0.9970	1496.9	447.6	1.3326
4.6	1.0356	1542.6	405.8	1.3407
9.8	1.0788	1594.3	364.7	1.3526
15.3	1.1269	1655.0	324.0	1.3634
19.3	1.1668	1707.4	294.0	1.3762
25.3	1.2214	1783.4	257.4	1.3897
29.8	1.2650	1845.3	232.2	1.3972
31.7	1.2870	1876.5	220.7	1.4019
T = 288.15 K				
0.0	0.9991	1466.4	465.5	1.3335
4.6	1.0385	1515.5	419.3	1.3419
9.8	1.0824	1571.7	374.0	1.3541
15.3	1.1313	1636.8	329.9	1.3650
19.3	1.1716	1694.4	297.3	1.3779
25.3	1.2268	1776.8	258.2	1.3917
29.8	1.2707	1844.6	231.3	1.3991
31.7	1.2928	1878.3	219.3	1.4038

each component. The mixture was stirred vigorously at constant temperature and settled for 24 h to ensure the equilibrium and a complete separation of phases. The uncertainty corresponding to the determination of mixture composition was ±2%.

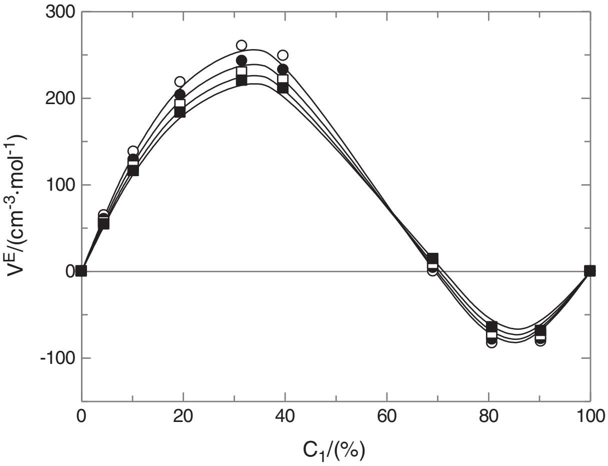

Fig. 2. Influence of surfactant concentration and temperature upon excess molar volume for Triton X-102 (1) + water (3). ●, T = 288.15 K; ○, T = 298.15 ■, T = 308.15 K; □, T = 318.15 K.

Density and speed of sound data corresponding to pure components (water and Triton X-102), binary, and ternary mixtures of different compounds were measured with an Anton Paar DSA 5000 vibrating tube densimeter and sound analyzer. The uncertainty of density and speed of sound measures was $\pm 2 \cdot 10^{-4}$ g·cm^{-3} and ±0.7 m·s^{-1}, respectively.

Refractive index data were measured using an Atago RX-5000 refractometer. The refractometer was calibrated using distilled–deionized water attending to instrument instructions. Pure compounds, binary and ternary mixtures were directly injected from the solution stored at working temperature to avoid evaporation processes. The measurements were done after the liquid mixtures reached a constant temperature. This procedure was repeated at least three times, and the uncertainty of the measurement was $\pm 1.1 \cdot 10^{-4}$.

3. Results and discussion

The first part of this work is focused on the characterization of this kind of systems for binary mixtures based on aqueous solutions of each solute: Triton X-102, sodium sulfate and sodium thiosulfate. The concentration ranges used for each solute were chosen on the basis of their solubility data [13]. The experimental values corresponding to refractive index, density and speed of sound of these binary systems are included in Tables 2–4 at different temperatures. The experimental values of refractive index corresponding to the binary system of Triton X-102 + water show an increase in this property with surfactant concentration. If temperature increases, the value of refractive index

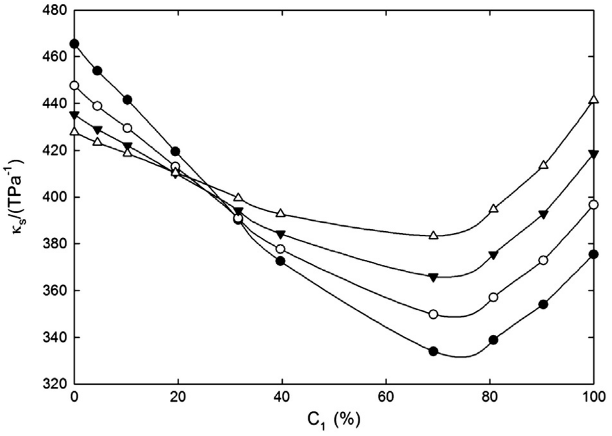

Fig. 1. Influence of Triton X-102 concentration and temperature upon isentropic compressibility for the binary mixture Triton X-102 (1)–water (3). ●, T = 288.15 K; ○, T = 298.15 K; ▼, T = 308.15 K; Δ, T = 318.15 K.

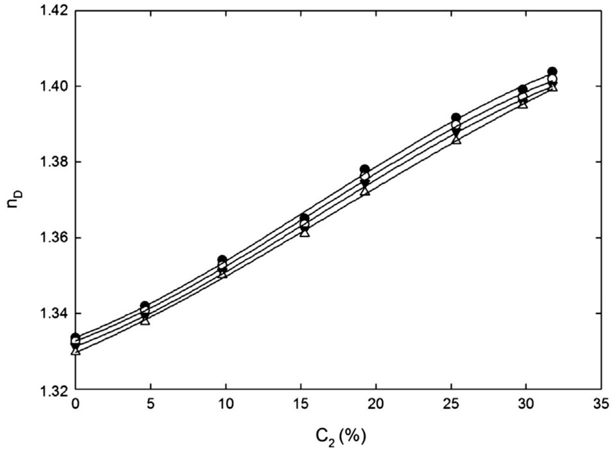

Fig. 3. Influence of salt composition and temperature upon refractive index for $Na_2S_2O_3$ (2) + water (3) system. ●, T = 288.15 K; ○, T = 298.15 K; ▼, T = 308.15 K; Δ, T = 318.15 K. Solid lines correspond with Eq. 1.

