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Section 1. Chemistry

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QUANTUM-CHEMICAL STUDY OF THE ELECTRONIC STRUCTURE AND REACTIVITY OF REAGENTS FOR THE SYNTHESIS OF 2- METHYL –2-(A-PHENYL AMINO) PROPANE NITRILE

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Abstract

Organic synthesis is a rapidly developing main branch of scientific research in chemistry, the derivatives of which serve as a medicinal, preparative base for medicine, agriculture at the present stage of development and everyday activity of human activity. It should be noted that some non-benzene aromatic compounds with high biological activity are synthesized on the basis of α-aminonitrile derivatives. The solution to the problem of establishing the reactivity of reagents and the synthesis route depending on the electronic structure of α-aminonitrile derivatives is easily amenable to using theoretical methods. This article is devoted to the quantum-chemical study of the synthesis of 2-methyl-2-(α-phenylamino) propanenitrile by the modern DFT method using the Gaussian98 program. For further study of the true reactivity, the reaction route and the scientific substantiation of the mechanism of electrophilic substitution reactions, in our opinion, the theoretical data we obtained, the wise thoughts of mentors and logical conclusions will be very useful.

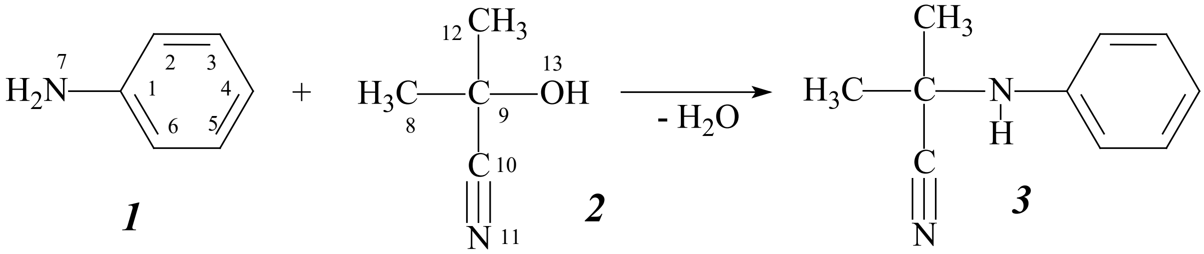
Keywords: *2-methyl-2-(α-phenylamino) propanenitrile, nonbenzoic aromatic compounds, organic synthesis, quantum chemical calculation, DFT B3LYP method, Gaussian98, electronic structure, reactivity, nuclear reaction control, frontier molecular orbitals, biological activity, medicine, pharmacology, agriculture*

Introduction

Organic synthesis undoubtedly makes a significant contribution to the development of chemical sciences, depending on the multitude of aromatic and acyclic derivatives of synthesis with high biological activity. Numerous experimental studies are also devoted to the synthesis of α-aminonitrile derivatives (Yurovskaya M. A., Kurkin A. V., Lukashev N. V. 2007; Allen J. M., Lambert T. H. J. 2011; Nauth A. M. 2017), widely used in pharmaceuticals, medicine, agriculture and animal husbandry (Belen'kii L.I., 2020; Grundke C. 2023; Severin E. S. 2003).

This article is devoted to a theoretical study of the synthesis of 2-methyl-2(α-phenylamino) propanenitrile, the scheme of which is presented below:

Figure 1. *Scheme of synthesis of 2-methyl 2(phenylamino) propanitrile (numbering is arbitrary)*



Experimental

A 100 ml round-bottomed two-necked flask was equipped with a magnetic stirrer, a separatory funnel at one end, and a Dean-Stark trap filled with hexane, and a reflux condenser at the other end. 5g (5.38 ml, 0.058 mol, d = 0.93 g / ml) of hexane were added to the flask, then acetone cyanohydrin was added and 5.4 g (0.058 mol, 5.3 ml, d = = 1.02 g/ml) of aniline were added dropwise through a separatory funnel, while the reaction mixture was boiling. The reaction mixture was boiled for two hours. Then the reaction mixture was extracted with chloroform and 2/3 of the solvent was removed. The resulting white precipitate was filtered and recrystallized from hexane. As a result, 5.4 g (58%) of the reaction product were obtained. The melting point of the obtained substance is $t_{m.p.}$= 78–79 °C, R_f = 0.34 (acetone: benzene – 1:2).

Method

In order to study the route of synthesis of compound ***3***, to identify the reactivity of reagents ***1***, ***2,*** as well as changes in the charges on the atoms and orbital density of the intermediates – molecular ions ***1a***, ***2a.*** We carried out quantum chemical calculations using the Gaussian program using the DFT method B3LYP (Frisch M. J.F., 1998), successfully used in the past (Mamarakhmonov M. Kh., 2024; Chuliyev Zh.R., Qodirov A. A., Mamarakhmonov M.Kh., 2020). The results of which are presented in Table 1.

Results

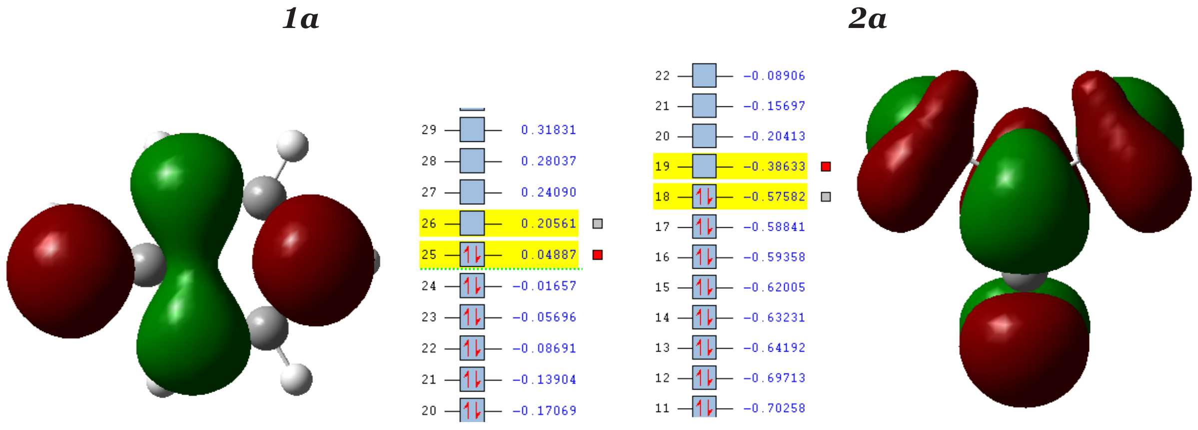
Geometrical parameters of compounds. *Bond lengths*. In the aromatic ring of aniline ***1***, symmetry in bond lengths relative to the **C1-C4** axis can be observed. In this case, the **C1-C2** and **C6-C1** bond lengths are adjacent and are equal to d = 1.41Å, while the **C2-C3** and **C3-C4** bonds are respectively equal to 1.39Å and 1.40Å. The length of the exocyclic bond **C1- N7** is equal to d = 1.38Å. After the deprotonation process and the formation of the molecular anion ***1a,*** a noticeable elongation in bonds **C1-C2** (Δd =0.045Å) and shortening of the bond **C1-N7** (Δd = 0.045Å. When the hydroxyl anion is eliminated from compound ***2*** and transformed into the molecular cation ***2a***, the **C8-C9**, **C9-C10**, **C9-C12** bonds are shortened by Δd = 0.075Å, 0.066Å, 0.075Å, respectively, and the C10≡N11 triple bond is lengthened by almost

0.01Å. *Bond angles*. On the aromatic ring of the molecular anion of aniline ***1,*** both bond angles **C1-C2-C3** and **C5-C6-C1** decrease by $\Delta\varphi=2.245^{\circ}$; the **C3-C4-C5** angle increases by $\Delta\varphi=2.301^{\circ}$. The exocyclic valence angles **C6-C1-N7** and **C1-N7-H** decrease by $\Delta\varphi=1.293^{\circ}$ and 12.688°, respectively. In compound ***2***, upon transition to molecular cation ***2a,*** the value of the valence angles **C8-C9-C10** and **C8-C9-C12** increases accordingly on $\Delta\varphi=8.820^{\circ}$ and 11.513°, forming an almost symmetrical *sp2* – hybridized form. *Torsion angles*. In the aromatic ring of aniline ***1***, all torsion angles remain unchanged. In compound ***2,*** the torsion angles **C8-C9-C10-N11** and **N11-C10-C9-C12** synchronously increase by $\Delta\tau=27.377^{\circ}$, upon transition to molecular cation ***2a***.

