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Research Article

The Nature of Processes Affecting the Solubility, Viscosity, and Density Characteristics of Aqueous Electrolyte Systems

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Abstract
This study investigates the key factors influencing the solubility, viscosity, and density of aqueous electrolyte systems. Model solutions of types 1-1, 1-2, 2-1, and 2-2 electrolytes were examined across a wide concentration range. The results show that solubility increases with temperature due to a higher proportion of free water molecules, while greater electrolyte concentrations lead to a rise in viscosity and density. It was found that ion radius and charge density strongly impact solution properties: larger ion radii and lower charge densities decrease viscosity and increase density, whereas smaller radii and higher charge densities have the opposite effect. The findings offer new insights into the relationship between ionic parameters and macroscopic solution behavior, supported by mathematical modeling and graphical analysis.

Keywords: solubility, viscosity, density, aqueous electrolyte systems, hydrated ions

1. INTRODUCTION

Currently, the theory of the liquid state of substances, including aqueous electrolyte solutions, is still in its early stages of development. To date, a significant amount of experimental and factual data has been accumulated regarding the diverse physicochemical properties of aqueous electrolyte solutions [1]-[3]. However, much of this highly reliable information has yet to receive a comprehensive scientific explanation. In this area of scientific inquiry, despite some relative progress in the theory of dilute solutions, no significant advancements have been made thus far [4].

Aqueous solutions play a significant role in engineering and technology. Currently, there is a wide variety of chemical-technological processes, most of which are carried out in liquid-phase systems, predominantly aqueous-electrolyte mixtures. The technological regimes and parameters of any processes occurring in aqueous-electrolyte systems are determined based on their concentration, density, viscosity, and various thermal properties. The current level of knowledge in the theory and practice of inorganic chemical technology indicates that the causal nature of changes in the viscosity and density of aqueous electrolyte solutions is still not fully understood. Additionally, there is a lack of clarity regarding the processes and phenomena underlying the hydration of ions in water. The existing literature primarily provides qualitative explanations from the perspectives of intermolecular interaction forces, the principles of chemical kinetics, hydrostatics, hydraulics, and similar fields [5][6]. Therefore, the development of new scientific principles concerning the nature and mechanisms of changes in the key physicochemical properties of aqueous electrolyte solutions, as well as establishing the dependence of ion hydration numbers on their specific charge density, represents a critical task.

Studies on the viscosity and density of aqueous electrolyte solutions cover a wide range of compounds, including salts of alkali and transition metals, acids, and mixed systems [7]. For example, the investigation of ternary solutions of $CaCl_2$ and KCl in the temperature range of 293–323 K revealed that the solution's viscosity exceeds that of water by 15% at low concentrations and increases up to 270% at high concentrations, with $CaCl_2$ having a more pronounced effect on viscosity compared to KCl [8]. Similar patterns have been established for aqueous and water-ethanol solutions of $MgSO_4$, where an increase in electrolyte concentration leads to a rise in viscosity, while an

Table 1. Radius and surface charge density of ions.

Metal ions	Ion radius (Å)	Surface ion charge density (C/Å^2)
Co^{+2}	0.720	0.4921
Ni^{+2}	0.736	0.4709
Mg^{+2}	0.740	0.4659
Li^{+}	0.780	0.2096
Mn^{+2}	0.800	0.3986
Fe^{+2}	0.815	0.3841
Zn^{+2}	0.830	0.3703
Na^{+}	0.980	0.1328
Cd^{+2}	0.997	0.2566
Cu^{+2}	1.010	0.2501
Ca^{+2}	1.030	0.2405
Sr^{+2}	1.200	0.1772
Pb^{+2}	1.320	0.1464
K^{+}	1.330	0.0721
Ba^{+2}	1.387	0.1326
Rb^{+}	1.490	0.0574
Cs^{+}	1.650	0.0468

increase in temperature causes its reduction. These studies confirm the structure-forming role of Mg^{2+} in aqueous solutions, as manifested in the enhancement of ion-ion interactions with increasing temperature [9].

The analysis of the density of aqueous electrolyte solutions is also a crucial research direction. In particular, recently obtained experimental data for pure and mixed solutions of NaCl and $CaCl_2$ in the temperature range of 293–353 K allowed for the refinement of existing numerical models for the density of geothermal fluids [10]. This confirms the significance of such studies for accurately predicting density parameters at high temperatures and pressures. However, previous studies have mainly focused on the effects of concentration and temperature on the macroscopic properties of specific electrolyte systems, without systematically analyzing the influence of intrinsic ion parameters, such as ionic radius and charge density. In contrast, the present study provides a comprehensive investigation into how the radius and charge density of hydrated ions affect the solubility, viscosity, and density of various aqueous electrolyte solutions. This integrated approach enables a deeper understanding of the structural and physicochemical behavior of electrolyte solutions across a wide range of concentrations and temperatures.

The structural characteristics of aqueous electrolyte solutions are largely determined by their ionic composition, concentration, and temperature conditions. Studies of colloidal systems have shown that surface charge and hydration are key factors influencing the stability of aqueous suspensions. It has been established that monovalent and divalent ions exert different effects on adsorption and hydration [11]. High electrolyte concentrations lead to enhanced long-range ionic correlations, which significantly impact the structure of interfacial water.

Furthermore, an important research direction is the ionic conductivity of solutions. In the case of acidic solutions such as HCl, HNO_3, H_2SO_4, and H_3PO_4, it has been established that conductivity depends not only on concentration but also on the characteristics of the phase diagram of the system. The analysis of ion transport in such solutions has identified two dominant mechanisms—"hopping" and "vehicular", which play a key role in charge

Table 2. Parameters of the studied water-electrolyte mixtures.

Water-electrolyte solutions	Range of changes in solution concentrations, mol %	Temperature of solutions, °C	
H_2O – LiCl	0.05:14.35	20	40
H_2O – NaCl	0.03:9.87	20	40
H_2O – KCl	0.03:6.48	20	40
H_2O – CsCl	0.01:13.95	20	40
H_2O – LiI	0.01:14.09	20	40
H_2O – NaI	0.01:15.27	20	40
H_2O – KI	0.01:11.66	20	40
H_2O – CsI	0.01:4.31	20	40
H_2O – Li_2SO_4	0.02:3.93	20	40
H_2O – Na_2SO_4	0.01:2.02	20	40
H_2O – K_2SO_4	0.01:2.27	20	40
H_2O – $Co(NO_3)_2$	0.01:7.46	20	40
H_2O – $Ni(NO_3)_2$	0.01:6.17	20	40
H_2O – $Mg(NO_3)_2$	0.01:7.49	20	40
H_2O – $Mn(NO_3)_2$	0.01:6.29	20	40
H_2O – $Zn(NO_3)_2$	0.01:5.96	20	40
H_2O – $Cd(NO_3)_2$	0.01:0.24	20	40
H_2O – $Cu(NO_3)_2$	0.01:8.76	20	40
H_2O – $Ca(NO_3)_2$	0.01:9.89	20	40
H_2O - $Sr(NO_3)_2$	0.01:5.37	20	40
H_2O – $Pb(NO_3)_2$	0.01:2.07	20	40
H_2O – $CoCl_2$	0.01:2.98	20	40
H_2O – $NiCl_2$	0.01:5.58	20	40
H_2O – $MgCl_2$	0.02:8.27	20	40
H_2O – $MnCl_2$	0.01:8.77	20	40
H_2O – $FeCl_2$	0.01:5.81	20	40
H_2O – $ZnCl_2$	0.01:23.50	20	40
H_2O – $CdCl_2$	0.01:7.58	20	40
H_2O – $CaCl_2$	0.02:3.40	20	40
H_2O – $SrCl_2$	0.01:14.61	20	40
H_2O – $BaCl_2$	0.01:2.84	20	40
H_2O – $CoSO_4$	0.01:4.32	20	40
H_2O – $NiSO_4$	0.01:3.93	20	40
H_2O – $MgSO_4$	0.02:3.18	20	40
H_2O – $MnSO_4$	0.01:6.04	20	40
H_2O – $FeSO_4$	0.01:2.88	20	40
H_2O – $ZnSO_4$	0.01:5.67	20	40
H_2O – $CdSO_4$	0.01:4.45	20	40
H_2O – $CuSO_4$	0.01:2.10	20	40

transfer across different concentration ranges [12]. Additionally, electrolytes are widely used in electrochemical systems, such as ChCl:AA (Choline Chloride–Acetic Acid) solutions, which exhibit promising properties as background electrolytes in electrochemical studies [13]. Experimental data on viscosity, electrical conductivity, and electrochemical window width confirm their suitability for use in electrochemical redox systems, making them promising for further investigation.