Table 5
Density ρ, speed of sound u, isentropic compressibility κ_S, and refractive index n_D, of Triton X-102 (1) + Na_2SO_4 (2) + water (3) from T = (288.15 to 318.15) K.

C_2/%	C_1/%	ρ/g·cm^{-3}	u/m·s^{-1}	κ_S/TPa^{-1}	n_D
T = 318.15 K					
0.0	0.0	0.9902	1536.6	427.7	1.3298
0.0	100.0	1.0532	1466.7	441.4	1.4798
2.4	0.0	1.0121	1561.8	405.1	1.3337
2.5	4.4	1.0162	1565.5	401.5	1.3406
2.5	10.3	1.0220	1571.0	396.5	1.3473
2.5	14.7	1.0261	1574.7	393.0	1.3535
2.5	17.5	1.0255	1573.9	393.7	1.3589
2.4	23.2	1.0329	1580.8	387.4	1.3681
2.5	25.8	1.0364	1584.0	384.6	1.3850
2.5	32.1	1.0417	1587.9	380.7	1.3831
2.5	29.4	1.0397	1586.7	382.0	1.3779
5.1	0.0	1.0353	1587.3	383.4	1.3379
5.0	5.5	1.0402	1590.9	379.8	1.3460
5.0	7.7	1.0417	1592.0	378.8	1.3499
5.0	8.2	1.0421	1592.4	378.4	1.3506
4.9	13.6	1.0466	1595.5	375.3	1.3508
5.0	16.7	1.0501	1598.8	372.5	1.3439
9.0	0.0	1.0710	1627.0	352.7	1.3427
9.1	0.5	1.0726	1628.6	351.5	1.3435
9.1	0.9	1.0723	1628.3	351.7	1.3442
9.0	1.1	1.0716	1627.5	352.3	1.3449
9.0	2.0	1.0726	1629.0	351.3	1.3450
T = 308.15 K					
0.0	0.0	0.9940	1520.3	435.3	1.3313
0.0	100.0	1.0609	1500.7	418.5	1.4836
2.4	0.0	1.0161	1546.8	411.3	1.3352
2.5	4.4	1.0205	1554.0	405.8	1.3425
2.5	10.3	1.0267	1564.0	398.2	1.3494
2.5	14.7	1.0311	1570.7	393.1	1.3590
2.5	17.5	1.0305	1570.9	393.3	1.3622
2.4	23.2	1.0384	1583.0	384.3	1.3702
2.5	25.8	1.0421	1589.3	379.9	1.3869
2.5	32.1	1.0477	1597.2	374.1	1.3874
2.5	29.4	1.0455	1593.7	376.6	1.3805
5.1	0.0	1.0396	1573.8	388.4	1.3406
5.0	5.5	1.0448	1581.9	382.5	1.3466
5.0	7.7	1.0465	1584.9	380.4	1.3521
5.0	8.2	1.0469	1585.4	380.0	1.3529
4.9	13.6	1.0574	1592.4	373.0	1.3457
5.0	16.7	1.0554	1598.2	370.9	1.3434
9.0	0.0	1.0756	1615.8	356.1	1.3446
9.1	0.5	1.0773	1617.8	354.7	1.3454
9.1	0.9	1.0772	1617.9	354.7	1.3461
9.0	1.1	1.0761	1617.5	355.2	1.3468
9.0	2.0	1.0774	1620.3	353.6	1.3472
T = 298.15 K					
0.0	0.0	0.9970	1496.9	447.6	1.3326
0.0	100.0	1.0688	1536.1	396.6	1.4874
2.4	0.0	1.0195	1525.4	421.6	1.3366
2.5	4.4	1.0242	1535.8	414.0	1.3441
2.5	10.3	1.0308	1551.5	403.0	1.3509
2.5	14.7	1.0354	1561.6	396.0	1.3610
2.5	17.5	1.0349	1562.8	395.6	1.3644
2.4	23.2	1.0433	1580.9	383.5	1.3724
2.5	25.8	1.0474	1590.7	377.3	1.3886
2.5	32.1	1.0533	1603.2	369.4	1.3897
2.5	29.4	1.0509	1597.1	373.1	1.3828
5.1	0.0	1.0433	1554.3	396.8	1.3417
5.0	5.5	1.0489	1567.2	388.2	1.3490
5.0	7.7	1.0507	1572.6	384.9	1.3540
5.0	8.2	1.0512	1573.1	384.4	1.3548
4.9	13.6	1.0564	1583.7	377.5	1.3479
5.0	16.7	1.0603	1594.0	371.2	1.3453
9.0	0.0	1.0797	1599.0	362.3	1.3461
9.1	0.5	1.0815	1601.2	360.6	1.3466
9.1	0.9	1.0814	1601.6	360.5	1.3469
9.0	1.1	1.0804	1601.4	360.9	1.3473
9.0	2.0	1.0817	1604.7	359.0	1.3482
T = 288.15 K					
0.0	0.0	0.9991	1466.4	465.5	1.3335
0.0	100.0	1.0767	1572.9	375.4	1.4912
2.4	0.0	1.0221	1496.7	436.8	1.3378
2.5	4.4	1.0271	1510.7	426.6	1.3454
2.5	10.3	1.0342	1532.4	411.8	1.3522
2.5	14.7	1.0392	1546.3	402.4	1.3617
2.5	17.5	1.0388	1548.5	401.5	1.3660
2.4	23.2	1.0477	1574.1	385.2	1.3747
2.5	25.8	1.0521	1588.1	376.9	1.3898
2.5	32.1	1.0584	1605.1	366.7	1.3920
2.5	29.4	1.0558	1596.5	371.6	1.3850
5.1	0.0	1.0463	1527.6	409.5	1.3428
5.0	5.5	1.0526	1545.6	397.7	1.3505
5.0	7.7	1.0543	1553.7	392.9	1.3555
5.0	8.2	1.0548	1554.4	392.4	1.3563
4.9	13.6	1.0604	1571.4	381.9	1.3498
5.0	16.7	1.0647	1584.5	374.1	1.3470
9.0	0.0	1.0833	1575.8	371.8	1.3474
9.1	0.5	1.0851	1578.3	370.0	1.3480
9.1	0.9	1.0850	1579.4	369.5	1.3483
9.0	1.1	1.0843	1579.3	369.8	1.3486
9.0	2.0	1.0854	1582.8	367.7	1.3491