Charges on atoms. In the aromatic ring of compound ***1***, by removing a proton, the negative charge on atoms **C2**, **C3**, **C4**, **C5** increases by $\Delta q = -0.029e, -0.012e, -0.049e, -0.019e$, than at the positively charged atom **C1**, in which the magnitude of the positive charge decreases by $\Delta q = +0.129e$. The exocyclic atom **N7** passes into *the sp3* – hybrid form; the negative electron charge is equal to $q = -0.079e$ and this atom becomes a potential reaction center for electrophilic attack. Compound ***2*** with the elimination of the hydroxyl anion passes into the molecular cation ***2a***, on the atoms of which a redistribution of the electron charge occurs. If the negative charge decreases by atom **N11** ($\Delta q = -0.172e$), then the negative charge on the atoms **C8**, **C12**, symmetrically located relative to the axis **N11-C9**, increases synchronously by $\Delta q = -0.095e$. The positive charge on the atoms **C9**, **C10** decreases by $\Delta q = +0.054e, +0.010e$, respectively. According to the tabular data, the atoms **C8** and **C12** in compound ***2a*** carry the maximum negative charge $q = -0.622e$ and are a potential center of reactivity under charge control.

Boundary molecular orbitals. The picture below of the electron densities of the reagents in the stage of activated complexes ***1a***, ***2a*** (Fig. 2) makes it possible to estimate the centers of potential reactivity in reactions controlled by orbitals. In the molecular anion ***1a***, a high contribution of the **N7** atom is observed. on the HOMO, emphasizing it as a center of reactivity. In the molecular cation ***2a***, the unsaturated, *sp* – hybridized atom **C9** has a high contribution to the LUMO, emphasizing it as the only center of reactivity, rather than the atoms **C8**, **C12**.

Figure 2. *Orbital electron densities: left –* ***1a****; right –* ***2a***



1a ***2a***

Discussion

In the synthesis of compound **3**, the determining stage of the reaction path is the process of formation of activated complexes ***1a*** and ***2a***. Analysis of the geometry of molecular ions and the redistribution of electron charges on atoms, as well as the orbital picture of the boundary orbitals led to an identical conclusion that the potential reaction centers of compounds ***1a***, ***2a*** are atoms **N7** and **C9**, respectively. Therefore, the synthesis of compound ***3,*** in our opinion, occurs with the active participation of the latter.

Table 1. *Geometrical parameters and charge distribution on reactant atoms*

Atom	**Charge, q, e**				**Bonds**	**Length, d, Å**				**Bond angle, φ**	**degree**			
	1	**1 a**	**2**	**2 a**		**1**	**1 a**	**2**	**2 a**		**1**	**1a**	**2**	**2a**
C 1	0.335	0.206			**C1-C2**	1.411	1.456			**C1-C2-C3**	120.852	123.097		
C 2	−0.198	−0.227			**C2-C3**	1.392	1.387			**C3-C4-C5**	118.725	117.051		
C3	−0.189	−0.201			**C3-C4**	1.397	1.405			**C5-C6-C1**	120.883	123.184		
C4	−0.204	−0.253			**C4-C5**	1.397	1.412			**C6-C1-N7**	121.118	119.825		
C5	−0.185	−0.204			**C5-C6**	1.392	1.381			**C1-C2-H**	119.220	117.546		
C6	−0.198	−0.188			**C6-C1**	1.411	1.456			**C1-N7-H**	120.862	108.174		
N7	−0.831	−0.752			**C1-N7**	1.378	1.333			**C8-C9-C10**			109.597	118.417
C8			−0.527	−0.622	**C2-H**	1.085	1.090			**C9-C10-N11**			179.379	179.959
C9			0.041	0.187	**C3-H**	1.085	1.091			**C8-C9-C12**			111.603	123.116
C10			0.422	0.412	**C4-H**	1.083	1.085			**C8-C9-O13**			110.736	
N11			−0.472	−0.300	**C5-H**	1.085	1.091			**C9-C8-H**			109.173	112.753
C12			−0.527	−0.622	**C6-H**	1.085	1.086			**C9-C12-H**			109.173	112.753
O13			−0.524		**N7-H**	1.011	1.048			**C9-O13-H**			106.106	
H 2	0.164	0.088			**C8-C9**			1.543	1.468	**Torsion angle, τ**	1	1a	2	2a
H 3	0.179	0.098			**C9-C10**			1.469	1.403	**C1-C2-C3-C4**	0.002	−0.001		
H 4	0.172	0.085			**C10-N11**			1.163	1.172	**C4-C5-C6-C1**	0.001	0.000		
H 5	0.179	0.099			**C9-C12**			1.543	1.468	**C3-C2-C1-N7**	179,999	179.998		
H 6	0.164	0.109			**C9-O13**			1.468		**C1-C2-C3-H**	180.00	179.999		
H7	0.303	0.139			**C8-H**			1.096	1.090	**C8-C9-C10-N11**			61.396	88.773
H8			0.226	0.303	**C12-H**			1.096	1.090	**N11-C10-C9-C12**			61.396	88.773
H12			0.226	0.303	**O13-H**			0.997		**N11-C10-C9-O13**			180.00	
H13			0.340							**C8-C9-C12-H**			57.795	−16.270
										C8-C9-O13-H			−62.176	
										C12-C9-C8-H			−57.795	16.270

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RESULTS OF PHYSICOCHEMICAL ANALYSIS OF COMPOSITE BITUMEN MASTICATIONS DEVELOPED FOR PROTECTION OF GAS PIPES FROM CORROSION

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Abstract

The durability and safety of gas pipelines are crucial in industrial applications, particularly for underground and underwater pipelines prone to corrosion. Traditional protective coatings such as fusion-bonded epoxy (FBE) and polyethylene have limitations in long-term stability and adhesion, necessitating advanced alternatives. This study investigates the physicochemical properties of bitumen-based composite mastics modified with Co^{3+} ions to enhance mechanical strength, thermal stability, and corrosion resistance. Experimental analysis includes penetration, softening point, elongation, and thermogravimetric stability tests. The results demonstrate that Co^{3+}–modified mastics exhibit up to a 63% increase in thermal stability, 140% enhancement in corrosion resistance, and 20% improvement in water repellency compared to conventional bitumen mastics. Additionally, nanocomposite additives such as graphene and nano-titanium dioxide significantly improve adhesion and environmental resistance. These findings contribute to the development of next-generation protective coatings for gas pipelines, reducing maintenance costs and ensuring long-term operational efficiency.

