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Article

Approximative approach to optimize concrete foaming concentration in two stage foaming

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Abstract. The article presents the results of a study on foam concentration for the production of foam concrete using a two-stage foam introduction method. The research was conducted by evaluating the strength and density of foam concrete samples manufactured using both the proposed and conventional methods. The optimal composition was determined through several iterations, considering adjustments to the overall quantity of foaming agent and the water-cement ratio. The study revealed that the two-stage foam introduction method enhances the strength properties of foam concrete by promoting the formation of a more uniform porous structure within the material. The initial introduction of a low-concentration foam solution in water creates favorable conditions for the subsequent introduction of a high-concentration foam solution, serving as a structural-forming component. The optimal approach for achieving a stable porous structure involves an initial foam introduction of 15% and a subsequent introduction of 85%. Furthermore, the research highlights the nuances of the relationship between foam concentration, strength, and density of foam concrete, offering deeper insights into the structural properties of the material. The effectiveness of the proposed methodology is substantiated by the achieved technological solution, which provides a pragmatic approach to enhancing the efficiency of foam concrete production through precise foam concentration at both the initial and subsequent stages of the manufacturing process.

Keywords: foam, microsilica, optimal foam, foam concrete, two-stage foaming.

1. Introduction

Lightweight concrete is increasingly finding applications in modern construction. Among the various lightweight concrete options, aerated concrete is predominantly favored by construction organizations. However, foam concrete has gained considerable traction recently due to its diverse range of applications. Unlike aerated concrete, foam concrete structures can be constructed monolithically, making it a more versatile material [1].

Certain distinct advantages of foam concrete over aerated concrete may include the closed pore structure of foam concrete compared to aerated concrete, rendering it stronger due to a more robust skeletal structure. Additionally, the relative durability of foam concrete can be attributed to the inclusion of cementitious binders in its composition, unlike aerated blocks which contain lime-gypsum binders, exhibiting lower resistance to mechanical forces, especially water-induced impacts. Nevertheless, these advantages often remain theoretical, as under equivalent reliability and durability conditions, the simplification of the production process takes precedence [2].

In the construction market today, three primary methods for foam concrete production exist: the classic method, the air entrainment method, and the dry foam mineralization method. The classic method involves blending cement slurry with water and foam, while the air entrainment method entails high-speed mixing of cement slurry with a foam concentrate [3]. The dry foam mineralization method involves mechanical blending of dry cement mix with foam. Each method possesses distinctive technological characteristics, advantages, and drawbacks. However, a common challenge faced by foam concrete producers is the instability of the foam concrete mixture's structure, shrinkage, uneven material density, consequently resulting in unstable strength and thermal conductivity of the product [4]. The unresolved matter of obtaining high-quality foam concrete has driven one of the objectives of this research – the development of an accessible foam concrete production technology. The technical outcome of this research aims to improve the material's pore structure by ensuring uniform pore distribution, thereby enhancing material strength by reducing the water-cement ratio and achieving an evenly distributed skeletal structure and to develop a technological solution for the optimal composition of primary and subsequent foam introductions for foam concrete production using the proposed method [5].

2. Methods

From a technological perspective, the proposed production method significantly deviates from preceding technologies, incorporating a novel two-stage foam introduction technique (Figure 1). This method ensures the maximal distribution of the foam concentrate throughout the sample volume [6]. The initial introduction of a low-concentration foam solution occurs during the preparation stage of the sand-cement mixture, enhancing its wetting capability and subsequently reducing the water-cement ratio (by mitigating foam quenching with water). Subsequently, during the secondary introduction of a high-concentration foam solution in the structural formation stage of cellular concrete, the reduction in water-cement ratio allows for the optimal preservation of the initial foam concentrate multiplicity. This aids in the formation of a uniform porous material structure [7].