and also density decreases. On the other hand the influence of Triton X-102 concentration and temperature upon speed of sound shows a very different and complex behavior in comparison with the previously commented properties. The influence of Triton X-102 shows a complex behavior because speed of sound increases until it reaches a maximum value. After this first increase, the opposite trend was observed. This behavior increases its complexity if the influence of temperature is analyzed because at low surfactant concentration an increase in speed of sound with the temperature is observed. But this influence is inverted at high surfactant concentration. This behavior is confirmed when isentropic compressibility is calculated. The influence of Triton X-102 concentration and temperature is shown in Fig. 1. The influence of temperature upon isentropic compressibility is the opposite than the previously commented for speed of sound but the effect caused by temperature is also observed for this property. A Triton X-102 aqueous solution with a concentration near to 25% in weight shows an isentropic compressibility value independent of temperature. This behavior indicates that a temperature-resistant structure is formed due to aggregation processes. Several studies [14,15] observed similar behaviors for other aqueous

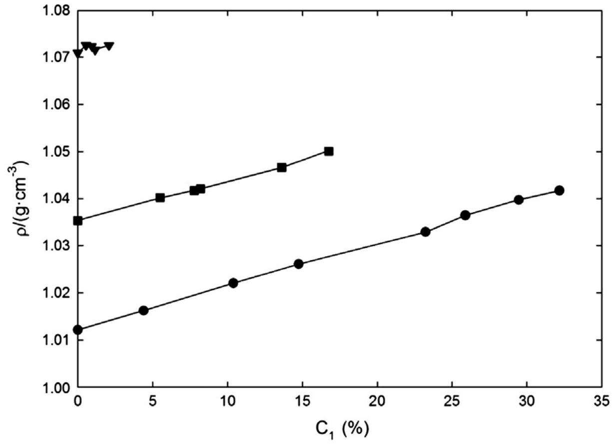

Fig. 4. Influence of surfactant and salt concentration upon density values for Triton X-102 (1) + Na_2SO_4 (2) + water (3) ternary system. T = 318.15 K. ●, C_2 = 2.52%; ■, C_2 = 5.00%; ▼, C_2 = 9.12%. Solid lines correspond with Eq. 1.

Table 6
Density ρ, speed of sound u, isentropic compressibility κ_s, and refractive index n_D, of Triton X-102 (1) + $Na_2S_2O_3$ (2) + water (3) from $T = (288.15 \text{ to } 318.15)$ K.