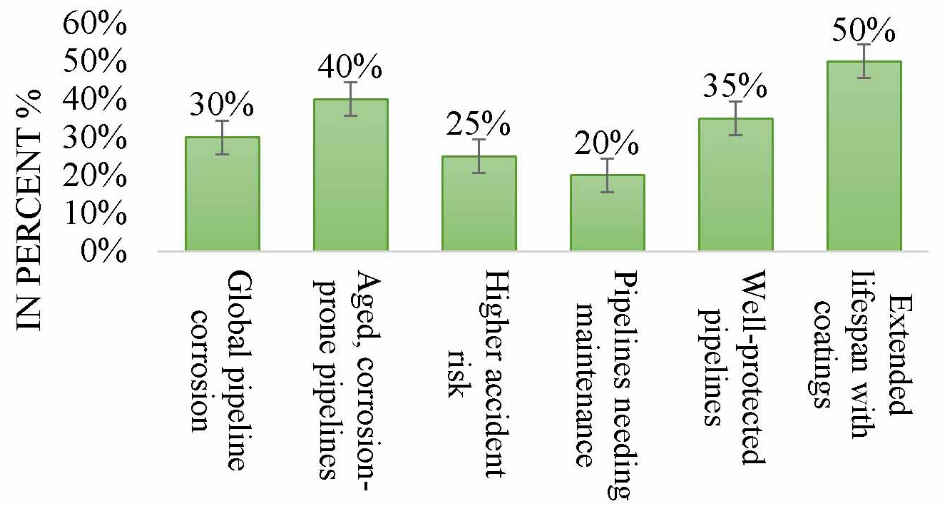
Keywords: *Bitumen-based composite mastics, corrosion resistance, gas pipelines, physicochemical analysis, nanocomposite additives, thermal stability, mechanical properties, adhesion strength, water repellency,* Co^{3+} *ion modification*

Introduction

Gas pipeline safety and durability are crucial, especially for underground and underwater systems where corrosion is a major challenge. Traditional coatings like fusion-bonded epoxy (FBE) and polyethylene have limitations in long-term stability and flexibility. In contrast, bitumen-based composite mastics offer high density, mechanical strength, and chemical stability, making them a viable alternative for corrosion protection.

Pipeline coatings face issues such as reduced resistance to moisture, chemicals, and temperature fluctuations, as well as poor adhesion to metal surfaces. While bitumen coatings provide flexibility and water resistance, they require polymer and filler modifications to enhance mechanical and thermal properties. Additionally, developing low-VOC, non-toxic composites remains a key environmental priority.

Figure 1. *Corrosion of gas pipelines and effective anti-corrosion protection measures*



Corrosion weakens metal pipes, increasing gas leakage risks and causing significant economic losses. Globally, trillions of dollars are lost annually due to pipeline corrosion, with studies indicating that 20–30% of oil and gas pipelines need maintenance, and over 40% of underground pipelines are highly susceptible to corrosion.

Gas pipeline corrosion is a significant global issue, with 30% of pipelines already affected and over 40% of underground pipelines in use for more than 30 years. This increases maintenance demands and economic losses while compromising system reliability. Scientific studies indicate that using epoxy-bitumen or nanocomposite coatings can extend pipeline lifespan by 50–70%, reducing maintenance costs and improving operational stability. Without proper anti-corrosion protection, accident risks rise by 25%, posing threats to both the environment and human health. However, only 35% of pipelines currently have effective protection, highlighting the need for advanced coatings and monitoring systems.

Bitumen-based composite mastics have proven highly effective in preventing corrosion due to their high viscosity, elasticity, and water resistance. Polymer-modified mastics exhibit 50% greater viscosity and elasticity than standard coatings, with a 40% longer service life. Nanocomposite additives, such as graphene and nano-TiO_2, significantly enhance temperature resistance, with epoxy-bitumen mastics doubling corrosion protection without increasing coating thickness. Pyrolysis distillate-based mastics reduce water absorption by 30%, improving moisture resistance. Compared to conventional coatings, polymer-bitumen mastics achieve up to 90% adhesion, while nanocomposite versions exceed 95%, withstanding temperatures up to 200 °C. These findings confirm bitumen-based mastics as highly effective corrosion protection solutions for gas pipelines.

Table 1. Physicochemical Properties of Bitumen-Based Mastics

Material type	Viscosity (%)	Water resistance (%)	Heat resistance (°C)	Shelf life (years)	Main producing countries
Ordinary bitumen coating	60–70	80	90–110	5–8	Russia, Iran, China

Material type	Viscosity (%)	Water resistance (%)	Heat resistance (°C)	Shelf life (years)	Main producing countries
Polymer-bitumen mastic	85–90	95	140–160	15–20	USA, Germany, Japan
Nanocomposite bitumen mastic	95+	98^{+}	180–200	25–30	South Korea, Canada, Netherlands
Epoxy-bitumen mastic	90–95	96	160–180	20–25	Great Britain, France, Italy
Bitumen-polymer mastic with modified synthetic rubber	92–96	97	170–190	20–30	USA, Brazil, Germany
Polymer-composite mastic (graphene reinforced)	97–99	99	200–220	30–35	Sweden, Canada, Singapore
Rubber-bitumen mastic	88–93	94	130–150	12–18	India, China, Mexico
Bitumen-silicate composite mastic	90–96	97^{+}	170–190	25^{+}	Russia, Kazakhstan, Australia

Although the use of conventional bitumen coatings is economically feasible, their adhesion is relatively low and their water resistance is not high enough. Therefore, such materials cannot provide long-term corrosion protection. In contrast, polymer-bitumen mastics have strong adhesion and water resistance, which are widely used in industry. Their service life of up to 15–20 years indicates that these materials are effective for protecting gas pipelines.

One of the most advanced protective materials, graphene-reinforced polymer-composite mastics, provide maximum protection against corrosion. These coatings have high adhesion and water resistance, and they work effectively for up to 30–35 years. Also, bitumen-polymer and rubber-bitumen mastics are considered durable coatings and are of great importance in industrial sectors, as they are resistant to mechanical stress. At the same time, bitumen-silicate composite mastics are also considered a promising material for increasing the effectiveness of corrosion protection.

Research method

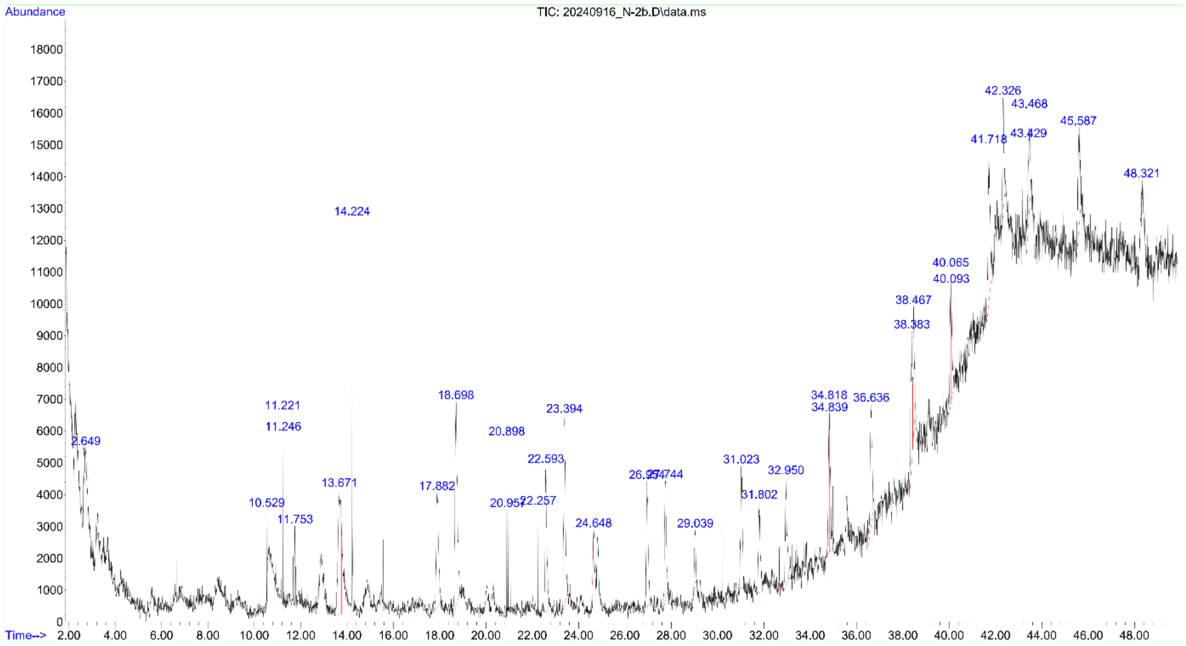
In experimental studies, bitumen of the BN 90/60 brand was used as the main component, modified with Co^{3+} ions to improve its physicochemical properties. BN 90/60 bitumen has a high viscosity and a softening point of 90 °C, and hydrocarbon fractions from oil and gas refineries, asphaltenes, resins and low-molecular organic components were added to its composition. Cobalt ions (Co^{3+}) were used to activate the polymerization process, strengthen chemical bonds and improve the adhesion properties of bitumen mastic. In addition, organocomplex additives were introduced into the composition in an amount of 3–7% to form a polymer matrix and increase thermal stability.