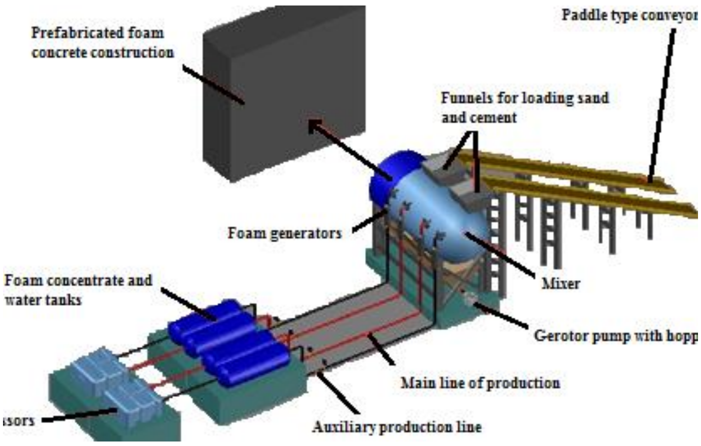


Figure 1 – Foam concrete production scheme using two-stage foam introduction

The variability in foam concentrations for which studies were conducted is outlined in Table 1. The diverse percentage ratio of foam concentrate in foam concrete composition is calculated based on the requirement of achieving D600 grade foam concrete. The mass fraction of the total foam concentrate is chosen considering its standard proportion in the composition of conventional D600 grade foam concrete [8]. Evaluating the varied compositions of primary and secondary foam introduction allows determining the best or optimal technological solution corresponding to: Best – highest material strength under the conditions of obtaining D600 grade foam concrete; Optimal – minimum foam concentrate consumption for standard strength D600 grade foam concrete.

In the context of the first point, the objective is to achieve the highest foam concrete strength through the uniform distribution of pores within the structure, rather than through foam quenching and obtaining a denser material. The latter can occur due to improperly observed foam concentrate proportions [9].

Regarding the second point, the aim is to reduce foam concentrate consumption, not driven by cost savings but resulting from an excess of foam concentrate due to an even distribution of the pore structure. This can lead to less foam quenching, hence a greater fractional participation of foam in the material's volume [10]. The outcome is a product with a higher degree of pore uniformity but lower density. Therefore, alignment with the foam concrete grade is necessary, with strength parameters being the evaluative criterion corresponding to the specific grade of conventional foam concrete [11].

If the research follows the second point, it will be necessary to adjust the overall quantity of foam concentrate, but in those percentage ratios corresponding to the best technological solution of the first approximation's variability (Table 1). The variability of the overall foam concentrate quantity will involve a multiple reduction in its composition within foam concrete by mass [12].

The conventional composition for foam concrete is adopted as follows: Portland cement of grade 400 – 350; fine sand – 250 kg, water-cement ratio 0.5. With such a water-cement ratio, the mass fraction of initial water addition will be 135 g, and secondary addition will be 40 g.

Table 1 – Compared foam concentration compositions

Type	Initial foam injection		Secondary foam injection	
	%	g	%	g
Type 1 – Reference type	0%	0	100%	1,5
Type 2	5%	0.075	95%	1.425
Type 3	10%	0.015	90%	1.350
Type 4	15%	0.225	85%	1.275
Type 5	20%	0.300	80%	1.200
Type 6	25%	0.375	75%	1.125

The main research methods included: Density assessment according to [13] and Strength determination according to [14] (Figure 2).

The tests were conducted on cubic specimens with dimensions of 10×10×10 cm. In order to obtain reliable results, six specimens of each type were tested, and the data were subjected to statistical analysis for accuracy [15].

Figure 2 – Laboratory testing of foam concrete samples

3. Results and Discussion

Figure 3 shows the results of the cubic samples strength measurement by hydraulic press.