C_2/%	C_1/%	ρ/kg·m^{-3}	u/m·s^{-1}	κ_s/TPa^{-1}	n_D
T = 318.15 *K*					
0.0	0.0	0.9902	1536.6	427.7	1.3298
0.0	100.0	1.0532	1466.7	441.4	1.4798
2.5	0.0	1.0104	1558.2	407.6	1.3420
2.5	4.4	1.0152	1562.8	403.3	1.3505
2.5	4.9	1.0151	1563.1	403.2	1.3494
2.5	9.4	1.0192	1566.4	399.9	1.3520
2.5	10.0	1.0194	1566.7	399.7	1.3611
2.5	14.8	1.0243	1571.4	395.4	1.3716
2.5	14.9	1.0246	1571.7	395.1	1.3881
2.5	19.7	1.0284	1575.4	391.8	1.3974
2.5	20.0	1.0294	1576.2	391.0	1.3633
2.5	23.9	1.0325	1580.1	387.9	1.4063
2.5	25.8	1.0332	1581.1	387.2	1.3630
2.5	30.4	1.0388	1585.0	383.2	1.3645
2.5	39.4	1.0461	1590.3	378.0	1.3420
2.5	45.9	1.0525	1592.7	374.6	1.3587
5.0	0.0	1.0306	1580.9	388.2	1.3505
5.0	5.5	1.0363	1584.7	384.3	1.3549
5.0	10.0	1.0393	1587.0	382.0	1.3506
5.0	15.1	1.0443	1591.2	378.2	1.3630
5.0	24.9	1.0535	1598.4	371.5	1.3536
7.5	0.0	1.0507	1601.1	371.3	1.3451
7.5	9.7	1.0602	1608.3	364.6	1.3566
7.5	13.2	1.0633	1608.9	363.3	1.3543
7.5	15.0	1.0652	1611.7	361.4	1.3583
7.5	20.0	1.0691	1619.3	356.7	1.3506
7.5	3.9	1.0550	1604.8	368.1	1.3510
9.9	0.0	1.0714	1624.0	353.9	1.3527
9.9	8.2	1.0793	1636.8	345.8	1.3451
9.9	12.2	1.0828	1643.1	342.1	1.3570
10.0	4.4	1.0758	1627.4	351.0	1.3587
12.4	0.0	1.0914	1646.1	338.2	1.3420
12.4	1.7	1.0946	1646.0	337.2	1.3566
12.4	3.2	1.0958	1649.6	335.4	1.3570
T = 308.15 *K*					
0.0	0.0	0.9940	1520.3	435.3	1.3313
0.0	100.0	1.0609	1500.7	418.5	1.4836
2.5	0.0	1.0144	1543.1	414.0	1.3436
2.5	4.4	1.0196	1550.9	407.8	1.3547
2.5	4.9	1.0194	1551.5	407.5	1.3519
2.5	9.4	1.0238	1558.3	402.2	1.3546
2.5	10.0	1.0240	1558.7	401.9	1.3614
2.5	14.8	1.0293	1567.3	395.5	1.3738
2.5	14.9	1.0296	1567.8	395.2	1.3912
2.5	19.7	1.0336	1574.9	390.1	1.4018
2.5	20.0	1.0347	1576.4	388.9	1.3660
2.5	23.9	1.0380	1582.7	384.6	1.4104
2.5	25.8	1.0393	1585.0	383.0	1.3659
2.5	30.4	1.0447	1592.3	377.6	1.3659
2.5	39.4	1.0525	1604.7	369.0	1.3436
2.5	45.9	1.0594	1612.9	362.9	1.3608
5.0	0.0	1.0351	1567.0	393.5	1.3547
5.0	5.5	1.0410	1575.1	387.2	1.3576
5.0	10.0	1.0443	1581.0	383.1	1.3530
5.0	15.1	1.0495	1588.8	377.5	1.3659
5.0	24.9	1.0593	1603.0	367.4	1.3557
7.5	0.0	1.0552	1588.6	375.5	1.3466
7.5	9.7	1.0654	1603.5	365.1	1.3588
7.5	13.2	1.0687	1608.9	361.5	1.3567
7.5	15.0	1.0711	1611.5	359.5	1.3589
7.5	20.0	1.0754	1618.4	355.0	1.3530
7.5	3.9	1.0598	1595.2	370.8	1.3537
9.9	0.0	1.0761	1612.7	357.3	1.3549
9.9	8.2	1.0849	1628.3	347.7	1.3466
9.9	12.2	1.0889	1635.2	343.4	1.3594
10.0	4.4	1.0809	1619.9	352.6	1.3608
12.4	0.0	1.0963	1636.3	340.7	1.3436
12.4	1.7	1.0998	1641.5	337.5	1.3588
12.4	3.2	1.1011	1644.4	335.9	1.3594
T = 298.15 *K*					
0.0	0.0	0.9970	1496.9	447.6	1.3326
0.0	100.0	1.0688	1536.1	396.6	1.4874
2.5	0.0	1.0178	1521.3	424.5	1.3450
2.5	4.4	1.0233	1532.3	416.2	1.3578
2.5	4.9	1.0231	1533.6	415.6	1.3536
2.5	9.4	1.0279	1545.1	407.5	1.3563
2.5	10.0	1.0281	1545.0	407.5	1.3563
2.5	14.8	1.0337	1558.0	398.6	1.3767
2.5	14.9	1.0340	1558.6	398.1	1.3939
2.5	19.7	1.0383	1569.7	390.9	1.4051
2.5	20.0	1.0395	1572.0	389.3	1.3681
2.5	23.9	1.0431	1581.1	383.5	1.4157
2.5	25.8	1.0445	1585.0	381.1	1.3680
2.5	30.4	1.0501	1596.2	373.7	1.3747
2.5	39.4	1.0586	1616.6	361.5	1.3450
2.5	45.9	1.0662	1631.4	352.4	1.3625
5.0	0.0	1.0387	1546.9	402.3	1.3578
5.0	5.5	1.0450	1559.8	393.3	1.3597
5.0	10.0	1.0486	1569.7	387.0	1.3549
5.0	15.1	1.0542	1581.7	379.1	1.3680
5.0	24.9	1.0646	1603.5	365.3	1.3636
7.5	0.0	1.0592	1570.4	382.9	1.3480
7.5	9.7	1.0700	1593.7	367.9	1.3602
7.5	13.2	1.0736	1604.9	361.6	1.3583
7.5	15.0	1.0761	1607.4	359.7	1.3593
7.5	20.0	1.0807	1616.0	354.4	1.3549
7.5	3.9	1.0640	1580.8	376.1	1.3558
9.9	0.0	1.0804	1595.8	363.5	1.3570
9.9	8.2	1.0898	1614.3	352.1	1.3480
9.9	12.2	1.0942	1624.1	346.5	1.3610
10.0	4.4	1.0855	1606.1	357.1	1.3625
12.4	0.0	1.1008	1621.1	345.7	1.3450
12.4	1.7	1.1044	1627.5	341.8	1.3602
12.4	3.2	1.1058	1630.9	340.0	1.3610
T = 288.15 *K*					
0.0	0.0	0.9991	1466.4	465.5	1.3335
0.0	100.0	1.0767	1572.9	375.4	1.4912
2.5	0.0	1.0203	1492.5	440.0	1.3462
2.5	4.4	1.0262	1507.1	429.1	1.3597
2.5	4.9	1.0260	1508.6	428.3	1.3577
2.5	9.4	1.0312	1524.5	417.2	1.3577
2.5	10.0	1.0314	1524.2	417.4	1.3577
2.5	14.8	1.0374	1542.3	405.2	1.3788
2.5	14.9	1.0377	1543.1	404.7	1.3964
2.5	19.7	1.0424	1558.8	394.8	1.4085
2.5	20.0	1.0437	1562.1	392.7	1.3697
2.5	23.9	1.0476	1574.6	385.0	1.4177
2.5	25.8	1.0491	1580.6	381.6	1.3697
2.5	30.4	1.0551	1596.4	371.9	1.3744
2.5	39.4	1.0643	1625.5	355.6	1.3462
2.5	45.9	1.0731	1647.8	343.2	1.3637
5.0	0.0	1.0417	1519.7	415.7	1.3597
5.0	5.5	1.0484	1537.8	403.3	1.3613
5.0	10.0	1.0524	1552.1	394.4	1.3563
5.0	15.1	1.0584	1569.1	383.8	1.3697
5.0	24.9	1.0694	1599.7	365.4	1.3669
7.5	0.0	1.0625	1545.2	394.2	1.3493
7.5	9.7	1.0741	1578.3	373.7	1.3617
7.5	13.2	1.0780	1596.3	364.1	1.3599
7.5	15.0	1.0806	1601.2	361.0	1.3609
7.5	20.0	1.0854	1612.4	354.4	1.3563
7.5	3.9	1.0677	1559.7	385.0	1.3575
9.9	0.0	1.0841	1572.9	372.9	1.3592
9.9	8.2	1.0942	1594.6	359.4	1.3493
9.9	12.2	1.0990	1607.0	352.4	1.3625
10.0	4.4	1.0896	1586.6	364.6	1.3637
12.4	0.0	1.1048	1600.2	353.5	1.3462
12.4	1.7	1.1087	1607.6	349.0	1.3617
12.4	3.2	1.1102	1611.4	346.9	1.3625

solutions due to the formation of chlatrates or other resistant structures.