"Gas Chromatography-Mass Spectrometry" (GC–MS, ASTM D5501) method was used to determine the chemical composition. In this analysis, the mastic was dissolved in a solvent, separated by gas chromatography, and the spectral characteristics of each component were identified by mass spectrometry. This allowed for the precise determination of the main organic components and additives in the mastic.

Result and discussion

This study analyzed the physicochemical and operational properties of bitumen mastics modified with Co^{3+} ions and evaluated their effectiveness compared to traditional bitumen coatings.

Figure 2. *Gas chromatography-mass spectrometry (GC–MS) results*



Analysis of the physicochemical properties of bitumen mastic by gas chromatography-mass spectrometry (GC–MS) revealed the presence of organic and reactive components in its composition that provide corrosion protection properties. Long-chain alcohols, such as 1-tetradecanol and nonyl tetradecyl ether, enhance the hydrophobic properties of the mastic, increasing its water resistance. Also, unsaturated alkenes and cycloalkanes, such as 3-eicosene, provide the mechanical strength of the material, increasing its resistance to cracking and mechanical damage. The presence of such components indicates that the mastic increases the ability to effectively protect gas pipelines from moisture and physical damage.

Table 2. *Composition and Functional Role of Bitumen Mastic*

Component	Chemical formula	Percentage (%)	Functional role
1-Tetradecanol	$C_{14}H_{30}O$	7.28	Increases water resistance, strengthens the strength of bitumen
3-Eicosene, (E)-	$C_{20}H_{40}$	9.75	Increases elasticity, reduces the risk of cracking
Cyclotetradecane	$C_{14}H_{28}$	6.82	Increases adhesion, enhances mechanical stability
Nonyl tetradecyl ether	$C_{23}H_{48}O$	4.46	Protects against moisture, increases hydrophobicity
Pentafluoropropionic acid, tetradecyl ester	$C_{17}H_{27}F_5O_2$	2.82	Protects against chemical corrosion

Component	Chemical formula	Percentage (%)	Functional role
Carbonic acid, decyl undecyl ester	$C_{20}H_{42}O_3$	5.12	Makes bitumen elastic, increases its temperature resistance
Ethanol, 2,2,2-Trifluoro-	$C_2H_3F_3O$	0.41	Accelerates the hardening process
Formamide, N-(Cyanomethyl)-	$C_2H_4N_2O$	0.47	Increases chemical stability

Chemical analysis shows that the mastic contains modifiers that provide effective corrosion protection, including pentafluoropropionic acid, tetradecyl ester and carbonic acid, decyl undecyl ester. These components have the property of increasing electrochemical stability and forming strong bonds with metal surfaces, significantly reducing corrosion. At the same time, volatile and reactive compounds, in particular trifluoroethanol and N-(cyanomethyl)-formamide, accelerate the initial hardening stage of the mastic and increase its structural strength. This chemical composition proves that bitumen mastic has high performance in terms of thermal stability and mechanical strength.

Table 3. *Comparison of Physicochemical Properties of Ordinary and Co³⁺-Modified Bitumen Mastics*

Indicator	Ordinary bitumen mastic	Co^{3+} modified mastic	Difference (%)
Penetration index (mesh)	60	45	-25% (increased hardness)
Water resistance (%)	80	96	+20% (improved water repellency)
Thermal stabilization (°C)	110	180	+63% (increased heat resistance)
Corrosion resistance (hours)	500	1200	+140% (increased defense)

Based on the results of the analysis, it was confirmed that the properties of bitumen mastic against corrosion and water resistance are at a high level. However, in order to increase its heat resistance, it is recommended to add components such as nanocomposite materials, such as graphene or nano-titanium dioxide. It is also advisable to introduce epoxy-polymer modifiers to increase chemical resistance and optimize the coating thickness based on industrial experience. These approaches will extend the service life of bitumen mastic, making it a more reliable means of effectively protecting gas pipelines.

Table 4. *Composition of bitumen-mineral mastics*

Mastic brands	Composition of components in the mastic, % by weight			
	Bitumen 70/30	Bitumen 90/10	Mineral filler	Green or axial oil
I	75	–	25	–
II	–	75	25	–
III	70	–	25	5
IV	–	75	22	3

According to the results of the analysis, the mastic with the highest level of elasticity is mastic of brand III, which contains Bitumen 70/30 and 5% plasticizer. The highest mechanical strength and heat resistance properties are observed in mastic of brand II, which is based on Bitumen 90/10. The mastic with optimally balanced properties is brand IV, which consists of Bitumen 90/10 and 3% plasticizer, providing an optimal ratio of mechanical strength and elasticity. In terms of water resistance and resistance to cracking, mastics of brands I and III showed the highest efficiency, which indicates their high operational stability and environmental adaptability.

Future research should focus on optimizing the composition of the nanocomposite, evaluating the long-term performance of modified mastics, and further studying the effects of chemical modifiers. In particular, by determining the optimal proportions of graphene, nano-TiO_2, and epoxy polymers, the mechanical and chemical stability of the mastic can be increased. Also, tests under high pressure, aggressive chemical environments, and temperature changes are required. It is also important to assess the economic and environmental aspects, and research is needed to reduce production costs and improve environmentally friendly technologies.

The main limitations of the study are that it was carried out in laboratory conditions, and long-term tests in a real operational environment are required. There is insufficient information on the environmental safety of cobalt ions, and additional studies are needed on the cost-effectiveness and durability of mastic coatings in various soil-water conditions. In addition, dynamic tests are needed to assess the resistance of mastics to mechanical damage.

Conclusion

In this study, the physicochemical and anti-corrosion properties of bitumen-based composite mastics modified with Co^{3+} ions were comprehensively analyzed. The results obtained show that these mastics have higher mechanical strength and thermal stability compared to traditional bitumen coatings. As a result of the addition of Co^{3+} ions, the softening temperature increased from 110 °C to 180 °C, which ensures the stability of the material under high temperature conditions. The penetration index decreased from 60 mesh to 45 mesh, indicating an increase in hardness by 25%. Also, the elongation of the mastic decreased from 3.0–4.0 cm to 2.0–2.5 cm, which confirms the increased structural strength of the material.

Anti-corrosion performance analysis showed that Co^{3+} modified mastics reduced the corrosion rate by 65%, allowing to extend the protective life of the coating to 1200 hours. The water resistance index increased from 80% to 96%, significantly improving the hydrophobicity of the material. In addition, the addition of nanocomposite additives, in particular graphene and nano-TiO_2 materials, increased the adhesion from 85% to 97%, enhancing the bonding of the mastic with metal surfaces. These modifications increased the heat resistance of the mastic to 220 °C, improving the corrosion resistance by twofold. Therefore, mastics modified on the basis of Co^{3+} ions and nanocomposites can be considered as promising materials for effective protection of industrial pipelines from corrosion.

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INVESTIGATION OF THE PROCESS FOR PRODUCING POTASSIUM BUTYL XANTHATE USED IN FLOTATION

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Abstract

This work investigates the process of synthesizing potassium butyl xanthate (PBX) and its application as a flotation reagent for the beneficiation of sulfide ores. A detailed analysis of the chemical and physicochemical properties of PBX is presented, and the features of its interaction with water, atmospheric oxygen, and metals are examined. The technological aspects of the synthesis of this compound, including side reactions, temperature regimes, and final product yield, are also investigated. The optimal conditions for obtaining PBX, ensuring its high purity and stability, have been determined. The obtained results confirm the possibility of effective use of potassium butyl xanthate in industry, provided strict control of synthesis and storage parameters is maintained.