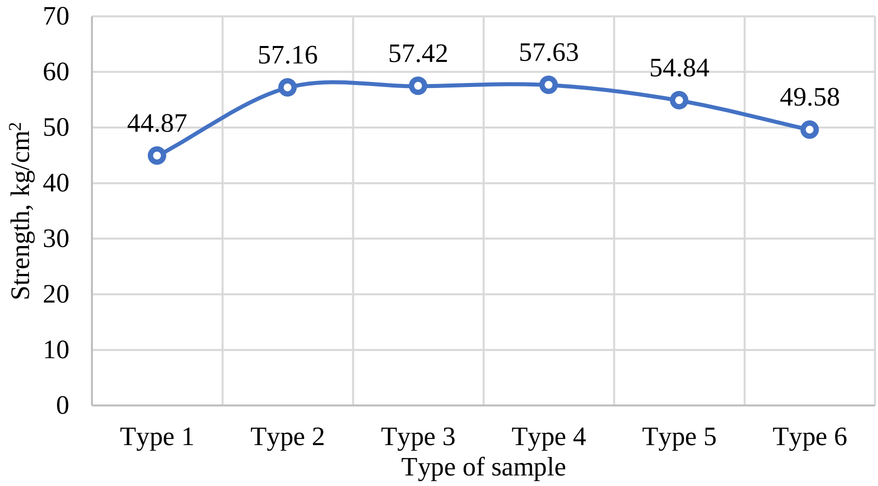


Figure 3 – Strength measurement results

According to the strength assessment results, the highest values, relative to the reference type, were exhibited by Type 3 specimens with a 15% foam concentrate introduction, while the lowest were observed in Type 6 specimens with a 25% introduction. In relative terms, Type 1 specimens showed a strength increase of 12.7%, Type 2 specimens showed an increase of 12.8%, Type 3 specimens showed an increase of 12.8%, Type 4 specimens showed an increase of 12.2%, and Type 5 specimens showed an increase of 11.1%. Thus, a peak dependence of strength on the amount of foam concentrate in its initial introduction is observed. The increase in strength is observed up to an initial foam concentrate increase of 15%. Beyond this concentration, a reduction in material strength characteristics occurs due to the subsequent increase in foam concentrate. Consequently, at excessively high foam concentrate concentrations exceeding 15%, the effectiveness of the two-stage foam introduction is diminished. This is because during the secondary foam introduction, the foam's multiplicity (density) increases due to its low concentration, rendering it less stable upon contact with the mixture from the primary foam introduction. On the other hand, excessively low concentrations below 15% do not achieve the maximum effect in improving strength characteristics. All obtained results exhibit a high degree of reliability, as the coefficients of variation range within 8-12%.

Figure 4 depicts the density measurement results of the compared foam concrete types.

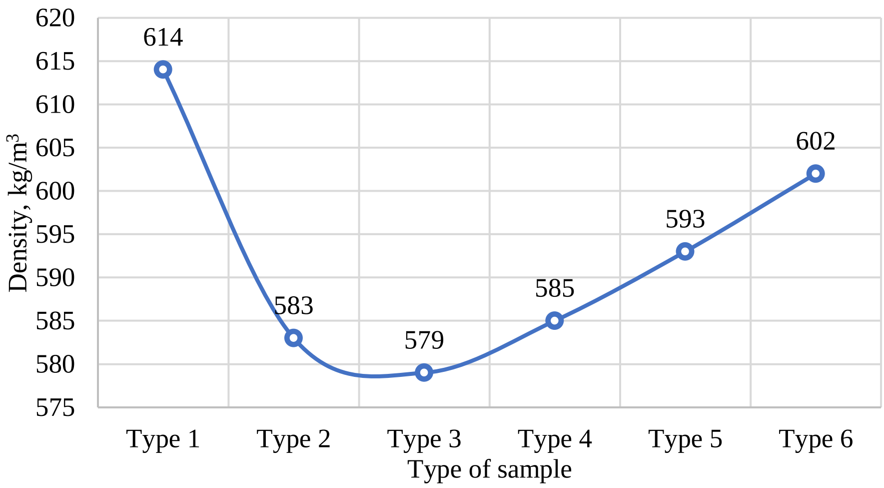


Figure 4 – Density measurement results

According to the obtained results, the maximum density values were observed in Type 1 specimens - the reference type, averaging at 614 kg/m³. The minimum density corresponds to Type 3 specimens, averaging at 579 kg/m³. Although Type 2 and Type 3 specimens showed similar density values in comparison to each other, they differed from the reference type, measuring 583 kg/m³ and 585 kg/m³ respectively. Type 5 specimens exhibited a density that closely matched the declared D600 foam concrete grade, with a minimal deviation from the reference type. The obtained results also demonstrate a high convergence of individual values, confirming the experiment's precision. The coefficients of variation do not exceed 10%.

From the above, it can be concluded that the two-stage foam introduction technology influences the material's pore structure. The shrinkage of Type 1 and Type 5 specimens is significantly greater than that of Type 3 specimens. The shrinkage of Type 2 and Type 4 specimens is relatively comparable to Type 3 specimens but still exceeds it. The relatively low density of Type 3 specimens indicates that foam quenching during the setting period was lower, resulting in fewer pore releases due to quenching. This indirectly suggests a more stable distribution of the pore structure within the material.

Despite the lower density compared to the other types, Type 3 specimens showed the highest strength values. The trend is very close to that of Type 2 and Type 4 specimens, with a slight difference in density values (not exceeding 2%) and strength values (within 5%) compared to Type 3. However, the best strength improvement with a reduction in density was observed in Type 3 specimens.