Studies of aqueous electrolyte systems cover a wide range of aspects—from macroscopic properties such as density and viscosity to molecular mechanisms of hydration and ion transport [14]. The obtained data hold both fundamental and applied significance, finding applications in geochemistry, biophysics, electrochemistry, and materials science. The aim of this study is to investigate the processes affecting the solubility, viscosity, and density of aqueous electrolyte systems and to identify the patterns of their changes depending on concentration, temperature, and the parameters of ionic components. The scientific novelty of this research lies in the fact that, for the first time, a comprehensive analysis of the influence of ion radius and charge density on the macroscopic parameters of aqueous electrolyte solutions (viscosity, density, and solubility) has been conducted. The study experimentally confirms a quantitative relationship between the radius of the hydrated ion, its charge density, and the structure of the aqueous electrolyte medium, which has not been previously examined in such a comprehensive manner.

2. MATERIALS AND METHODS

The research was conducted on model aqueous solutions of electrolytes of types 1-1, 1-2, 2-1, and 2-2. The model solutions were prepared using reagent-grade samples of LiCl, NaCl, KCl, CsCl, LiI, NaI, KI, CsI, Li_2SO_4, Na_2SO_4, K_2SO_4, $Co(NO_3)_2$, $Ni(NO_3)_2$, $Mg(NO_3)_2$, $Mn(NO_3)_2$, $Zn(NO_3)_2$, $Cd(NO_3)_2$, $Cu(NO_3)_2$, $Ca(NO_3)_2$, $Sr(NO_3)_2$, $Pb(NO_3)_2$, $CoCl_2$, $NiCl_2$, $MgCl_2$, $MnCl_2$, $FeCl_2$, $ZnCl_2$, $CdCl_2$, $CaCl_2$, $SrCl_2$, $BaCl_2$, $CoSO_4$, $NiSO_4$, $MgSO_4$, $MnSO_4$, $FeSO_4$, $ZnSO_4$, $CdSO_4$, $CuSO_4$ (≥99.9% purity), and distilled water obtained using an AQUA-DISTILLER DE-4-2 over a wide concentration range. The salts were dried at 105 °C for 2 h prior to use to remove surface moisture. Solutions were prepared gravimetrically by weighing the appropriate amounts of solid using an analytical balance (accuracy ±0.0001 g) and diluting to the required volume using calibrated volumetric flasks (class A, tolerance ±0.05 mL for 100 mL flasks). Concentrations were calculated based on the mass of solute and the final volume of the solution. The uncertainty in concentration was estimated to be less than ±0.1%.

The physicochemical properties of the investigated aqueous-electrolyte mixtures were determined using standard analytical methods and modern control instruments. The obtained results were subjected to comparative analysis with publicly available reference data. Graphical and

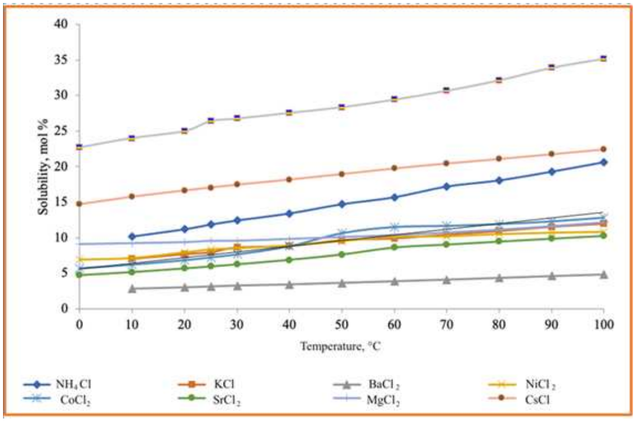

Figure 1. Temperature dependence of chloride solubility.

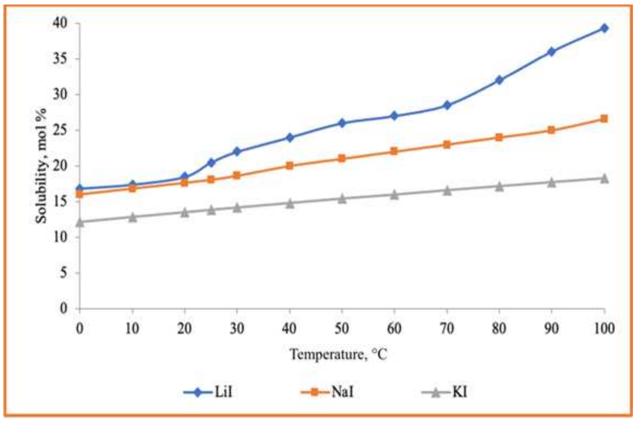

Figure 2. Temperature dependence of iodide solubility.

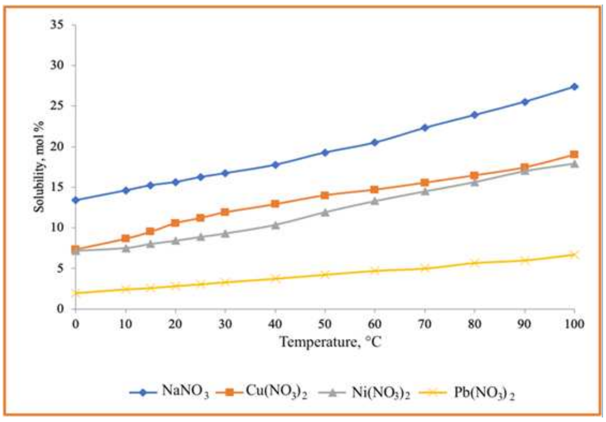

Figure 3. Temperature dependence of nitrate solubility.

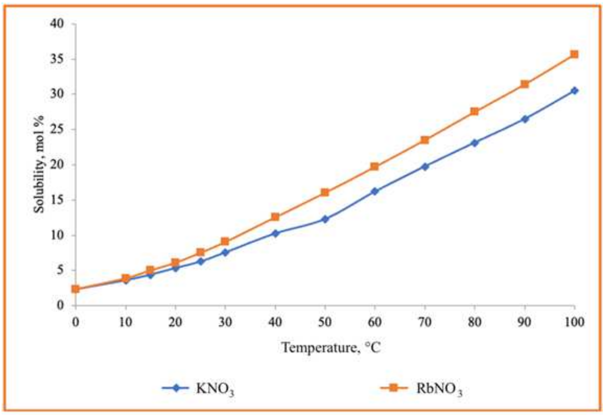

Figure 4. Temperature dependence of the solubility of potassium and rubidium nitrates.

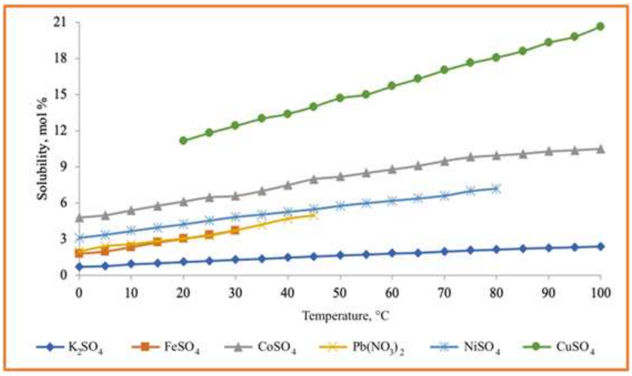

Figure 5. Temperature dependence of sulfate solubility.

mathematical methods were employed to analyze and summarize the literature data and experimental findings regarding the influence of ion radius, ion charge density, and solution concentration on the changes in viscosity and density of the studied solutions (Å (angstrom) is used as a unit of length, where 1 Å = 0.1 nm). When necessary, experiments were conducted under thermostatic conditions using a liquid laboratory thermostat, model SJML-19/2.5-I1. The research was conducted taking into account the most reliable data on the radius and charge density of ionic components in binary and ternary electrolyte solutions of types 1-1, 1-2, 2-1, and 2-2 (Table 1) over a wide concentration range at a constant temperature (Table 2).