The experimental density data corresponding to the system Triton X-102 + water have been employed to calculate the excess molar volume (see Table 2 and Fig. 2). The data corresponding to this binary mixture shows an expansive behavior in the main part of the mixtures, but a contractive behavior is observed in the surfactant-rich solutions. This behavior can be due to a better distribution of water molecules with the surfactant ones.

The experimental values corresponding to studies about physico-chemical characterization using sodium sulfate and thiosulfate aqueous solutions are shown in Tables 3 and 4. These data were compared with literature values [16] observing a good agreement between them. Fig. 3 shows the influence of mixture composition and temperature upon the experimental data corresponding to the refractive index for sodium thiosulfate aqueous solutions. An increase in salt concentration produces also an increase on this physical property. On the other hand, when temperature increases, this property shows a clear decrease. These behaviors are similar than the corresponding one obtained for density data.

The experimental data of density and refractive index corresponding to sodium sulfate aqueous solutions show similar trends than the data corresponding to Triton X-102 + water. In the case of speed of sound and isentropic compressibility data, the opposite behavior is observed: an increase in speed of sound and a decrease in isentropic compressibility with salt. This behavior is different than the previous one analyzed for Triton X-102 aqueous solutions. Also systems with this salt present certain type of molecular interaction because the influence of temperature upon speed of sound and isentropic compressibility data is different as low and high solute concentration. The presences of temperature-resistant structures for this system are produced at high salt concentration (about 31%).

The experimental data corresponding to density and refractive index were fitted using different equations previously used in literature [17] and based on the use of a polynomic equation as Eq. 1.

$$n_D = A + B \cdot x_1 + C \cdot x_1^2 + D \cdot x_1^3 \qquad (1)$$

where A, B and C are the fitting parameters and x_1 is the polymer mass fraction. This kind of equation was used also to fit the density neperian logarithm value.

In this work two ternary systems were studied in the homogeneous zone (analyzing different solute concentrations and temperatures) and also at equilibrium obtained from a mixture in the heterogeneous zone. The characterization of these ternary systems (polymer + salt + water) was performed using Triton X-102 as polymer and sodium sulfate and sodium thiosulfate as salts. The experimental values corresponding to density, speed of sound and refractive index are shown in Tables 5 and 6. These properties were studied in the homogeneous zone of this kind of ternary mixtures. Fig. 4 shows an example of the influence of both solutes (polymer and salt) upon density. This figure indicates that both solutes cause a significant increase in this property.

Table 7
Fit parameters and standard deviation corresponding to Eq. 1 for density ρ, for Triton X-102 (1) + Na_2SO_4 (2) + water (3) from T = (288.15 to 318.15) K.

$C_2 = 2.52\%$					
T (K)	A	B	C	D	σ
288.15	6.929	0.1086	−0.0497	0.1661	$3 \cdot 10^{-6}$
298.15	6.927	0.1019	−0.0561	0.1812	$2 \cdot 10^{-6}$
308.15	6.923	0.0973	−0.0633	0.1887	$2 \cdot 10^{-6}$
318.15	6.919	0.0913	−0.0626	0.1911	$2 \cdot 10^{-6}$
$C_2 = 5.00\%$					
T (K)	A	B	C	D	σ
288.15	6.953	0.1326	−0.6429	2.8239	$2 \cdot 10^{-8}$
298.15	6.950	0.1140	−0.4365	1.9827	$6 \cdot 10^{-9}$
308.15	6.946	−0.0781	3.2188	−13.1818	$2 \cdot 10^{-6}$
318.15	6.942	0.1034	−0.4607	2.0854	$5 \cdot 10^{-9}$
$C_2 = 9.12\%$					
T (K)	A	B	C	D	σ
288.15	6.987	0.6833	−79.9488	2477.3570	$1 \cdot 10^{-8}$
298.15	6.984	0.7441	−91.1714	2866.7912	$5 \cdot 10^{-8}$
308.15	6.980	0.7359	−92.1423	2912.7560	$7 \cdot 10^{-8}$
318.15	6.976	0.6519	−80.9560	2548.6247	$1 \cdot 10^{-8}$

Table 8
Fit parameters and standard deviation corresponding to Eq. 1 for refractive index n_D, for Triton X-102 (1) + Na_2SO_4 (2) + water (3) from T = (288.15 to 318.15) K.

$C_2 = 2.52\%$					
T/K	A	B	C	D	σ
288.15	1.337	0.1584	−0.0533	0.2410	$2 \cdot 10^{-6}$
298.15	1.336	0.1676	−0.1397	0.3913	$2 \cdot 10^{-6}$
308.15	1.335	0.1667	−0.1680	0.4584	$2 \cdot 10^{-6}$
318.15	1.334	0.1225	0.1001	−0.0235	$8 \cdot 10^{-7}$
$C_2 = 5.00\%$					
T/K	A	B	C	D	σ
288.15	1.342	0.2863	−1.8529	1.7114	$5 \cdot 10^{-6}$
298.15	1.341	0.2838	−1.9430	2.2004	$6 \cdot 10^{-6}$
308.15	1.340	0.2511	−1.6169	1.2216	$7 \cdot 10^{-6}$
318.15	1.337	0.1062	1.4810	−11.3619	$1 \cdot 10^{-7}$
$C_2 = 9.12\%$					
T/K	A	B	C	D	σ
288.15	1.347	0.1066	−0.7364	−22.8424	$5 \cdot 10^{-9}$
298.15	1.346	0.0820	3.2247	−112.0258	$5 \cdot 10^{-9}$
308.15	1.344	0.0530	21.2179	−848.8871	$9 \cdot 10^{-9}$
318.15	1.342	0.0494	21.0534	−872.6175	$1 \cdot 10^{-8}$

In relation with the behavior observing for refractive index in these ternary systems, the experimental data show a similar behavior than the previous one observed for density, that is, an increase in this property when Triton X-102 and/or salt concentration increase. An increase in temperature also produces in all cases a decrease in density and refractive index. Then the influence of concentration and temperature using

Table 9
Fit parameters and standard deviation corresponding to Eq. 1 for density ρ, for Triton X-102 (1) + $Na_2S_2O_3$ (2) + water (3) from T = (288.15 to 318.15) K.