Despite the positive results, the obtained composition does not meet the requirements of the D600 foam concrete grade. Therefore, adjustments were made to the total foam concentrate amount concerning the initial foam introduction ratio, with a fixed ratio of primary and secondary foam introduction (15% and 75%).

Figure 5 shows the results of the corrective composition actions.

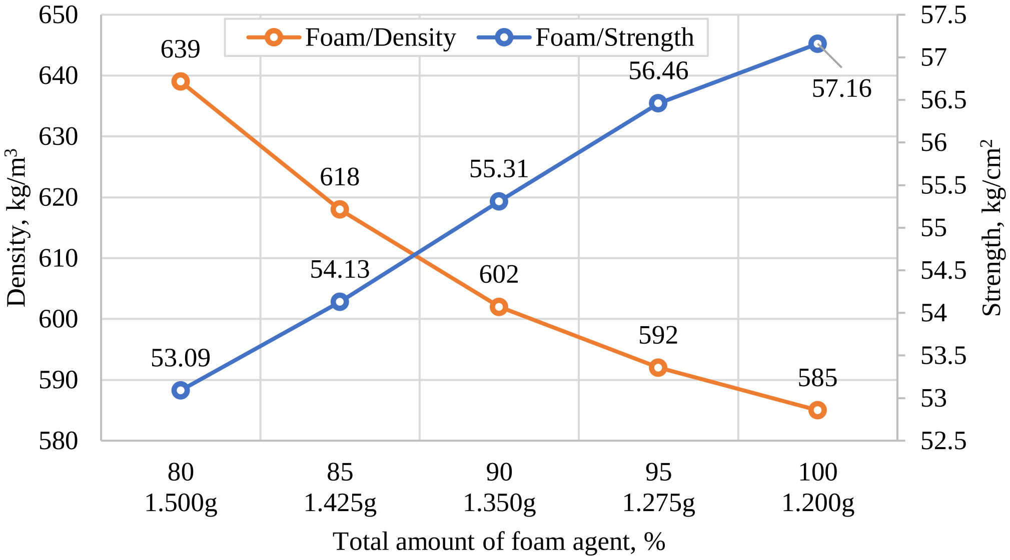


Figure 5 – Composition adjustment results

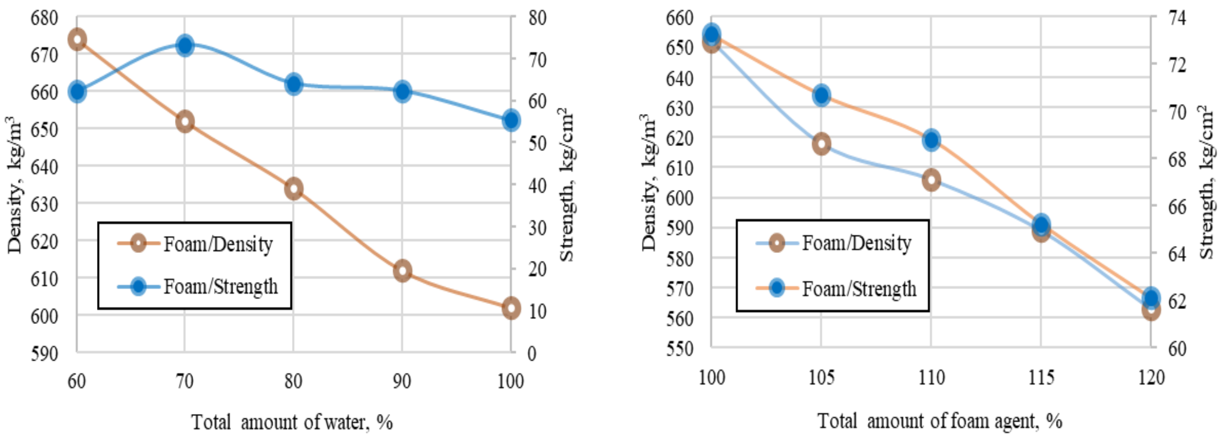
According to the obtained results, a reduction in the total foam concentrate amount leads to an increase in density due to increased shrinkage. This is a result of increased foam multiplicity, leading to more significant foam quenching before the setting period completes. The best indicator for the total foam concentrate content is 1.35 g of foam concentrate and 175 g of water, representing a 10 % reduction from the initial amount in the composition. With this foam concentrate ratio, the density corresponds to the D600 foam concrete grade, measuring 602 kg/m³.