2.1. Determination of Solution Density using a Pycnometer

Equipments used were analytical balance, weight set, pycnometer, vessel containing the test liquid, vessel with distilled water, vessel with water at room temperature, thermometer, and filter paper. The density of solutions was determined using a calibrated pycnometer (volume 25.000 ± 0.002 mL) at a controlled temperature of 20.0 ± 0.1 °C. The pycnometer was calibrated using distilled water prior to each series of measurements. A pycnometer is a vessel of a precisely defined and constant volume. By sequentially filling it with the test solution and distilled water and weighing, the density of the solution can be determined using the following expression 1.

$$\rho_1 = \frac{P - p}{Q - p}\delta \tag{1}$$

where, P is the mass of the pycnometer with the solution (g), Q is the mass of the pycnometer with water (g), p is the mass of the pycnometer (g), and δ is the density of water at a given temperature (g/cm^3).

2.2. Determination of Solution Viscosity using a V3-Type Viscometer

The V3-type viscometer is a falling ball viscometer compliant with TGL 29 202/03 and DIN 53 015 standards. The viscometer measures the time

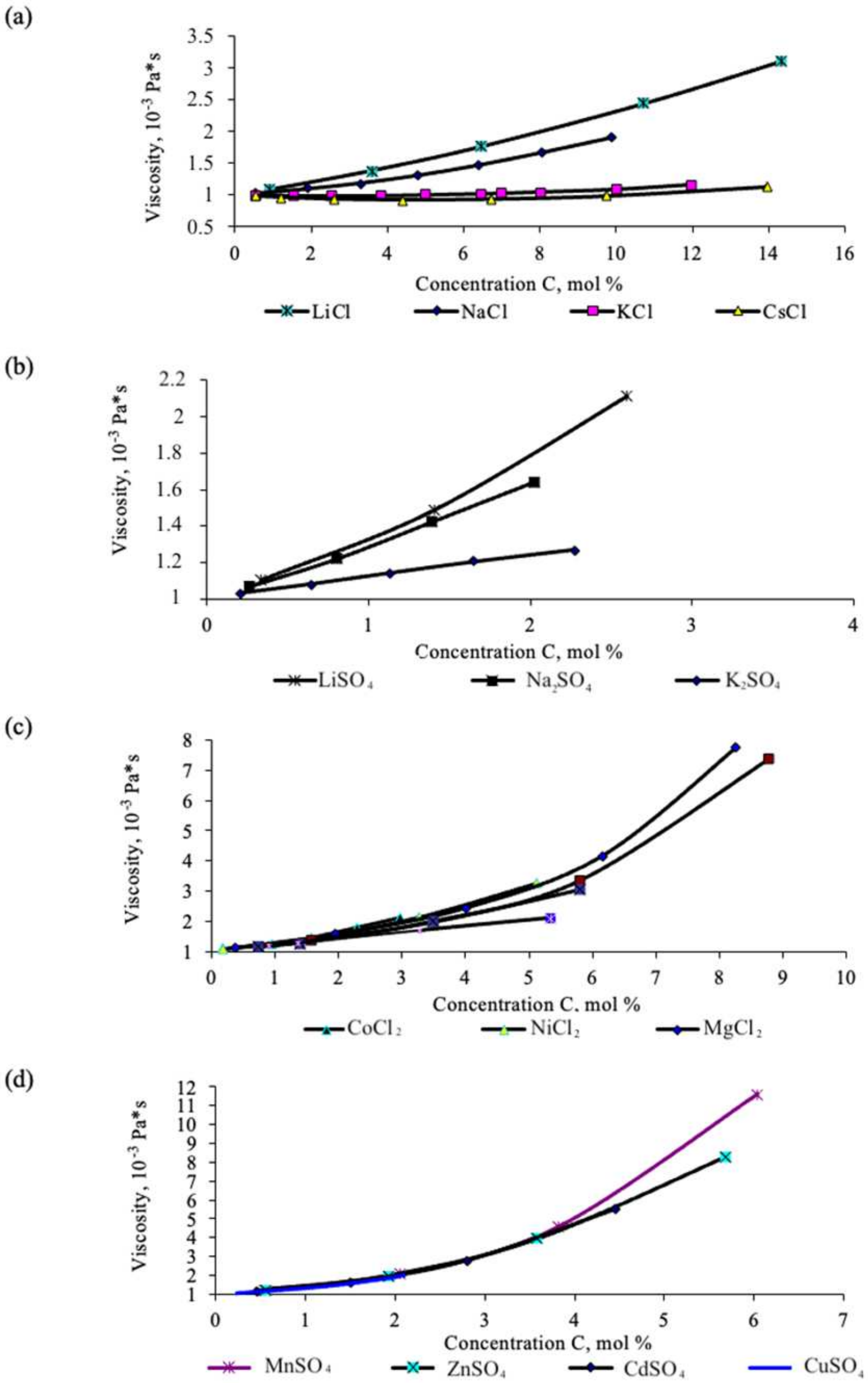

Figure 6. Dependence of solution viscosity on concentration at constant temperature of 20 °C.

it takes for a ball to fall through a cylindrical tube filled with the test liquid, inclined at 10° from the vertical. The V3-type viscometer is primarily designed for measuring the viscosity of Newtonian fluids. The viscometer was calibrated using standard viscosity fluids and distilled water (dynamic viscosity of water at 20 °C: 1.002 mPa·s). All measurements were performed in triplicate to ensure reproducibility. Measured Quantity: Dynamic viscosity, expressed in Pa·s or mPa·s. The dynamic viscosity is calculated using the following formula 2.

$$\eta = \tau(q_1 - q_2) \cdot K \quad \textbf{(2)}$$

where: η = dynamic viscosity in millipascal seconds (mPa·s), q_1 = density of the ball (g/cm^3), q_2 = density of the liquid at the operating temperature (g/cm^3), τ = time of ball fall (s), and K = ball constant (mPa·cm^3/g). Both q_1 and K are given for each ball in the test certificate. The expression in brackets ($q_1 - q_2$) is a correction for the buoyancy force acting on the ball in the solution.

To describe the physicochemical properties of aqueous electrolyte systems, polynomial approximations of different orders were employed based on the behavior of the experimental data. The dependencies of solubility (M_s), viscosity (η), and density (ρ) on temperature (T) and concentration (C) were modeled using quadratic equations, as these properties exhibited smooth, monotonic trends without inflection points across the studied ranges. In contrast, to characterize the relationships between viscosity and microscopic ionic parameters, such as ionic radius and charge density, cubic polynomial models were utilized to capture more complex, nonlinear behaviors observed in the experimental results.

Solubility (M_s) of electrolytes in water, expressed in molar percentage, is approximated by a quadratic function of temperature (3). where a_1, b_1, c_1 are empirical coefficients determined for each compound.

$$M_s = a_1T^2 + b_1T + c_1 \quad \textbf{(3)}$$

Viscosity (η) of solutions at a constant temperature depends on the concentration of the dissolved substance and is also described by a quadratic function 4. where a_2,b_2,c_2 are polynomial regression coefficients determined for each electrolyte.

$$\eta = a_2C^2 + b_2C + c_2 \quad \textbf{(4)}$$

Density (ρ) of aqueous electrolyte solutions is similarly described by a concentration-dependent equation 5. where a_3,b_3,c_3 are empirical parameters defined for specific salts.

$$\rho = a_3C^2 + b_3C + c_3 \quad \textbf{(5)}$$

The approximation of solubility, viscosity, and density dependencies was conducted using the multiple nonlinear regression method based on experimental data. The least squares method (LSM) was applied to minimize fitting errors. The regression analysis was performed using Microsoft Excel (built-in LINEST and trendline fitting tools). For each fitted equation, the coefficient of determination (R^2) was calculated to evaluate the goodness of fit. Where applicable, 95% confidence intervals for the regression coefficients were also determined. Polynomial models were employed to achieve an accurate empirical description of viscosity and density behavior over a broad concentration range, especially where classical models like the Jones–Dole equation are less effective. However, it is acknowledged that such models are valid strictly within the studied concentration and temperature limits and lack a fundamental theoretical basis for extrapolation beyond these conditions.