$C_2 = 2.50\%$					
T (K)	A	B	C	D	σ
288.15	6.928	0.1190	−0.0679	0.1003	$3 \cdot 10^{-7}$
298.15	6.925	0.1083	−0.0449	0.0594	$3 \cdot 10^{-7}$
308.15	6.922	0.1006	−0.0344	0.0420	$3 \cdot 10^{-7}$
318.15	6.918	0.0943	−0.0340	0.0451	$4 \cdot 10^{-7}$
$C_2 = 5.00\%$					
T (K)	A	B	C	D	σ
288.15	6.948	0.1142	−0.1262	0.3559	$1 \cdot 10^{-7}$
298.15	6.945	0.1083	−0.1456	0.4247	$1 \cdot 10^{-7}$
308.15	6.942	0.1024	−0.1557	0.4610	$1 \cdot 10^{-7}$
318.15	6.938	0.0990	−0.1618	0.4677	$1 \cdot 10^{-7}$
$C_2 = 7.48\%$					
T (K)	A	B	C	D	σ
288.15	6.968	0.1193	−0.0684	0.0192	$8 \cdot 10^{-8}$
298.15	6.965	0.1108	−0.0627	0.0500	$8 \cdot 10^{-8}$
308.15	6.961	0.1078	−0.1003	0.1710	$8 \cdot 10^{-8}$
318.15	6.957	0.1032	−0.1192	0.1790	$2 \cdot 10^{-8}$
$C_2 = 10.03\%$					
T (K)	A	B	C	D	σ
288.15	6.988	0.1147	−0.0282	0.0000	$5 \cdot 10^{-10}$
298.15	6.985	0.1075	−0.0325	0.0000	$2 \cdot 10^{-11}$
308.15	6.981	0.1026	−0.0504	0.0000	$5 \cdot 10^{-12}$
318.15	6.976	0.0949	−0.0708	0.0000	$5 \cdot 10^{-10}$
$C_2 = 12.55\%$					
T (K)	A	B	C	D	σ
288.15	7.007	0.1996	−1.3057	0.0000	$8 \cdot 10^{-8}$
298.15	7.003	0.1836	−1.1532	0.0000	$7 \cdot 10^{-8}$
308.15	6.999	0.1790	−1.1605	0.0000	$8 \cdot 10^{-8}$
318.15	6.995	0.1653	−1.0885	0.0000	$6 \cdot 10^{-8}$

Table 10
Fit parameters and standard deviation corresponding to Eq. 1 for refractive index n_D, for Triton X-102 (1) + $Na_2S_2O_3$ (2) + water (3) from $T = (288.15 \text{ to } 318.15)$ K.

$C_2 = 2.50\%$					
T/K	A	B	C	D	σ
288.15	1.338	0.0828	0.5101	−0.7456	$2 \cdot 10^{-5}$
298.15	1.337	0.0798	0.5085	−0.7375	$2 \cdot 10^{-5}$
308.15	1.336	0.0699	0.5517	−0.8170	$1 \cdot 10^{-5}$
318.15	1.334	0.0620	0.5822	−0.8703	$1 \cdot 10^{-5}$
$C_2 = 5.00\%$					
T/K	A	B	C	D	σ
288.15	1.347	0.1563	0.4264	−2.8851	$1 \cdot 10^{-5}$
298.15	1.346	0.1039	1.0755	4.7745	$1 \cdot 10^{-5}$
308.15	1.344	0.1238	0.7655	−4.2835	$4 \cdot 10^{-6}$
318.15	1.342	0.0565	1.4091	−5.8051	$2 \cdot 10^{-6}$
$C_2 = 7.48\%$					
T/K	A	B	C	D	σ
288.15	1.349	0.2413	−2.2116	6.2657	$4 \cdot 10^{-7}$
298.15	1.347	0.2200	−1.9036	5.1427	$3 \cdot 10^{-7}$
308.15	1.346	0.2075	−1.7902	4.8005	$5 \cdot 10^{-7}$
318.15	1.345	0.2448	−2.3822	6.7410	$5 \cdot 10^{-7}$
$C_2 = 10.03\%$					
T/K	A	B	C	D	σ
288.15	1.354	0.0919	−0.3101	0.0000	$1 \cdot 10^{-8}$
298.15	1.353	0.0861	−0.2774	0.0000	$8 \cdot 10^{-9}$
308.15	1.351	0.0599	$-4.3961 \cdot 10^{-3}$	0.0000	$4 \cdot 10^{-9}$
318.15	1.350	0.0114	0.4158	0.0000	$1 \cdot 10^{-8}$
$C_2 = 12.55\%$					
T/K	A	B	C	D	σ
288.15	1.360	0.0625	0.0244	0.0000	$1. \cdot 10^{-9}$
298.15	1.359	0.0531	0.3363	0.0000	$1. \cdot 10^{-8}$
308.15	1.357	0.0811	−0.1712	0.0000	$5. \cdot 10^{-8}$
318.15	1.355	0.0631	0.1361	0.0000	$8. \cdot 10^{-8}$

ternary systems is similar than the corresponding ones for binary systems, and the influence caused by a third compound is not very important.

Tables 7–10 show the values corresponding to fitting parameters of Eq. 1 used to fit experimental data of density and refractive index under the experimental conditions used in present work for homogeneous ternary mixtures. Also the standard deviation corresponding to each system is included in these tables. This kind of data allows to conclude that this equation calculates the value of these properties with slight deviations in comparison with the experimental results.

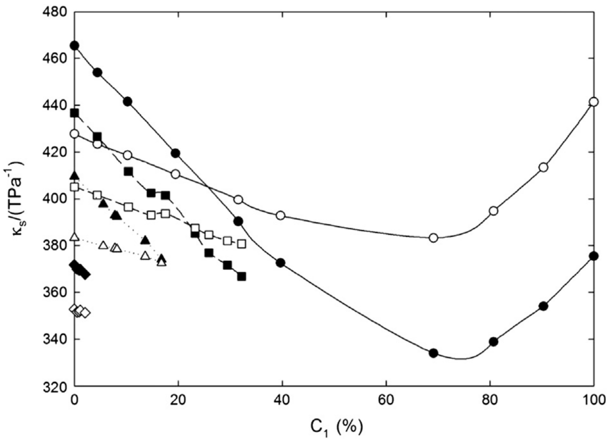

Fig. 5. Influence of surfactant and salt concentration and temperature upon isentropic compressibility value for Triton X-102 (1) + $Na_2S_2O_3$ (2) + water (3) (○ and ●), $C_2 = 0\%$; (□ and ■), $C_2 = 2.52\%$; (△ and ▲), $C_2 = 5.00\%$; (and ◆),$C_2 = 9.12\%$; Full symbols, $T = 288.15$ K; Open symbols, $T = 318.15$ K.