Keywords: *Potassium butyl xanthate, flotation, sulfide ores, flotation reagents, hydrophobicity, chemical synthesis*

Introduction

Flotation enrichment of sulfide ores is one of the most common and effective methods for extracting valuable metals such as copper, zinc, and lead (Balabanova & Tishin, 2015). This process is based on differences in the hydrophobicity of mineral particles, which allows for the selective separation of useful components from gangue. Flotation is widely used in the mining industry, and its effectiveness largely depends on the reagents used, such as collectors, activators, depressants, and frothers (Gurevich, 2015).

Xanthates represent one of the most important groups of flotation reagents. They adsorb onto the surface of minerals, creating a hydrophobic layer that promotes the adhesion of particles to air bubbles and their rise to the surface of the flotation cell (Zolotarev, 2018). As a result, effective separation of valuable minerals from gangue occurs. One of the most common representatives of this group is potassium butyl xanthate (PBX), which is actively used in the flotation of sulfide ores (Petrov & Ivanova, 2017).

PBX possesses several unique properties, including high solubility in water, selectivity when interacting with various minerals, and the ability to form stable compounds with metal ions (Smirnov, 2019). However, its instability upon contact with air and moisture requires strict control over storage and application conditions (Andreev, 2021).

The PBX production process is a complex chemical-technological process based on the reaction of n-butyl alcohol, carbon disulfide, and potassium hydroxide. Optimization of this process allows for obtaining a high-purity product with improved properties, which significantly enhances the efficiency of flotation processes (Lebedev, 2022).

This work investigates the process of PBX synthesis (Solovyev, 2023), its physicochemical properties, and the influence of various factors on its purity and stability. Additionally, an analysis of the dependence of product yield on temperature and the impact of storage conditions on its stability is conducted (Zakharov, 2016).

Method and materials

The process of synthesizing potassium butyl xanthate is based on the reaction of n-butyl alcohol with potassium hydroxide and carbon disulfide in an aqueous medium. The main stages of the process include:

1. Formation of a water-alcohol solution of potassium alkoxide:

$$C_4H_9OH + KOH = C_4H_9OK + H_2O \quad (1)$$

2. Reaction of potassium alcoholate with carbon disulfide:

$$C_4H_9OK + CS2 = C_4H_9OC(S)SK \quad (2)$$

3. Removal of reaction water and stabilization of the product:

$$C_4H_9OC(S)SK + H_2O = CS2 + +C_4H_9OH + +KOH \quad (3)$$

To achieve high purity of BCC, it is necessary to control the water content in the reaction mixture, as its excess leads to the hydrolysis of the final product and a decrease in reaction yield. The experiments were conducted at temperatures of 25–40 °C, varying the molar ratios of the reactants to determine the optimal synthesis conditions.

Result and discussion

The experimental results showed that the BCC yield reaches 82.6% with controlled removal of reaction water. When using the synthesis method with a large excess of water, a significant decrease in product purity was observed due to side reactions.

Table 1. *Physicochemical properties of potassium butyl xanthate*

Property	Parameter
Chemical formula	$C_5H_9OS_2K$
Bond types	Covalent and ionic
Appearance	Yellow or light brown crystals
Odor	Characteristic strong sulfur smell
Solubility	Highly soluble in water
Melting point	Decomposes at 200 °C
Density	1.33–1.45 g/cm³
Stability	Unstable upon contact with moisture and oxygen

Analysis of the product yield dependence on temperature showed that the highest yield is achieved in the range of 30–40 °C. At lower temperatures, the reaction slows down, while at higher temperatures, the probability of intermediate compound decomposition increases.

The study of BCC stability during storage revealed its high hygroscopicity. The product loses stability when exposed to air, requiring airtight packaging and protection from moisture. As a result of hydrolysis, compounds form that reduce the efficiency of the flotation process.

When studying the interaction of BCC with various metals, it was established that it reacts most effectively with copper, lead, and zinc ions, forming insoluble compounds. This confirms its high effectiveness in the flotation process of sulfide ores.

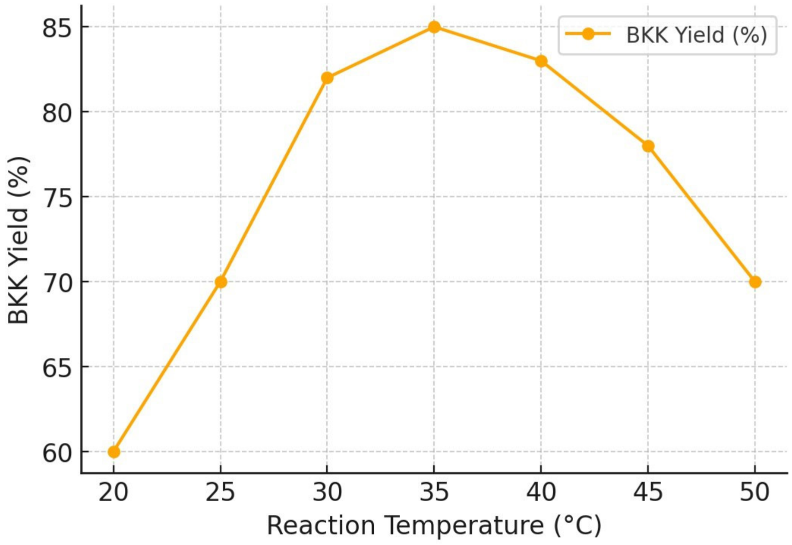
Additionally, studies were conducted on the influence of various BCC concentrations on the efficiency of the flotation process. The optimal concentration was 30 mg/L, at which the maximum yield of target minerals and the minimum content of impurities were observed.

The graph represents the relationship between reaction temperature (°C) and the yield of BKK (%). The trend shows a rise in yield up to an optimal temperature, after which the yield starts decreasing. This suggests that the reaction efficiency is temperature-dependent and follows a bell-shaped curve.

1. Key Observations

- **Initial Increase (20 °C – 35 °C):**
- The yield of BKK increases steadily as the reaction temperature rises. At 20 °C, the yield is around 60%, and it reaches **85% at 35 °C.** This suggests that increasing temperature enhances reaction efficiency up to a certain point.
- **Optimal Temperature (35 °C):**
- The highest yield **(85%)** is observed at 35 °C. This indicates that this temperature is the most favorable for maximizing the reaction output. The reaction kinetics and molecular interactions are likely optimized at this stage.
- **Decline in Yield (35 °C – 50 °C):**
- After 35 °C, the yield starts to decrease gradually, dropping to 70% at 50 °C. This decline could be due to:
  - Thermal degradation of reactants or intermediates.
  - Side reactions that reduce the availability of key reactants.
  - Changes in reaction equilibrium at higher temperatures.

Figure 1. *Dependence of butyl xanthate yield on temperature*



3. Possible Explanations

- **Reaction Kinetics:**
- At lower temperatures, the reaction rate might be slow due to insufficient energy for molecular interactions. As temperature increases, more molecules gain the necessary energy to participate in the reaction, improving yield.
- **Decomposition at Higher Temperatures:**
- Beyond 35 °C, decomposition of intermediate products or thermal instability could lead to reduced efficiency, resulting in a lower yield.
- **Optimization Consideration:**
- If the goal is to maximize BKK yield, maintaining the reaction temperature close to 35 °C is ideal. Exceeding this temperature might lead to unnecessary energy consumption with reduced benefits.

4. Practical Implications

- **Industrial Applications:**
- If BKK is used in a manufacturing process, the reaction temperature should be carefully controlled to prevent losses.
- **Further Research Needs:**
  - Conducting additional experiments at narrower temperature intervals (e.g., every 2 °C instead

of 5 °C) to pinpoint the exact optimal temperature.
- Studying the by-products formed at temperatures above 35 °C to understand why the yield declines.
- Investigating catalysts or reaction conditions that might sustain a higher yield even at elevated temperatures.