3. RESULTS AND DISCUSSIONS

3.1. Solubility of Electrolytes

The results of the graphical analysis of data on the solubility changes of the studied aqueous-salt systems with temperature are shown in Figures 1 – 5. From the results, it is evident that the solubility of the examined aqueous-electrolyte mixtures consistently increases with rising temperature. This observed pattern remains consistent throughout the entire studied temperature range of the solutions.

Recent studies using molecular dynamics and field-theoretical modeling have demonstrated that while ions affect the dielectric properties and

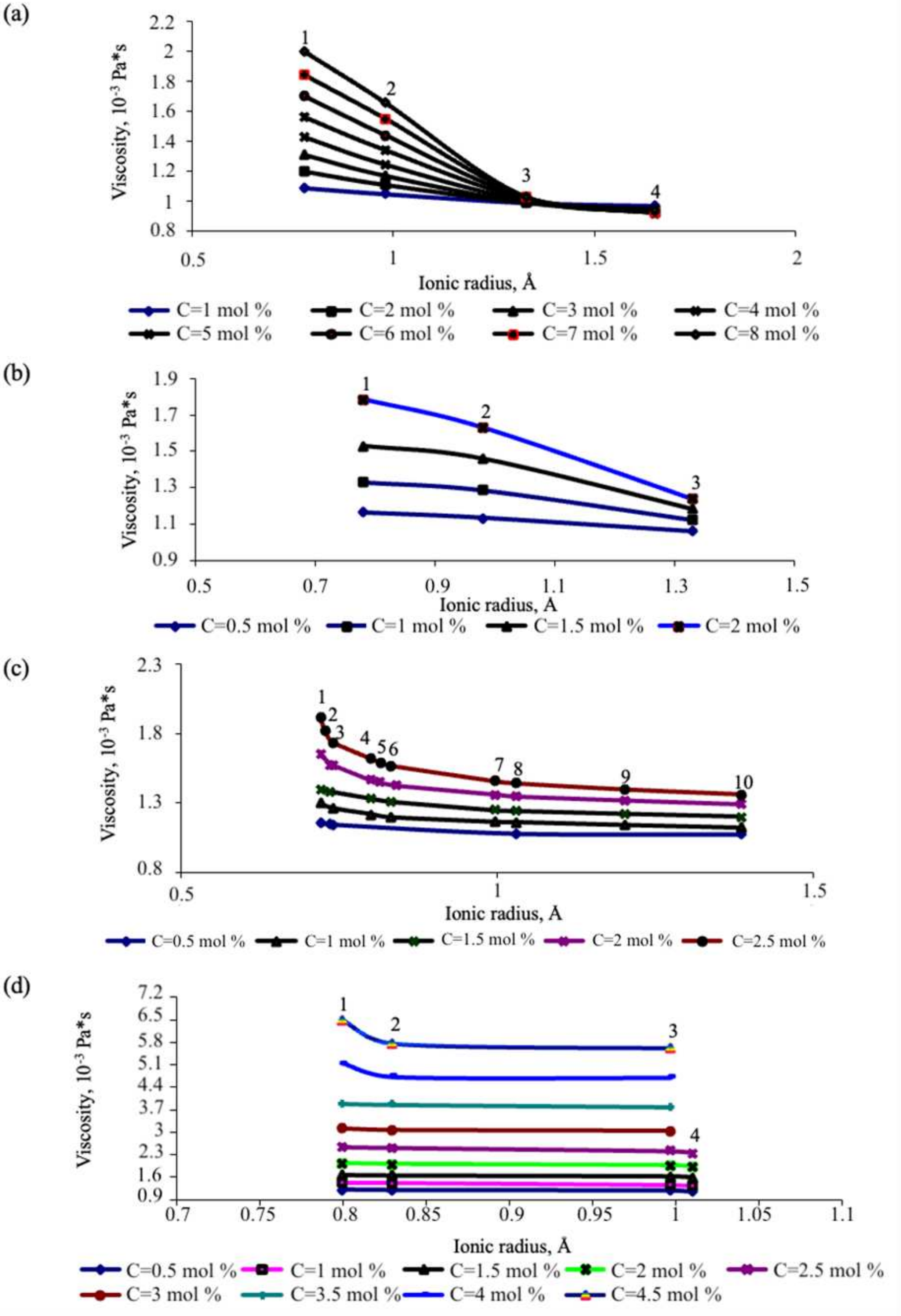

Figure 7. Dependence of the viscosity of solutions on the ion radius at constant concentration and temperature (20 °C)

induce screening in aqueous solutions, the hydrogen-bonded network of bulk water remains largely intact away from the hydration shells [15]. This distinction between localized structured water and bulk-like free water supports the assumption that increasing temperature enhances the proportion of free water molecules, facilitating the solubility of electrolytes. This is confirmed by the polynomial dependencies obtained for the molar solubility of salts such as NH_4Cl, KCl, $BaCl_2$, $CoCl_2$, $NiCl_2$, $SrCl_2$, $MgCl_2$, CsCl, and LiCl, presented as follows:

$$\text{Ms } NH_4Cl = 0.00007T^2 + 0.108T + 9.021$$
$$\text{Ms } KCl = -0.0001T^2 + 0.0666T + 6.4292$$
$$\text{Ms } BaCl_2 = 0.00003T^2 + 0.018T + 2.618$$
$$\text{Ms } CoCl_2 = -0.0004T^2 + 0.1178T + 5.0344$$
$$\text{Ms } NiCl_2 = -0.0003T^2 + 0.0711T + 6.6601$$
$$\text{Ms } SrCl_2 = -0.0001T^2 + 0.0685T + 4.4370$$
$$\text{Ms } MgCl_2 = 0.0002T^2 + 0.0080T + 9.1278$$

As can be seen, the group of dependencies is identical to expression 6, and differ from the latter only in the order of constants preceding the temperature factor, which should be understood as a reflection of the physicochemical properties of the salt components in the solution.

$$N = -0.0634T^2 + 2.7475T + 16.3315 \qquad \textbf{(6)}$$

The bound fraction of water molecules does not exert a significant influence on the solubility of electrolytes, as these molecules exist as large and hydrophobic complexes. A key distinction between these insights and the currently accepted concepts of electrolyte solubility in water lies in the fact that, for the first time in scientific practice, these findings are based on the actual identical temperature dependence of the solubility of aqueous-salt mixtures and the quantitative composition of free water molecules in the solvent. Thus, a system should be conceptualized as a mixture of aqueous-salt complexes composed of the ionic components of the salt, the free fraction of water molecules, the residual fraction of water molecules, and hydrophobic water formations that do not participate in any significant medium-altering interaction with the electrolyte molecules.

As the temperature rises, the concentration of aqueous-ionic complexes increases, which should theoretically lead to a reduction in the total number of free water molecules and, consequently, a slowdown in the dissolution process. However, with increasing temperature, the bound portion of bulk water, which does not effectively interact with the electrolyte molecules and does not decrease in number, undergoes thermal destruction. This thermal breakdown results in the formation of new free water molecules in the solution, which are capable of further enhancing the solubility of electrolytes as the temperature increases [15].

3.2. Viscosity Characteristics of Aqueous Electrolyte Mixtures

The potential diversity of properties in any solution depends on the physicochemical characteristics of its individual components—the dissolved substances and solvents—as well as on the properties of newly formed structural elements and their assemblies derived from the original substances in the solution. In aqueous electrolyte systems, the primary constituents are various types of positively and negatively charged ions. According to modern concepts of solution structure, these ions are surrounded by hydration shells formed from solvent water molecules, which can be categorized into two distinct types: bound water and free water [16][17]. Bound water refers to molecules directly coordinated to the ions, forming the first hydration shell with restricted mobility and altered hydrogen bonding. In contrast, free water denotes the bulk-like molecules not directly involved in ion coordination and retaining their dynamic properties. The ions in solution therefore exist as hydrated complexes—structural units whose behavior depends strongly on their charge density and radius.