From the generated diagrams, we can observe the inverse trend of decreasing strength parameters of foam concrete. This could be attributed to the constant water-cement ratio. Therefore, subsequent modifications to the composition were made by altering the water-cement ratio and adjusting the total foam concentrate amount.

In Figure 6a, the diagrams illustrating the dependence of strength and density on changes in the water-cement ratio are presented, while Figure 6b shows the same dependence on changes in the total foam concentrate amount.

According to the results from the diagrams in Figure 6a, we observe a tendency of increased strength with a decrease in the water-cement ratio. However, the obtained dependency reaches a peak value, meaning the trend is disrupted when reducing the water content by 60% (a reduction of 70 g from the initial 175 g). Lowering the water-cement ratio leads to an insufficient amount of water required for the complete hydration process, resulting in reduced strength gain of the foam concrete. Consequently, the optimal value of the water-cement ratio was chosen where the peak strength is observed.

However, decreasing the water-cement ratio collectively leads to increased density due to reduced foam multiplicity (and consequently reduced foam quenching). Based on the previously derived patterns, additional adjustments were made to reduce density by decreasing foam multiplicity, i.e., increasing the total foam concentrate amount.



a) b)

Figure 6 – Composition adjustment results

At first glance, the carried out manipulations might appear to have a cyclic nature, but this is not the case. The influence of the water-cement ratio on strength and density and the influence of the total foam concentrate amount on strength and density have distinct mechanics. Through numerous iterations, it is possible to arrive at an optimal solution. Figure 5b demonstrates the relationship of key transformational processes, according to which the final proportions of the water-cement ratio and foam concentrate were determined. Based on the research, the optimal composition for foam concrete production using the two-stage foam introduction method was obtained, as presented in Table 2.

Table 2 – Optimal Composition of the Proposed Production Method

Indicator	Unit	Quantity
M400 grade cement	kg	350
Fine sand	kg	250
Foaming agent to water ratio at primary injection	g : l	0.23 : 85
Foaming agent to water ratio at secondary injection	g : l	1.27 : 40

4. Conclusions

1. A comprehensive set of laboratory experiments was conducted to determine the optimal composition of foam concrete produced using the proposed technology, employing the two-stage foam introduction method. Strength and material density were the evaluative criteria for the composition selection. The optimal composition was determined through several approximations.
2. According to the obtained results, it was determined that the two-stage foam introduction contributes to the improvement of strength characteristics of foam concrete by forming a more uniform pore structure in the material. During the primary foam introduction with a low-concentration foam-forming agent solution in water, the initial transformation of the pore structure occurs. Although a high foam concentration of the low-concentration solution leads to faster foam extinguishing upon contact with the mixture, it still contributes favorably to the primary transformation of the pore structure. In other words, during the primary foam introduction, the cement-sand mixture becomes less dense, more mobile, and, most importantly, hydrated. Thus, favorable conditions are created for the secondary introduction of the high-concentration foam-forming agent solution, which is essentially a structure-forming component. The foam extinguishing process during the secondary introduction proceeds more slowly, as the already moistened mixture has a more loose structure. Earlier setting of the mixture (during the primary introduction) reduces the setting time of foam concrete compared to the secondary introduction of the structure-forming foam concentrate.
3. According to the initial approximations, the optimal option for obtaining foam concrete with a more stable pore structure is Option 3: 15% introduction of the primary foam concentrate in water, followed by the secondary introduction of an 85% foam concentrate. However, at this concentration of the foam-forming agent for both primary and secondary introductions, the total foam concentrate adopted in the first approximation is not rational, as a decrease in specimen shrinkage led to a reduction in material density. The subsequent approximation was made considering corrections to the water-cement ratio, as a negative trend in material strength indicators was observed. The resulting factor for corrective actions was a subsequent adjustment of the total foam-forming agent amount at a specific peak (optimal) water-cement ratio. The final composition of the method's components is presented in Table 2.

Acknowledgments

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Zhibek Zhantlesova – data collection, testing.
Aliya Altynbekova – visualization, drafting.
Anatolij Smoljaninov – interpretation, editing.