The graph clearly illustrates that temperature has a significant impact on BKK yield. The best yield is achieved at 35 °C, and exceeding this temperature leads to a decline in efficiency. Controlling the reaction conditions within the optimal range is crucial for maximizing product yield while minimizing losses.

Conclusion

The study confirmed that the process of obtaining potassium butyl xanthate is a complex chemical and technological process requiring strict parameter control. The optimal reaction temperature ranges from 25 to 40 °C, and the removal of reaction water plays a crucial role in ensuring high product purity. The resulting potassium butyl xanthate exhibits excellent flotation characteristics but requires stringent storage condition control to prevent decomposition. Future research may focus on improving synthesis methods to minimize by-product formation and enhance the stability of potassium butyl xanthate under industrial conditions.

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Section 2. Materiarls science

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THE EFFECT OF GERMANIUM ON THE MICROSTRUCTURE OF ALUMINUM ALLOY

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Abstract

This article investigates the changes in the structure of the D16 (Al-Cu) alloy, which belongs to the aluminum-copper system, under the influence of the germanium element using experiments. A resistance furnace was used for casting the samples. The samples were cast into sand-clay molds at a temperature of 750 °C. The microstructure of the cast samples was analyzed using an optical microscope, and the authors' conclusions are presented in the article.

Keywords: *furnace, germanium, microstructure, alloying, aluminum, copper, temperature, sand-clay mold*

Introduction

A number of scientific studies of aluminum alloys are aimed at obtaining high-quality foundry products with enhanced casting and mechanical properties. The world's leading countries in this field are Canada, the USA, Japan, China, Sweden, Germany, Russia, Ukraine and others. In the above-mentioned countries and in Uzbekistan, in subsequent years, due to the increase in the number of non-ferrous alloys in the production of foundry products in the foundry industry, great attention has been paid to creating a technology for producing high-quality, durable foundry products based on an effective method that ensures resource conservation (Robson, J. D., 2004; Lin, R., Liu, B., Zhang, J., & Zhang, S., 2022; Gao, L., Xue, S., Zhang, L., Sheng, Z., Ji, F., Dai, W., ... & Zeng, G., 2010; Tursunbaev, S., Turakhodjaev, N., Zhang, L., Wang, Z., Mardonov, U., & Saidova, M., 2024; Habazaki, H., Shimizu, K., Skeldon, P., Thompson, G. E., Wood, G. C., & Zhou, X., 1997; Tursunbaev, S., Turakhodjaev, N., Odilov, F., Mardanokulov, S., & Zokirov, R., 2023; Davis, R. M., & Koch, C. C., 1987). The scientists from Al-Baha University and King Khalid University (Saudi Arabia) investigated the changes in Sn-

Ag-Cu alloy properties when Ge (0.0, 0.05 and 0.5wt%) is added. The finding reveals that the addition of germanium in the amount of 0.05 and 0.5wt% can potentially promise a noticeable improvement in mechanical properties, namely tensile strength, elongation, etc., and in the microstructure of the alloys. Experiment shows that the addition of Ge (0.5wt%) can increase the values of elongation, ultimate and yield tensile strength from 45.6%, 47.5MPa, 40.6 MPa to 58.3%, 56.3MPa and 49.4MPa respectively. Not only were the characteristics improved, but the addition of Ge (0.5wt%) to the alloy caused the development of tiny germanium particles, whereas adding 0.05wt% germanium reduced the shape of β-Sn grains. The authors concluded that the best percentage of germanium for improved performance was 0.5% (El-Taher, A.M., Ali, H. E., & Algarni, H., 2024).

Comparatively, in the study Muna Khethier Abbass et al. (Iraq) and Vesna Maksimovic et al. (USA), the researchers analyzed the performance of Al alloys while adding microalloying element (Ge). Vesna Maksimovic et al. found that alloying Aluminum alloys with Ge accelerates aging kinetics, while increasing the hardness level three times more quickly (Abbass, M.K., Radhi, M.M., & Adnan, R.S.A., 2017). Experts Muna Khethier Abbass et al. from University of Technology (Iraq) approved that the mechanical properties and microstructure can be enhanced by adding germanium to the alloy, however, as the amount of germanium increases, the hardness of the alloy decreases slightly. Three samples were analyzed (0.3% by weight, 1% by weight, 3% by weight) to study changes in the microstructure and mechanical properties of the alloy. As a result of the study, it was noticed that the Young's modulus increased with an increase in the amount of germanium, while the addition of this metal led to a decrease in hardness. The best performance was recorded with a Ge content of 3% by weight (Maksimović, V., Zec, S., Radmilović, V., & Jovanović, M.T., 2003). Based on experiments, the article analyzes the change in the structure of a D16 alloy under the influence of germanium, which is one of the alloys in the aluminum-copper system.

Materials and methods

The research investigated the effect of germanium oxide on the microstructure of the D16 alloy in the aluminum-copper system. The chemical composition of the D16 alloy is shown in Table 1. This aluminum alloy contains 94.7% aluminum (Mueller, A., Wang, G., Rapp, R.A., Courtright, E.L., & Kircher, T.A., 1992). On the other hand, copper, the main alloying element, accounts for 4.9%. A resistance furnace was used to dilute the samples. The furnace used is mainly intended for the manufacture of small parts, up to 3 kg of metal can be liquefied in the crucible. The furnace crucible is made of graphite material, which helps to cast liquid metal without sticking to the base of the crucible. Germanium oxide from 0.1% to 0.3% was introduced into the composition of the aluminum alloy, and the samples were poured into sand-clay molds.

Table 1. Chemical composition of D16 alloy

Fe	Si	Mn	Cr	Ti	Al	Cu	Mg	Zn	Mixtures	–
up to 0.5	up to 0.5	0.3–0.9	up to 0.1	up to 0.15	90.9–94.7	3.8–4.9	1.2–1.8	Up to 0.25	all 0.15	Ti+Zr < 0.2

Results

The cast samples were ground and micro sections were made. The structural analysis of the prepared samples was carried out using an optical metrological microscope. The microstructures of the samples are shown in Figure 2 and Figure 3. Figure 2 shows the microstructure of the added sample, calculated so that in "a" there remains an alloy of aluminum and copper without the addition of Germanium oxide, and in "b" – germanium in the alloy in an amount of 1%. Figure 3 shows the microstructure of the added sample, calculated so that 2% of germanium in "a" remains in the alloy, and 3% in "b", calculated so that germanium remains in the alloy.