To date, all aspects of the critical question regarding the influence of the structural components of solutions on their characteristic physicochemical properties remain unresolved, lacking exhaustive and scientifically grounded explanations. Existing insights and the associated hypotheses often lack irrefutable quantitative validation and are predominantly of a contentious nature [18]. An analysis of the current level of knowledge in the theory and practice of inorganic chemical technology indicates that the causal relationships governing the impact of external factors on the

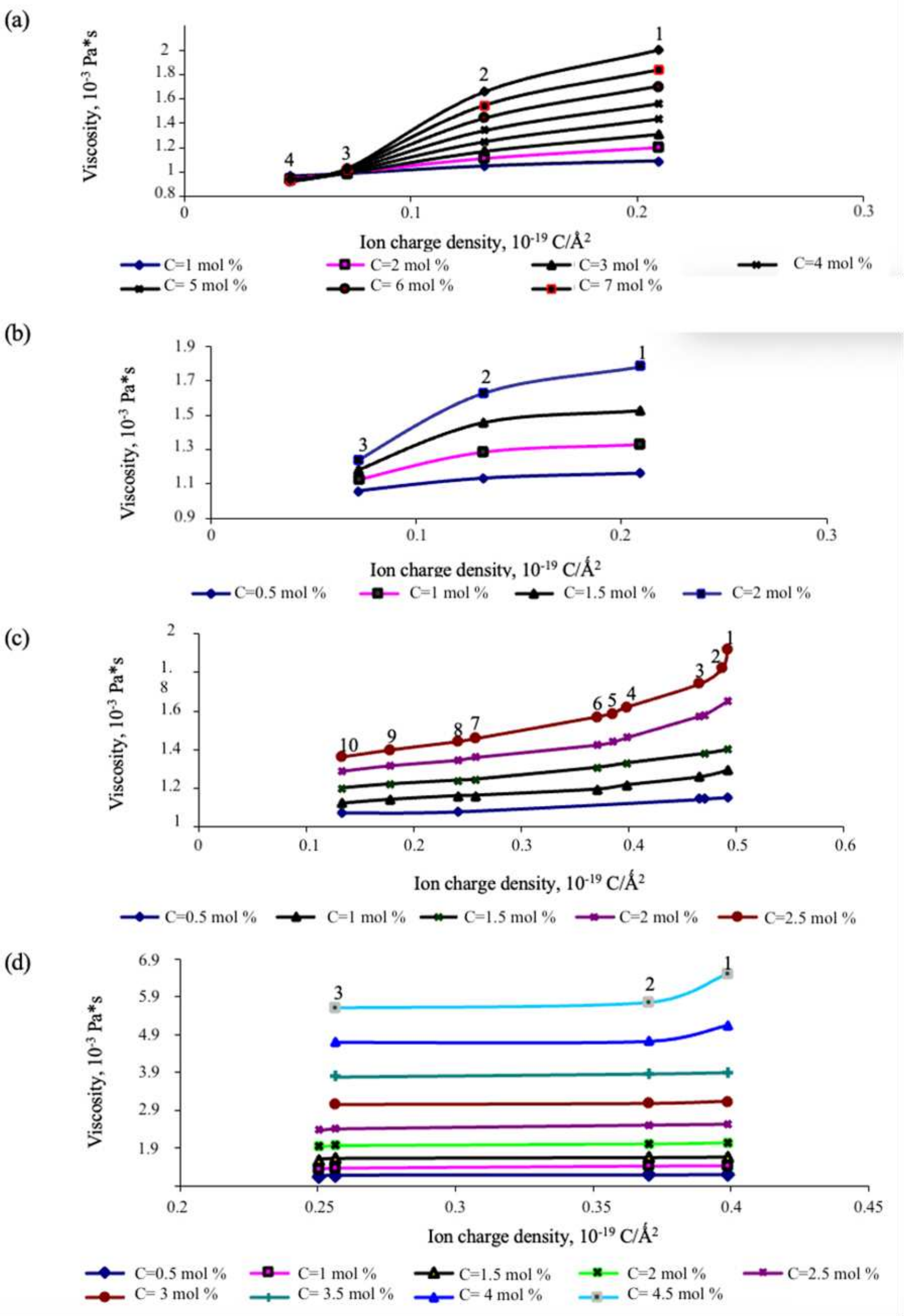

Figure 8. Dependence of solution viscosity on the ion charge density at constant concentration and temperature of 20 °C

changes in viscosity, density, heat capacity, and thermal conductivity of aqueous-electrolyte solutions have yet to be adequately and comprehensively elucidated. Existing literature on this subject largely provides only qualitative explanations based on intermolecular interaction forces, the principles of chemical kinetics, hydrostatics, and hydraulics. In our view, these explanations fall short of thoroughly and scientifically addressing the underlying mechanisms.

In this regard, the objectives of this part of the study were focused on developing new scientific principles regarding the nature and behavior of viscosity changes in aqueous electrolyte solutions as a function of temperature and concentration and formulating a fundamentally new approach to explaining these phenomena [19]. The targeted research was based on contemporary concepts of the structure of water and aqueous systems, as well as the key principles and conclusions established to date regarding the structure and properties of aqueous-electrolyte mixtures.

The results of the graphical analysis of viscosity parameters for the studied aqueous-electrolyte mixtures of types 1-1, 1-2, 2-1, and 2-2, exemplified by the systems H_2O–LiCl, H_2O–NaCl, H_2O–KCl, H_2O–CsCl, H_2O–Li_2SO_4, H_2O–Na_2SO_4, H_2O–K_2SO_4, H_2O–$CoCl_2$, H_2O–$NiCl_2$, H_2O–$MgCl_2$, H_2O–$MnCl_2$, H_2O–$FeCl_2$, H_2O–$ZnCl_2$, H_2O–$MnSO_4$, H_2O–$ZnSO_4$, H_2O–$CdSO_4$, H_2O–$CuSO_4$, H_2O–LiI, H_2O–NaI, H_2O–KI, H_2O–CsI, H_2O–$Mg(NO_3)_2$, H_2O–$Pb(NO_3)_2$, H_2O–$Cd(NO_3)_2$, H_2O–$Sr(NO_3)_2$, H_2O–$Mn(NO_3)_2$, H_2O–$FeSO_4$, and H_2O–$MgSO_4$ at constant temperature of 20 °C are shown in Figures 6 – 8.

The examined aqueous-salt systems at contant temperature of 40 °C exhibit similar dependencies. Figures 7 and 8 illustrate the behavior of viscosity changes in various electrolyte solutions differing in concentration but maintaining consistent concentrations within each individual type. The group of experimental points labeled as "1" in Figures 7(a) and 8(a) corresponds to the radii and surface charge densities of ions listed in Table 1.