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Article

Utilizing granulated blast furnace slag as an alternative cement binder

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Abstract. This study addresses the challenges associated with the accumulation of technogenic waste in the production of ferrous and non-ferrous metals. We present the findings of global research on the utilization of blast furnace slag as a sustainable alternative to traditional cement binders. Our scientific investigation focuses on the laboratory exploration of replacing cement binders with a highly efficient clinkerless alternative based on blast furnace slag. The fundamentals of formulating clinkerless binders from slag were thoroughly examined for binder design. Through an extensive review, we conducted tests to identify an optimal composition, constrained within the ranges of 70-90% blast-furnace granulated slag, 14% lime, 1.5-2% gypsum, 1.5-2% C-3, and 2-25% microsilica. The outcome of these tests resulted in the development of a novel binder that combines the characteristics and properties of a lime-slag binder with the advantages of a low water consumption binder. This clinker-free binder presents a sustainable solution for construction, serving as a viable substitute for traditional cement. Our findings contribute to the ongoing efforts in adopting environmentally friendly practices in the construction industry.
Keywords: clinkerless binder, concrete, slag, waste, microsilica, superplasticizer, gypsum.

1. Introduction

Kazakhstan is one of the world leaders in the production of mining industry, strongly developed ferrous, non-ferrous metallurgy, oil and gas extraction industry. The total volume of production of solid minerals has brought the Republic of Kazakhstan to the 13th place in the world among 70 mining countries [1]. In the technological process of production of steel, pig iron, rolled steel and other non-ferrous metals, a large amount of solid waste is generated, which is a source of environmental pollution [2]. Over the last twenty years, the world production of pig iron, steel has increased almost 2-fold, which has led to an increase in the amount of slag recycled [3].

The construction industry directly depends on the quality and cost of building materials. Resource saving is an urgent problem facing research teams in the field of production of building materials, products and structures. To save and reduce the cost of building materials, to protect and protect the environment, the use of recycled slag as a binder or partial replacement of cement binder with technogenic waste is an urgent issue at present [3–10]. Iron and steel slags can be reused in bituminous mixtures, concrete and cement production, metallurgy, hydraulic engineering, internal recycling in iron and steel production processes, and for fertilizer and soil stabilization due to their unique characteristics [3].

The article [4] presents the results of research on the replacement of cement binder in the concrete mixture with finely dispersed blast-furnace granulated ground slag. The authors of [5] considered the possibility of using slag concrete in underground construction. To increase the use of slag in the mining industry, [6] presented a new slag binder (SB) consisting of 91% slag powder and 9% activator (3% clinker, 5% desulfurized gypsum and 1% mirabilite. The paper [11] considers the results of experimental studies on the production of high-performance clinkerless binders in order to ensure the possibility of obtaining high-strength composites on their basis. The authors of [3] presented a review of the production of iron and steel slags and their reuse in concrete as a replacement for cement, fine or coarse aggregates. Due to their physical and chemical properties, blast-furnace slags are widely used for partial replacement of cement in concrete production and allow significant cement savings from 20 to 70% [3].

Regarding the treatability of concrete with blast furnace slag as a partial replacement of cement, an improvement has been observed [9-10-12-13]. The use of ground granulated blast furnace slag (GGBFS) as SCM (supplementary cement materials) or partial replacement of binder components in concrete offers advantages both in terms of economy and performance improvement. It has been found that GGBFS can replace cement up to 50 %, with compressive strength comparable to conventional concrete [12]. In [13], cement was replaced by 30 % and 40 % with fly ash, GGBS and metakaolin for M30 and M35 grade concrete. According to [14] it is found that blast furnace slag is very suitable as a cement substitute, providing properties superior to those of the reference concrete.

The research is aimed at studying the properties of granulated blast furnace slag of JSC «ArcelorMittal» (Temirtau) in order to establish the possibility of its use for the production of economically beneficial binders.

The purpose of the work is the development of binders from waste metallurgical production of Karaganda region (granulated blast furnace slag of JSC «ArcelorMittal») and obtaining on their basis the optimal compositions of concrete.

To achieve the objectives of the study the following tasks were set:

- Analytical review of the state and theoretical basis for the use of secondary industrial raw materials;
- Analytical review of receipt, characteristics, properties and ways of application of granulated blast furnace slag of JSC «ArcelorMittal» (Temirtau, Kazakhstan);
- Consideration of the requirements for the developed binder using granulated blast furnace slag;
- Study of properties and characteristics of initial materials, selection of research methods and experimental study of properties of the developed binder;
- Conducting research on selection of raw material mixture composition;
- Analytical review and experimental study of the process of hardening and strength gain of the developed binder.