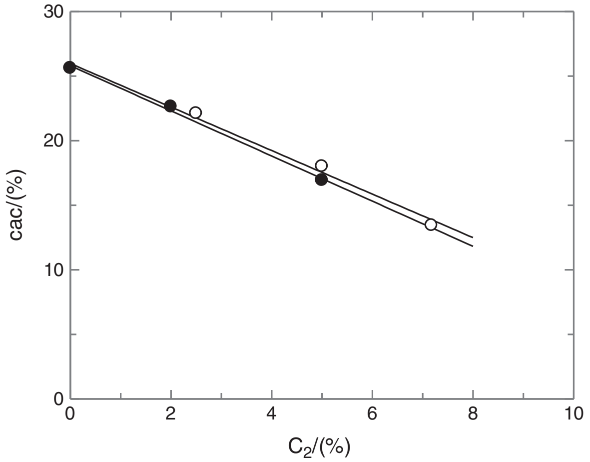

Fig. 6. Influence of salt type and concentration upon critical aggregation concentration. ●, sodium sulfate; ○, sodium thiosulfate.

As for binary systems previously described, the most complex behavior corresponds to the speed of sound and isentropic compressibility data. Fig. 5 shows the behavior observed for isentropic compressibility when solute concentration and temperature were varied. Density and speed of sound data were used to calculate the isentropic compressibility. The effect caused by the salt ($Na_2S_2O_3$) in this property is a clear decrease for all the surfactant concentrations and temperatures. The effect caused by the surfactant is different and consists in a decrease in this property until a minimum is reached, but this behavior is only observed in the absence of salt. On the other hand temperature produces a different impact depending on the surfactant concentration in the mixture. A different influence of temperature upon isentropic compressibility was observed depending of surfactant concentration in the liquid mixture: At low surfactant concentrations an increase in temperature produces a decrease in isentropic compressibility but the opposite effect is obtained at high surfactant concentration. This behavior indicates that a temperature-resistant structure was formed in the presence of different amounts of salt. The salt concentration has certain influence upon the critical aggregation concentration (surfactant concentration) needed to form this aggregation. When salt concentration increases in the ternary system the surfactant concentration needed to achieve the temperature-resistant structure decreases (see Fig. 6). This fact is produced due to the interactions of electrolytes with the surfactant that modifies the aggregation processes [18]. A similar behavior was obtained for systems using the other salt employed in the present work (sodium sulfate) with the same effects caused by the surfactant and the salt concentration, and temperature.

Present work also analyzes the physical properties corresponding to liquid ternary mixtures at equilibrium joined by tie lines. The experimental data for refractive index, density and speed of sound are included in Tables 11 and 12 for the ATPS employed in present work. These equilibrium phases are obtained by mixing certain amounts of each

Table 11
Density ρ, speed of sound u, isentropic compressibility κ_s, and refractive index n_D, of Triton X-102 (1) + Na_2SO_4 (2) + water (3) phases at equilibrium at $T = 298.15$ K.

Tie line	C_1/%	C_2/%	ρ/kg·m^{-3}	u/m·s^{-1}	κ_s/TPa^{-1}	n_D
1	43.43	0.55	1.074461	1593.67	366.45	1.43419
2	32.25	2.80	1.069493	1593.67	368.15	1.37086
3	45.12	0.34	1.043269	1573.24	387.27	1.42266
1	0.32	10.58	1.074681	1593.61	366.40	1.34562
2	0.75	10.13	1.071838	1589.93	369.08	1.34566
3	0.13	11.58	1.081889	1603.03	359.69	1.34725

Table 12
Density ρ, speed of sound u, isentropic compressibility κ_s, and refractive index n_D, of Triton X-102 (1) + $Na_2S_2O_3$ (2) + water (3) phases at equilibrium at T = 298.15 K.

Tie line	C_1/%	C_2/%	ρ/kg·m^{-3}	u/m·s^{-1}	κ_s/TPa^{-1}	n_D
1	47.72	2.67	1.069616	1637.36	348.73	1.44540
2	31.54	6.14	1.070740	1640.83	346.89	1.43453
3	54.47	1.23	1.073006	1620.88	354.73	1.43927
1	0.56	15.34	1.109024	1634.04	337.70	1.36075
2	1.49	14.02	1.082105	1600.15	360.92	1.35465
3	0.18	16.65	1.134443	1666.70	317.32	1.36561

compound, stirred and settled them for 24 h. Then the composition was determined and the physical properties were measured.

Fig. 7 shows an example of some experimental data corresponding to the system composed of Triton X-102 + sodium sulfate + water at 298.15 K. In some properties such as density and refractive index, the weight of each solute upon the value of these properties does not show a clear behavior. For instance a higher presence of surfactant in the mixture causes a decrease in density and an increase in refractive index. This behavior is observed for all the equilibrated mixtures. For density, the importance of salt concentration is an important parameter while for refractive index, polymer concentration has a higher importance. The same type of trend is observed when the experimental data for the other sodium salt is analyzed. In general, in the system Triton X-102 + sodium thiosulfate the polymer-rich phase takes similar values for density and refractive index while in Triton X-102 + sodium sulfate very important changes in these properties for the polymer-rich phases are found. The changes observed in salt-rich phases are similar for both systems.