The data in Figures 6–8 show that: the viscosity of mixtures at constant temperature increases with increasing concentration and can be described by polynomial dependencies of the following types:

η LiCl $= 0.003C^2 + 0.096C + 0.989$
η NaCl $= 0.005C^2 + 0.039C + 1.006$
η KCl $= 0.001C^2 – 0.009C + 0.996$
η CsCl $= 0.002C^2 – 0.028C + 0.993$

The viscosity characteristics of solutions with other types of salts exhibit similar dependencies. For all the studied types of aqueous-electrolyte mixtures, it is observed that when the dissolved salts contain identical anions, at the same solution concentration, the smaller the cation radius, the higher the viscosity of the solution (Figures 6(a)–(d)). The viscosity characteristics of aqueous-electrolyte systems at constant temperature are influenced by the ion radius. It has been established that there is a specific mathematical relationship between the viscosity of solutions and the ion radius, described by the following types of dependencies:

For solutions of LiCl, NaCl, KCl, and CsCl
$\eta = 0.127r^3 – 0.341r^2 + 0.103r + 1.156$ (1%)
$\eta = 0.123r^3 – 0.185r^2 – 0.410r + 1.574$ (2%)
$\eta = 0.172r^3 – 0.195r^2 – 0.758r + 1.938$ (3%)
$\eta = 0.328r^3 – 0.620r^2 – 0.594r + 2.115$ (4%)
$\eta = 0.806r^3 – 2.206r^2 + 0.901r + 1.816$ (5%)
$\eta = 1.367r^3 – 4.042r^2 + 2.625r + 1.463$ (6%)
$\eta = 2.168r^3 – 6.791r^2 + 5.443r + 0.696$ (7%)
$\eta = 2.841r^3 – 8.961r^2 + 7.442r + 0.298$ (8%)

For solutions of Li_2SO_4, Na_2SO_4, and K_2SO_4
$\eta = -0.121r^2 + 0.066r + 1.186$ (0.5%)
$\eta = -0.441r^2 + 0.557r + 1.164$ (1%)
$\eta = -0.792r^2 + 1.044r + 1.197$ (1.5%)
$\eta = -0.616r^2 + 0.310r + 1.918$ (2%)

The viscosity characteristics of solutions with other types of salts exhibit similar dependencies. For all types of the studied aqueous-electrolyte mixtures, it is evident that as the ion radius (in this case, cation radius) increases, in all cases where the concentration of the aqueous-electrolyte mixtures is constant and the same anionic components are present, the viscosity of the solutions decreases (Figures 7(a)–(d)). As shown in Figures 8(a)–(d), the viscosity characteristics of solutions, in cases with identical anionic components and the same solution concentration, are also influenced by the charge density of the cations. It has been

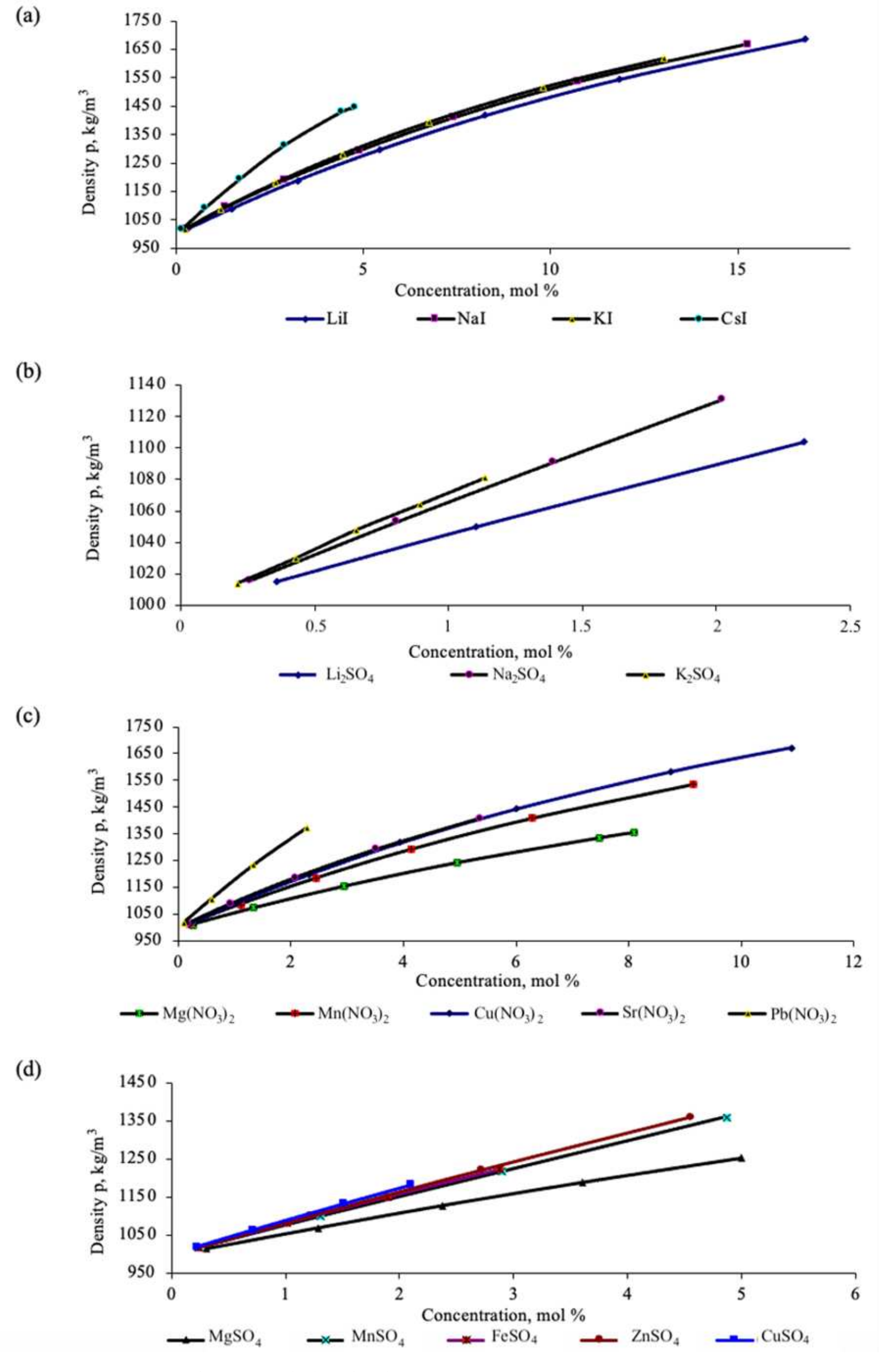

Figure 9. Dependence of solution density on concentration at constant temperature (20 °C)

established that there is a specific mathematical relationship between the viscosity of aqueous-electrolyte systems and the charge density of the cations, described by the following types of dependencies:

For solutions of LiCl, NaCl, KCl, and CsCl
$\eta = -35.02Pe^3 + 11.11Pe^2 - 0.154Pe + 0.95$ (1%)
$\eta = -50.12Pe^3 + 14.92Pe^2 + 0.543Pe + 0.892$ (2%)
$\eta = -93.45Pe^3 + 30.42Pe^2 - 0.240Pe + 0.884$ (3%)
$\eta = -140.4Pe^3 + 46.16Pe^2 - 0.855Pe + 0.874$ (4%)
$\eta = -249.1Pe^3 + 84.55Pe^2 - 3.815Pe + 0.938$ (5%)
$\eta = -397.9Pe^3 + 139.2Pe^2 - 8.718Pe + 1.073$ (6%)
$\eta = -567.2Pe^3 + 199.6Pe^2 - 13.88Pe + 1.200$ (7%)
$\eta = -767.2Pe^3 + 274.7Pe^2 - 21.04Pe + 1.407$ (8%)

For solutions of $MnSO_4$, $ZnSO_4$, $CdSO_4$, and $CuSO_4$
$\eta = 178.9Pe^2 - 110.8Pe + 22.27$ (0.5%)
$\eta = 102.9Pe^2 - 64.32Pe + 14.43$ (1.0%)
$\eta = 3.129Pe^2 - 1.346Pe + 3.929$ (1.5%)
$\eta = 10.89Pe^2 - 6.609Pe + 4.033$ (2.0%)
$\eta = -3.782Pe^2 + 3.334Pe + 1.788$ (2.5%)
$\eta = 0.841Pe^2 + 0.004Pe + 1.896$ (3.0%)
$\eta = -0.795Pe^2 + 0.921Pe + 1.420$ (3.5%)
$\eta = -4.918Pe^2 + 3.783Pe + 0.706$ (4.0%)
$\eta = -0.818Pe^2 + 0.769Pe + 1.031$ (4.5%)

The viscosity behavior of all studied systems exhibits a consistent pattern: viscosity increases with higher electrolyte concentration and with increasing charge density of the cations. At constant temperature, this rise in viscosity is attributed to the greater number of hydrated ions in the solution, which enhances molecular interactions and resistance to flow. Additionally, variations in the ionic radius and charge density significantly influence the viscosity. Smaller ionic radii and higher charge densities promote stronger coordination with water molecules, leading to the formation of larger hydrated complexes and a corresponding increase in solution viscosity (Figures 6–8). These findings confirm that aqueous-electrolyte mixtures behave as molecular-kinetic systems composed of hydrated ions (aqueous-electrolyte complexes) whose structural and dynamic properties are primarily governed by the concentration, ionic radius, and charge density of the dissolved species [20].