The subject of the study is the production of binder using industrial wastes of Karaganda region. The object of the study is a binding agent obtained by joint grinding of granulated blast furnace slag, lime, gypsum, microsilica and addition of superplasticizer C-3.

Microsilica (MC), generated during ferrosilicon and alloy smelting, is a finely condensed product with spherical particles rich in amorphous silica. It finds extensive application in cement, dry building mixtures, concrete, and foam concrete production [15].

2. Methods

The research work was carried out to study the binder obtained by joint grinding of lime, gypsum, blast furnace slag of JSC «ArcelorMittal» (Temirtau, Kazakhstan), microsilica and superplasticizer C-3.

Table 1 shows the requirements for the chemical composition of the used powdered hydraulic lime that meets the requirements of [16] (Table 1). Gypsum used in the preparation of the raw material mixture meets the requirements of [17].

Table 1 – Chemical composition of hydraulic lime [16]

Chemical composition	Norm for lime, %, by weight	
	Semi-hydraulic	Electro-hydraulic
Active CaO + MgO:		
- not more	65	40
- at least	40	5
Active MgO: not more than	6	6
CO_2: not more than	6	5

According to [16] strength of samples, MPa (kgf/cm^2), after 28 days of hardening in bending not less than 0.4 (4.0) for weak hydraulic lime; 1.0 (10) for strong hydraulic lime; in compression not less than 1.7 (17) for weak hydraulic lime; 5.0 (50) for strong hydraulic lime. The degree of dispersibility of powdered hydraulic lime when sieving a sample of lime through a sieve with mesh №02 and №008 was at least 98.5 and 85% of the mass of the sieved sample, respectively [16].

The blast-furnace granulated slag used in the manufacture of the binder meets the requirements of [18]. According to the results of studies of chemical composition of blast furnace granulated slag (Table 2) from the plant «ArcelorMittal» (Temirtau, Kazakhstan) the following indicators (%) were determined [19]: the basicity modulus of the studied granulated slag is equal to 0.75, therefore, this slag is considered acidic. Quality coefficient of blast furnace granulated slag K is equal to 1.56, in accordance with the classification by grades, this slag belongs to the second grade.

Table 2 – Chemical composition of granulated slag [19]

Sample	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	MgO	K_2O	CaO	SO_3	Na_2O	P_2O_5	Impurities
I	33.86	15.90	1.97	0.67	0.02	7.16	0.93	29.94	0.25	0.95	0.06	7.56

Superplasticizer C-3 met the requirements of [20] and [21].

Table 3 shows the chemical composition of microsilica.

Table 3 – Chemical composition of microsilica [22]

Name	Grade	Batch no.	Mass fraction, %								
			SiO_2	Stv	moisture	Fe_2O_3	Al_2O_3	CaO	pH	*p*, *g*/cm^3	Impurities
Condensed microsilica	MKU-95	27	96.85	1.31	1.07	0.07	0.24	0.46	7.89	0.44	1.68

Water and sand used in the laboratory experiments met the requirements of [23] and [24].

The fineness of grinding was determined in accordance with [25]. Sieving was carried out using a sieve with sieve №008 according to [26]. Control sieving was performed manually with the bottom removed on paper for 1 minute. The fineness of cement grinding was determined as the residue on the sieve with mesh No. 008 as a percentage of the initial mass of the sieved sample with an accuracy of 0.1%. Normal density, setting time and uniformity of volume change were determined in accordance with [27]. All these properties of the binder were determined on the verified instruments and equipment of the accredited laboratory of «KaragandaTechnoService» LLP (Karaganda, Kazakhstan). The cone blur and tensile and compressive strength were determined in accordance with [28].

Strength properties were determined on specimen beams of size 40×40×160 mm at the age of 28 days of curing in water. The bending and compressive strength at steaming was determined on beam specimens after curing in a steaming chamber at the age of 24 hours from the moment of manufacture. The steaming chamber of the construction laboratory of the Faculty of Architecture and Civil Engineering of Abylkas Saginov Karaganda Technical University was used for testing.

3. Results and Discussion

During the period of research work, laboratory tests were conducted to study the properties of the prepared binders (Table 4).