In relation with speed of sound experimental values, in some cases the surfactant-rich phase shows a greater value for the speed of sound than salt-rich phases. But the opposite behavior is also observed. These changes in the speed of sound behavior are due to changes in the concentration of critical aggregation states. When the other salt is employed (sodium thiosulfate) the values obtained for the speed of sound are higher than the previously commented for sodium sulfate, but the influence of surfactant and salt concentration is similar. On the other hand, the influence of composition upon speed of sound in each phase (heavy or light) is similar for both systems.

4. Conclusions

Present work characterizes liquid mixtures that involve the components of two aqueous two phase systems based on surfactant + salt + water mixtures. The blends analyzed were binary and ternary aqueous solutions. The last type was divided in mixtures corresponding to the homogeneous zone and equilibrium phases. Salt aqueous solutions showed the same behavior than previous studies but the influence of composition in surfactant solutions showing aggregation phenomena forming a temperature-resistant structure shows the same experimental value of speed of sound and isentropic compressibility for all temperatures.

For ternary mixtures in the homogeneous zone, an increase in density and refractive index is observed when salt and/or surfactant concentration increases in the mixture. Speed of sound and isentropic compressibility show a similar behavior than Triton X-102 + water system. The presence of salt modifies slightly the critical aggregation concentration producing a decrease in its value.

Equilibrated phases were characterized in relation with these physical properties observing the influence of each solute and the joint effect (salt and surfactant). Also the influence of critical aggregation concentration is also observed producing changes in the slope of tie-lines.

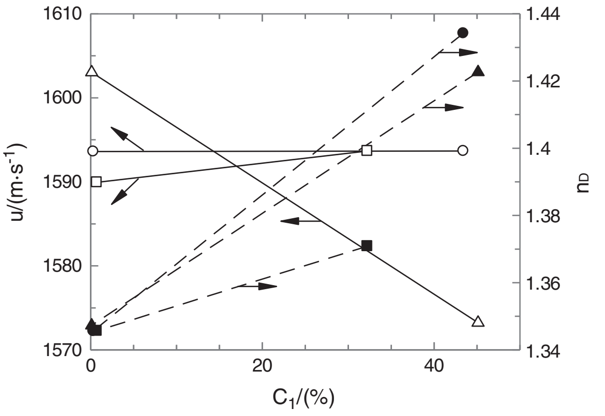

Fig. 7. Influence of phase composition upon speed of sound and refractive index in phases at equilibrium for Triton X-102 (1) + $Na_2S_2O_3$ (2) + water (3). (● and ○) Tie-line 1; (■ and □) Tie line 2; (▲ and △) Tie line 3.

Acknowledgments

Financial support for this work was provided by the regional government Xunta de Galicia (Project Number: 10MDS265021PR). Diego Gómez-Díaz acknowledges Ministerio de Ciencia e Innovación the “Ramón y Cajal” position. Authors also acknowledge F. J. Deive for his help with the ATPS equilibrium data.

References

[1] Vanessa S. Sampaio, Renata C. F. Bonomo, Elias S. Monteiro Filho, Valéria P. R. Minim, Luis A. Minim. 57 (2012), 3651–3657.
[2] G. Ulloa, C. Coutens, M. Sánchez, J. Sineiro, J. Fábregas, F.J. Deive, A. Rodríguez, M.J. Núñez, Green Chem. 14 (2012) 1044–1051.
[3] Ebrahim Nemati-Kande, Hemayat Shekaari, J. Chem. Thermodyn. 57 (2013) 541–549.
[4] Sara C. Silvério, Anna Wegrzyn, Estela Lladosa, Oscar Rodríguez, Eugénia A. Macedo, J. Chem. Eng. Data 57 (2012) 1203–1208.
[5] Helena Passos, Margarida P. Trindade, Tatiana S.M. Vaz, Luiz P. da Costa, Mara G. Freire, João A.P. Coutinho, Sep. Purif. Technol. 108 (2013) 174–180.
[6] Pedro P. Madeira, Ana Bessa, Luís Álvares-Ribeiro, M. Raquel Aires-Barrosc, Alírio E. Rodrigues, Boris Y. Zaslavsky, J. Chromatogr. A 1274 (2013) 82–86.
[7] Yang Liu, Wu. Zhongyang, Yanglong Zhang, Haihua Yuan, Biochem. Eng. J. 69 (2012) 93–99.
[8] Frank Luechau, Tau Chuan Ling, Andrew Lyddiatt, Biochem. Eng. J. 50 (2010) 90–98.
[9] Leonie A. Sarubbo, Luciana A. Oliveira, Ana Lúcia F. Porto, José Luiz Lima-Filho, Galba Maria Campos-takak, Elias B. Tambourgi, Biochem. Eng. J. 16 (2003) 221–227.
[10] Florian Buchbender, FerdyOnink, WytzeMeindersma, Andre' de Haan, Andreas Pfennig, Chem. Eng. Sci. 82 (2012) 167–176.
[11] P.A.J. Rosa, A.M. Azevedo, S. Sommerfeld, W. Bäcker, M.R. Aires-Barros, J. Chromatogr. B 880 (2012) 148–156.
[12] Marcos Larriba, Pablo Navarro, Julián García, Francisco Rodríguez, Ind. Eng. Chem. Res. 52 (2013) 2714–2720.
[13] W.M. Haynes, D.R. Lide, CRC Handbook of chemistry and physics: a ready-reference book of chemical and physical data, CRC Press, Boca Raton, 2010.
[14] Miguel Iglesias, Abel Torres, Rafael González-Olmos, J. Salvatierra, J. Chem. Thermodyn. 40 (2008) 119–133.
[15] Antonio Blanco, Alicia García-Abuín, Diego Gómez-Díaz, José M. Navaza, Isabel Vidal-Tato, J. Chem. Eng. Data 55 (2010) 962–965.
[16] R.C. West, D.R. Lide, Handbook of Chemistry and Physics", 70th Edition CRC Press, Boca Ratón. USC, 2007.
[17] M.E. Taboada, H.R. Galleguillos, T.A. Graber, J. Alvarez-Benedí, Fluid Phase Equilib. 235 (2005) 104–111.
[18] Th. van den Boomgaard, Sh.M. Zourab, J. Lyklema, Progr. Coll. Pol. Sci. 68 (1983) 25–32.