3.3. Density Characteristics of Aqueous-Electrolyte Mixtures

The objectives of this part of the study were to develop new scientific principles regarding the nature and behavior of density changes in aqueous electrolyte solutions as a function of temperature and concentration and to formulate a fundamentally new approach to explaining these phenomena. The results of the graphical analysis of the density characteristics of the studied binary and ternary aqueous-electrolyte mixtures of types 1-1, 1-2, 2-1, and 2-2, exemplified by the systems H_2O–LiCl, H_2O–NaCl, H_2O–KCl, H_2O–CsCl, H_2O–Li_2SO_4, H_2O–Na_2SO_4, H_2O–K_2SO_4, H_2O–$CoCl_2$, H_2O–$NiCl_2$, H_2O–$MgCl_2$, H_2O–$MnCl_2$, H_2O–$FeCl_2$, H_2O–$ZnCl_2$, H_2O–$MnSO_4$, H_2O–$ZnSO_4$, H_2O–$CdSO_4$, H_2O–$CuSO_4$, H_2O–LiI, H_2O–NaI, H_2O–KI, H_2O–CsI, H_2O–$Mg(NO_3)_2$, H_2O–$Pb(NO_3)_2$, H_2O–$Cd(NO_3)_2$, H_2O–$Sr(NO_3)_2$, H_2O–$Mn(NO_3)_2$, H_2O–$FeSO_4$, and H_2O–$MgSO_4$ at constant temperature (20 °C) are shown in Figures 9, 10, and 11. The studied aqueous-salt systems at constant temperature (40 °C) exhibit similar dependencies.

The data in Figures 9–11 show that the density of mixtures at constant temperature increases with increasing concentration and can be described by polynomial dependencies of the following types:

$\rho\ CsI = -7.493C^2 + 130.4C + 996.3$
$\rho\ KI = -1.752C^2 + 70.01C + 1003$
$\rho\ NaI = -1.437C^2 + 65.21C + 1006$
$\rho\ LiI = -1.139C^2 + 59.69C + 1002$

The density characteristics of solutions with other types of salts exhibit similar dependencies. For all studied types of aqueous-electrolyte mixtures, it is observed that when the dissolved salts contain identical anions, at the same solution concentration, the smaller the cation radius, the lower the solution density (Figures 9 (a)–(d)). The density characteristics of solutions at constant temperature are influenced by the ion radius. It has been established that there is a specific mathematical relationship between the density of aqueous-electrolyte systems and the ion radius, described by the following types of dependencies:

For solutions of CsI, KI, NaI, and LiI
$\rho = 925.1r^3 - 3008r^2 + 3249r + 109.0$ (4.5%)

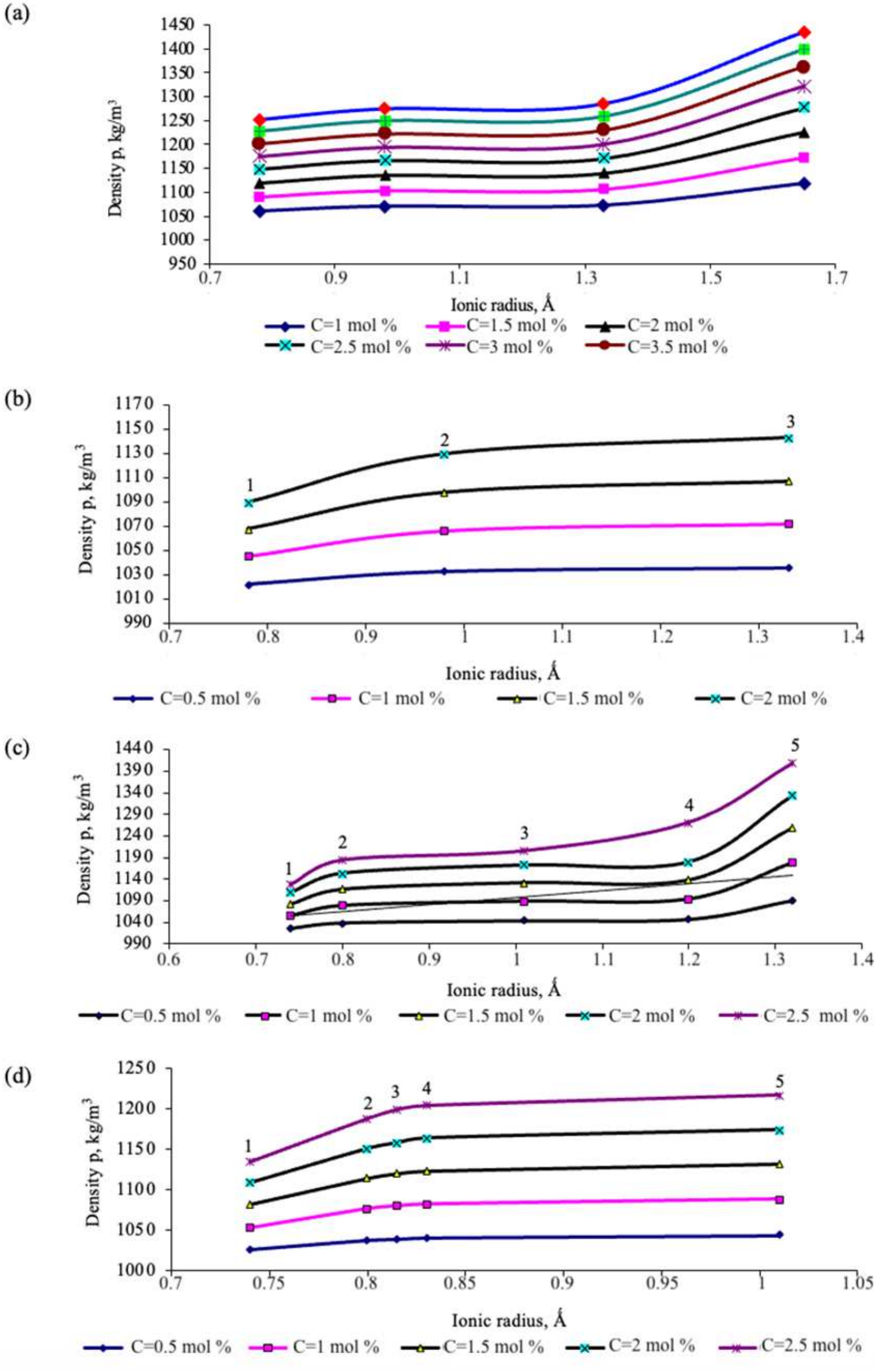

Figure 10. Dependence of solution density on the ion radius at constant concentration and temperature (20 °C)

$\rho = 889.0r^3 - 2899r^2 + 3139r + 120.6$ (4.0%)
$\rho = 829.6r^3 - 2704r^2 + 2923r + 173.3$ (3.5%)
$\rho = 779.8r^3 - 2549r^2 + 2762r + 201.5$ (3.0%)
$\rho = 714.4r^3 - 2350r^2 + 2559r + 242.5$ (2.5%)
$\rho = 584.7r^3 - 1931r^2 + 2115r + 366.8$ (2.0%)
$\rho = 461.3r^3 - 1528r^2 + 1678r + 491.8$ (1.5%)
$\rho = 329.3r^3 - 1098r^2 + 1214r + 624.6$ (1.0%)

For solutions of Li_2SO_4, Na_2SO_4, and K_2SO_4
$\rho = -293.5r^2 + 716.5r + 709.1$ (2.0%)
$\rho = -225.9r^2 + 547.7r + 778.2$ (1.5%)
$\rho = -156.7r^2 + 378.3r + 845.7$ (1.0%)
$\rho = -79.87r^2 + 193.0r + 920$ (0.5%)