Figure 1. *Resistance furnace*

Figure 2. *Microstructure of the samples: a – D16; b – D16+ 1% Ge*

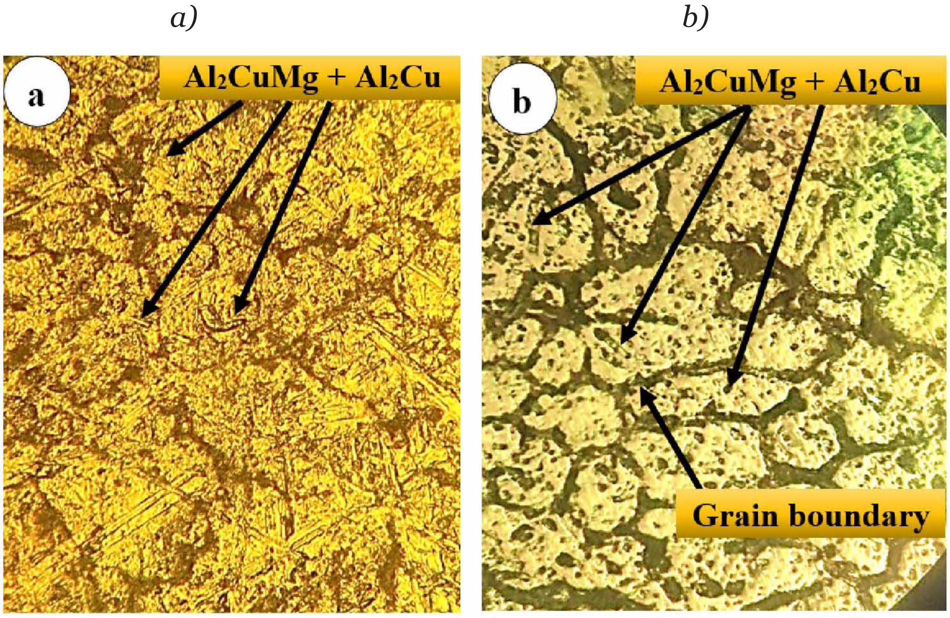
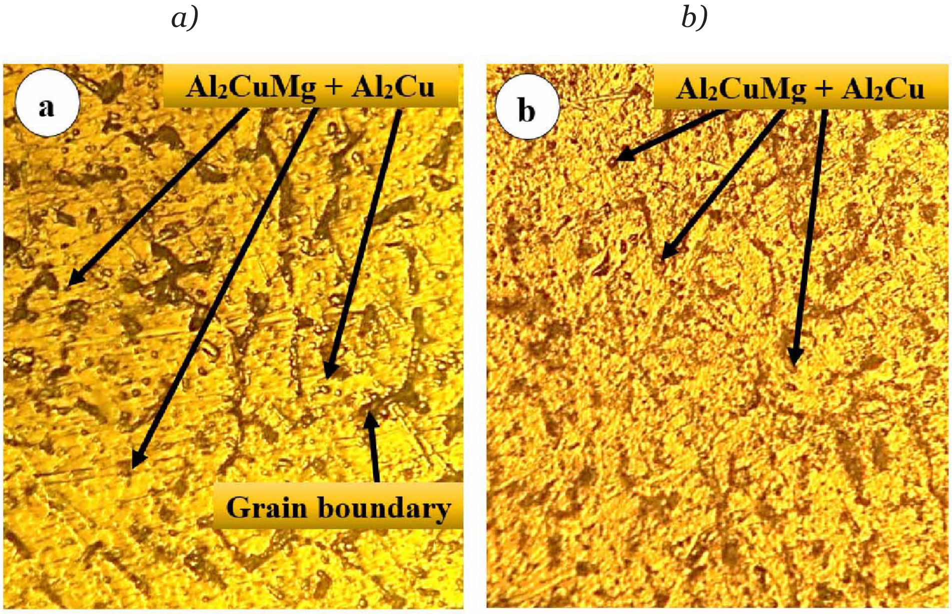


Figure 3. *Microstructure of the samples: a – D16+2% Ge; b – D16+ 3% Ge*



The microstructure of the samples in Figures 2 and 3 above was analyzed based

on the standard grain sizes of Table 3 (GOST 5939–82).

Figures 2 and 3 show that the microstructure of the aluminum-copper alloy is the base metal aluminum and copper, in addition, the main component contains a solid solution of copper and magnesium in aluminum and the intermetallic phases Al2CuMg and Al2Cu. Melting foci located near accumulations of intermetallic compounds and periodic eutectic precipitation are not visually detectable.

Table 3. *Standard grain sizes (GOST 5939–82)*

Number grains (*G*)	Average area grain cross sections *a*, mm^2	Number of grains per area 1 mm^2, *m*			Average number of grains in 1 mm^3 (*Nv*)	Average grain diameter (*dm*), mm	Average conditional grain diameter (*dL*), mm
		minimum	medium	maximum			
1.	0.0625	12	16	24	64	0.250	0.222
2.	0.0312	24	32	48	181	0.177	0.157
3.	0.0156	48	64	96	512	0.125	0.111
4.	0.00781	96	128	192	1448	0.088	0.0783
5.	0.00390	192	256	384	4096	0.062	0.0553
6.	0.00195	384	512	768	11585	0.044	0.0391
7.	0.00098	768	1024	1536	32768	0.031	0.0267
8.	0.00049	1536	2048	3072	92682	0.022	0.0196

Figure 2 (a) The grain dispersion size of the sample corresponds to size No. 7–8 according to GOST 5639–82. The grains of intermetallides are columnar, elongated 9–10 × × 3 microns. Figure 2 (b) The grain dispersion size of the sample corresponds to size No. 6 according to GOST 5639–82. In the sample with the addition of 1% Germanium, the grains of intermetallides were reduced to a maximum of 5–6 microns.

Figure 3 (a) The grain dispersion dimensions of the sample according to GOST 5639–82 correspond to the dimensions of sample No. 6–7 according to GOST 5639–82. Germanium intermetallic grain grinders up to 3–4 microns when the sample contained 2% Germanium. Figure 3 (b) the presence of 3% Germanium in the composition, crushing of intermetallic grains to 2–3 microns.

Conclusion

According to the research results, it was found that germanium contained in germanium oxide remains in the aluminum alloy during liquefaction, destroying the microstructure of the alloy. In this case, the Germanium contained in it combines with other metals to form intermetallides. "Germanium can form a solid solution with aluminum, which restricts the movement of dislocations and increases the hardness of the alloy. In particular, Al-Ge alloys are used in applications requiring high mechanical strength."

An increase in the germanium content led to a decrease in the grains of the microstructure of the samples. When 3% is added, especially with respect to the germanium charge, the alloy granules are crushed to 2– –3 microns. From this it can be concluded that the germanium element improves the microstructure of aluminum alloys. However, an increase in the Germanium content in the aluminum alloy was accompanied by a decrease in its absorption in the alloy and its release into the slag during melting. Therefore, it is recommended to introduce the German element in an amount of 2–3% compared to the charge.

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Section 3. Technical sciences in general

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PRINCIPLES AND MODEL OF THE DIFFERENTIATED APPROACH IN ENGINEERING EDUCATION (USING THE EXAMPLE OF THE COURSE "ARTIFICIAL STRUCTURES ON HIGHWAYS")

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Abstract

This article examines both the theoretical foundations and practical implementation of a differentiated approach to training engineers – an approach that accommodates individual student characteristics (e.g., knowledge level, learning style, professional interests) while ensuring that all students acquire essential competencies. Drawing on various pedagogical theories and concepts (the theory of multiple intelligences, constructivism, social learning theory, personalized learning, and universal design for learning), the authors identify seven principles that demonstrate how to organize the educational process effectively in technical universities. Illustrative examples of differentiated assignments and project-based activities are presented, using the course "Artificial Structures on Highways" as a case study. The article also proposes a step-by-step model for developing professional skills. In the concluding section, the authors discuss limitations related to the need for additional resources, adaptation to specific university contexts, and cultural factors. The findings may be applied in designing curricula, developing assessment strategies, and enhancing the professional development of engineering faculty.

Keywords: *differentiation of instruction, engineering training, individualization, professional competencies, pedagogical theories*

Introduction

Under current conditions for the development of engineering education, the foremost challenge is to balance mandatory training standards with the need to accommodate the individual characteristics of students (Trilling & Fadel, 2004; Froyd et al., 2012; Aleksankov, 2017; Ivanov et al., 2013), a concern reflected in several decrees and regulations adopted in Uzbekistan (Presidential Decree of the Republic of Uzbekistan, 2021; Presidential Decree of the Republic of Uzbekistan, 2024). Numerous studies, including the works of Snigirev, Sukhovetskaya, and Khomyakov, as well as Boelt, Kolmos, Holgaard, Cabedo, Royo, Moliner, and Guraya (Snigirev et al., 2014; Boelt et al., 2022; Cabedo et al., 2018), emphasize that without considering factors such as learning style, initial knowledge level, motivation, and professional interests, it is difficult to ensure the full mastery of competencies required for future engineering activities.

The complexity of engineering tasks, the interdisciplinary nature of projects, and the constantly evolving demands of the labor market all require universities to create a flexible educational environment. In response, the scholarly and pedagogical community has been expanding on the idea of a differentiated approach that adapts the content and methods of instruction to the diverse characteristics of students. Building on contemporary pedagogical theories and concepts, this study systematizes various approaches to differentiation in engineering education and formulates seven principles aimed at aligning instructional processes with desired educational outcomes while accommodating individual learning trajectories.