The density characteristics of solutions with other types of salts exhibit similar dependencies. For all studied types of aqueous-electrolyte mixtures, it is observed that as the ion radius (in this case, cation radius) increases, in all cases where the concentration of the aqueous-electrolyte mixtures is constant and identical anionic components are present, the solution density increases (Figures 10 (a)–(d)). As shown in Figures 11 (a)–(d), the density characteristics of systems, in cases with identical anionic components and the same solution concentration, are also influenced by the charge density of the cations. It has been established that there is a specific mathematical relationship between the density of aqueous-electrolyte systems and the charge density of the cations, described by the following types of dependencies:

For solutions of CsI, KI, NaI, and LiI
$\rho = -38788Pe^3 + 38640Pe^2 - 12607Pe + 2533$ (2.5%)
$\rho = -36463Pe^3 + 35735Pe^2 - 11335Pe + 2314$ (2.0%)
$\rho = -28431Pe^3 + 27905Pe^2 - 8867Pe + 2027$ (1.5%)
$\rho = -19950Pe^3 + 19601Pe^2 - 6232Pe + 1718$ (1.0%)
$\rho = -10294Pe^3 + 10115Pe^2 - 3216Pe + 1369$ (0.5%)

For solutions of Li_2SO_4, Na_2SO_4, and K_2SO_4
$\rho = -2170Pe^2 + 222.3Pe + 1138$ (2.0%)
$\rho = -1762Pe^2 + 212.8Pe + 1100$ (1.5%)
$\rho = -1258Pe^2 + 163.9Pe + 1066$ (1.0%)
$\rho = -634.8Pe^2 + 80.66Pe + 1033$ (0.5%)

The density characteristics of solutions with other types of salts exhibit similar dependencies. For all studied types of aqueous-electrolyte mixtures, it is observed that as the charge density of cations increases, the solution density decreases. It is evident that the key factors influencing the changes in the density characteristics of aqueous-salt systems are the concentration of dissolved substances, the radius, and the charge of the ionic components [21]. In all cases, at constant temperature, the increase in solution density should be understood as a result of the quantitative increase in hydrated ions within the solution volume as concentration rises. The behavior of density changes in the studied solutions at the same solution concentration, depending on the radius and charge density of the ions, indicates that the smaller the radius and the higher the charge density of the ion, the greater the degree of coordination of the ions with water molecules. As a result, the geometric dimensions of the hydrated ions increase, leading to the growth of free voids in the solution, which in turn decreases the solution density (Figures 9(a)–(d)).

The observations in Figures 10(a)–(d) and 11(a)–(d), obtained under conditions where several solutions differ in concentration, but each individual solution maintains a constant concentration, demonstrate that the geometric dimensions of hydrated ions also change depending on their radius and charge density [22]. This is reflected in the corresponding patterns of density changes. Based on the aforementioned results and the analysis of the behavior of density changes in the studied aqueous-electrolyte mixtures, it can also be concluded that the aqueous-electrolyte medium represents a molecular-kinetic system where the primary medium-forming role is assigned to hydrated ions, also known as aqueous-electrolyte complexes with a specific and finite degree of coordination. The parameters and characteristics of hydrated ions are significantly influenced by the concentration, radius, and charge density of the ionic components in the solution. These factors, in turn, have a consequential impact on the behavior of all physicochemical properties of the solution, including its density.

4. CONCLUSIONS

The solubility of electrolytes in water is primarily influenced by the free component of bulk water. An increase in its quantity in the aqueous

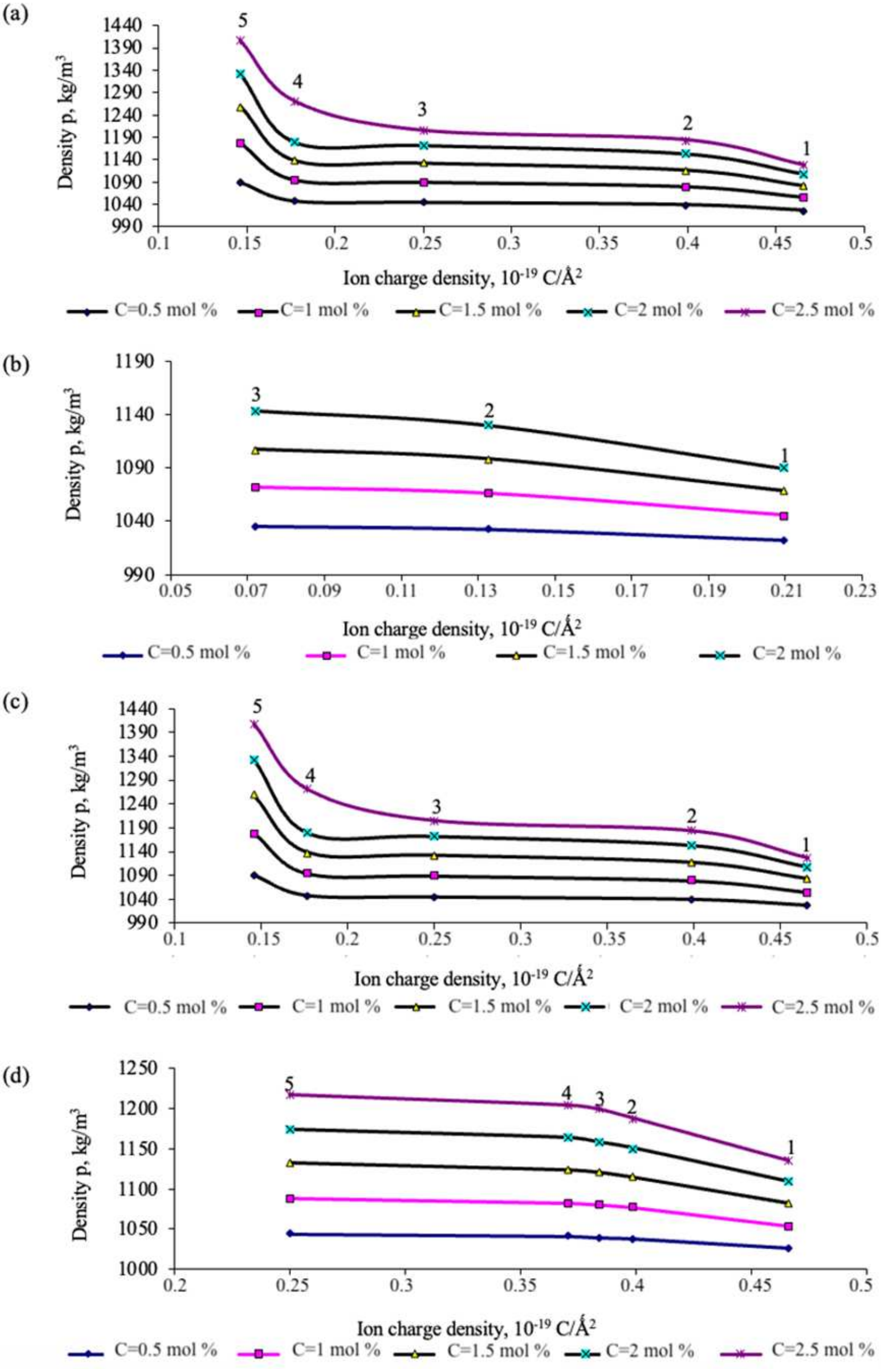

Figure 11. Dependence of solution density on the ion charge density at constant concentration and temperature (20 °C)

medium with rising temperature promotes higher solubility of electrolytes. The higher the concentration of dissolved electrolytes in water, the greater the number of hydrated ions in the solution. Consequently, as the concentration of electrolyte solutions increases, their viscosity and density also increase. Under constant concentration and temperature conditions, the viscosity and density of electrolyte solutions are determined by the radius and charge density of the ionic components in the solution. For all types of aqueous-electrolyte mixtures at constant concentration and temperature, an increase in the radius of the ionic components and a corresponding decrease in their charge density lead to a reduction in viscosity and an increase in solution density. Conversely, a decrease in the radius of hydrated ions and a corresponding increase in their charge density result in the opposite effect—an increase in viscosity and a decrease in solution density.

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Conflicts of Interest

The authors declare no conflict of interest.

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