The research proceeded in three stages:

1. **Literature Review:** This stage involved surveying and analyzing academic sources. Works by both Uzbek and international researchers on individualization and differentiation in higher education were examined, with an emphasis on literature addressing engineering training. Particular attention was paid to theories that focus on individual differences.
2. **Comparative Analysis of Concepts and Development of Principles:** Various definitions of "differentiation" and "differentiated approach" in engineering education were compared, and ideas from inclusive, personalized, and project-based learning were reviewed. Common and distinctive features were extracted and distilled into seven principles of the differentiated approach, along with a four-stage model for competency development.
3. **Application to "Artificial Structures on Highways":** Consultations were held with technical university instructors experienced in implementing differentiated methods (e.g., project-based assignments, hackathons, flexible assessment). The engineering course "Artificial Structures on Highways" was selected as an illustrative example, given the variety of constructions and solutions – bridges, overpasses, tunnels, etc. – that clearly demonstrate the possibilities of differentiation.

Results

The ideas behind the differentiated approach are rooted in multiple academic traditions. Gardner's theory of multiple intelligences underscores that students possess dominant types of intelligence (linguistic, logical-mathematical, spatial, etc.) which should be considered in selecting tasks and learning materials (Faiziyeva, 2020). Constructivist perspectives advanced by Piaget, Vygotsky, and Bruner emphasize that learners actively construct knowledge, with instructors serving as facilitators (Ulanovsky, 2009). Bandura's social learning theory highlights the importance of interaction and observation, particularly relevant in project-based learning formats (Bandura, 2000). Personalized learning (associated with researchers such as B. Bloom and S. Khan) calls for tailoring instruction to each student's individual goals (Artikova, 2019), while universal design for learning advocates for creating an accessible and effective educational environment for all, including students with special needs (Shutova, 2018).

Table 1. *Principles of the differentiated approach and their implementation in engineering education (illustrated by the course "Artificial Structures on Highways")*

Principle	Description	Example of Implementation
1. Multi-format and flexible	Employ various instructional formats (lectures, practicums, online modules, lab work, and project-based	In bridge-construction lectures, one group of students (already familiar with basic beam-structure calculations) receives advanced materials on dynamic load calculations for

Principle	Description	Example of Implementation
learning process	activities) that account for differences in knowledge level and interests.	bridge spans; another group receives in-depth guides with visual diagrams and video reviews for analyzing simplified calculation models.
2. Guaranteed attainment of professional skills	Ensure that each learner reaches at least the minimum required level of proficiency. Organize intermediate assessments to promptly identify skill gaps and provide additional resources to remedy them.	A "checklist" of key competencies is developed (e.g., basic skills for calculating loads on overpass supports, knowledge of common bridge-span designs, and the relevant calculation algorithms). After a midterm test, students with low scores are invited for extra consultations and receive additional exercises.
3. Differentiation by abilities and learning style	Consider students' preferred modes of perception (visual, auditory, kinesthetic, etc.), their cognitive styles (analytical or creative), and their level of independence.	At the beginning of "Artificial Structures on Highways," students complete a VARK questionnaire. Visual learners receive diagrams showing crack development in bridge structures, auditory learners are provided with audio lectures on overpass construction technologies, and kinesthetic learners use physical models of supports in lab sessions.
4. Active and proactive learning	Encourage students to engage in project-based and research tasks, shape individual learning trajectories, and take initiative in selecting topics and assignments.	A mini-conference on tunnel construction is organized. Students choose their own project (e.g., a tunnel in a mountainous region), form groups, and delegate roles: some handle geological surveys, others do arch calculations or schedule the construction phases. The instructor offers guidance and monitors progress.
5. Networked and collaborative learning	Form teams to tackle common problems, sometimes involving participants from other universities and related disciplines.	A joint project is established with the Materials Science Department: technology students develop a concrete mix for bridge structures, while civil engineering students in the "Artificial Structures" course calculate strength parameters and analyze the material's behavior under temperature fluctuations.
6. Progression and continuous personal growth	Each subsequent step or topic is more complex than the previous one, remaining within the learner's "zone of proximal development."	After mastering basic bridge-structure calculations, high-achieving students move on to designing reinforced concrete spans in seismically active areas. Those who need more practice continue working on standard calculations without seismic factors to solidify foundational knowledge.

Principle	Description	Example of Implementation
7. Optimization of learning effort	Allocate time and resources so that the most prepared students can engage in advanced learning while others receive extra practice to address any difficulties.	At the end of a test on "Methods for Calculating Bridge Spans," some students are assigned nonstandard, multi-span bridge designs, while others are asked to refine simpler models or perform additional load analyses for deeper understanding of standard calculations.

By synthesizing these core ideas and relating them to the specifics of engineering disciplines, we developed seven principles of a differentiated approach in engineering education, shown in Table 1. These principles articulate key guidelines for adapting the educational process to individual student characteristics while ensuring the formation of required professional competencies in engineering.

Collectively, these principles provide a way to blend solid foundational training – ensuring all students attain a baseline level of expertise – with individualized learning trajectories that reflect each student's preferences and potential. To facilitate this, we organized the application of differentiation into a four-stage model:

1. **Diagnostics.** At this stage, baseline knowledge (e.g., in mechanics, materials science, and strength of materials) and preferred learning styles are identified.
2. **Fundamental Mastery.** All students are introduced to basic structural concepts and calculations (for instance, beam bridges, standard span configurations).
3. **Deepening.** Some students choose more complex tasks (e.g., span calculations for nonstandard conditions such as tunnels in seismic zones), while others focus on reinforcing fundamental skills.
4. **Final Integration.** The capstone projects (a bridge, overpass, tunnel, etc.) are completed through collaborative efforts. Students with different skill levels assume tasks that match their competencies and interests.

This model offers a logical progression of increasingly complex tasks while providing opportunities to revisit foundational concepts and receive extra support as needed. For effective differentiation, a comprehensive approach to assessing students' initial data is recommended. This includes diagnostic tools such as the VARK questionnaire to identify primary learning channels, subject-specific tests, brief case studies to gauge cognitive styles (analytical or creative), and instructor observation during laboratory or practical sessions. The resulting data enable instructors to adjust the complexity and content of course materials, while students can choose learning trajectories that best align with their current needs and capabilities.

Discussion

The presented principles and the proposed model for competency development align with the classical theoretical underpinnings of differentiated instruction. In engineering education, these aspects are especially pertinent because engineering tasks are often multifaceted, requiring diverse forms of student engagement to accommodate varying levels of readiness and learning preferences. Examples from "Artificial Structures on Highways" clearly illustrate how to implement differentiation: from assigning specialized roles in a tunnel-construction project to customizing calculation tasks for bridge design.

For such strategies to be effective at the institutional level, systematic methodological support is needed, along with consistent assessment criteria and a flexible curriculum that facilitates multiple skill levels and adaptable learning trajectories. Questions remain regarding how best to quantitatively evaluate the effectiveness of the proposed differentiated approach and the four-stage model in actual engineering training. Further structured studies are required, including empirical experiments and statistical analyses, to examine how differentiation affects academic performance, engineering thinking, and graduate employability.

When piloting these ideas, one must also account for resource demands related to creating differentiated assignments and providing additional consultations, as well as for the professional development needed to prepare instructors for new teaching conditions. Consequently, the proposed principles of differentiated instruction may be implemented with varying degrees of success across different cultural and institutional contexts.

Conclusion

Overall, an analysis of pedagogical concepts and the practices of technical universities demonstrates the potential of a differentiated approach to enhance the effectiveness of engineering education. The principles presented here, derived from current learning theories, offer guidelines for flexibly designing instructional processes – ranging from multi-format lessons and attention to individual learning styles, to the step-by-step intensification of tasks and the creation of collaborative teams. Concrete examples tied to the course "Artificial Structures on Highways" underscore the applicability of these ideas in real teaching contexts. Future research and pilot programs are needed to collect statistical data on the outcomes of implementing a differentiated approach, to factor in the cultural and organizational nuances of universities, and ultimately to develop unified methodological recommendations.

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