Table 4 – Mass fraction of components in the composition of binders prepared, %

No.	C-3 additive	Hydraulic lime	Bi-hydro gypsum	Granulated blast furnace slag	Condensed microsilica
1	2	14	2	72	10
2	2	14	2	82	-
3	1.5	14	1.5	68	15
4	1.5	14	1.5	83	-
5	1.5	14	1.5	63	20
6	1.5	14	1.5	78	5
7	1.5	14	1.5	78	25
8	1.5	14	1.5	80	2

The tests were carried out to determine the fineness of grinding, normal density, setting time, cone blurring, uniform volume change, and tensile and compressive strength. Also, the samples of the tested binder were subjected to treatment in a steaming chamber.

Table 5 – Test results of clinkerless binder bar samples

No.	Grinding fineness, %	Normal density, %	Setting time (Start / End), min	W/C	Steaming mode, hours	Tensile / Compressive strength after 2 days of steaming, kgf/cm^2	Tensile / Compressive strength after 28 days of steaming, kgf/cm^2	Uniformity of volume change
1	90.20	0.14	25.00 / 50.00	0,22	2+12+2	98.30 / 374.25	67.00 / 346.00	Uniform
2	90.00	0.16	34.53 / 39.05	0,24	2+12+2	67.70 / 265.13	71.00 / 310.00	Uniform
3	91.76	0.14	20.39 / 26.36	0,24	2+12+2	88.00 / 384.34	68.00 / 322.20	Uniform
4	94.48	0.16	45.20 / 53.20	0,24	2+12+2	71.50 / 287.78	66.00 / 327.70	Uniform
5	88.00	0.14	18.35 / 48.50	0,24	2+12+2	93.70 / 450.00	72.00 / 401.10	Uniform
6	96.00	0.15	28.43 / 59.39	0,24	2+12+2	90.00 / 401.60	62.00 / 435.11	Uniform
7	95.00	0.14	15.15 / 17.35	0,24	2+12+2	84.00 / 542.00	70.15 / 397.27	Uniform
8	99.00	0.16	18.00 / 28.00	0,25	2+12+2	73.10 / 316.93	74.60 / 386.70	Uniform

Selection of quantitative ratios between the starting materials was carried out by analytical review of literature and theoretical bases of the use of blast furnace granulated slag, lime, gypsum, superplasticizer and microsilica in the production of binders, fine grinding of composite raw material mixtures, as well as through experimental determinations of the properties of the manufactured binder, different composition in laboratory conditions.

In the design of binder were considered the basics of the manufacture of slag clinkerless binders, in particular lime-slag, sulfate-slag substances and theoretical aspects of the use of superplasticizer C-3, the impact of fine grinding, and therefore the production of binders of low water consumption.

The components of the raw material mixture of the studied binder are a base of blast-furnace granulated slag and raw material additives to improve hydration, strength set and increase strength characteristics. So, lime is an alkaline activator of potential hydraulic properties of blast furnace slag constituents, gypsum acts on slag as a sulfate activator. Superplasticizer is a complex modifier of binder.

As a result of the review, tests were conducted to select the composition within the following limits: blast-furnace granulated slag – 70-90 %, lime – 14 %, gypsum – 1.5-2 %, C-3 – 1.5-2 %. microsilica – 2-25 %.

In the course of research work was obtained binder using blast furnace granulated slag of JSC «ArcelorMittal» two experimental compositions. Binder of the first composition was obtained by joint grinding of the given blast furnace granulated slag, lime, gypsum and superplasticizer C-3. The binder of the second composition was obtained by joint fine grinding of the same raw materials, but with the addition of microsilica.

Thus, a new binder was obtained, including the characteristics and properties of lime-slag binder and low water consumption binder [7].

Joint grinding of raw material components was carried out in a ball mill of the construction laboratory of the architectural and construction faculty of the Abylkas Saginov Karaganda Technical University. The duration of grinding was 8 hours, and grinding balls of different diameters were used in the experimental production of binder samples.

During the production of experimental samples of binders were also taken into account research data that at fine grinding in a ball mill, the content in the raw mix of additive C-3 at the same duration of the process increases the fineness of grinding of the finished product [29]. Figure 1 shows the dependence of specific surface area on the content of C-3.

The fineness of grinding of the studied binder was in the range of 88-99 %. When determining the uniformity of fracture volume change, radial cracks and distortions were not found in the samples. The normal density of the binder with gypsum corresponded to a water-cement ratio of 0.22-0.24. The beginning and end of setting corresponded to quick-setting cement, so it is desirable to use this binder not directly in production.

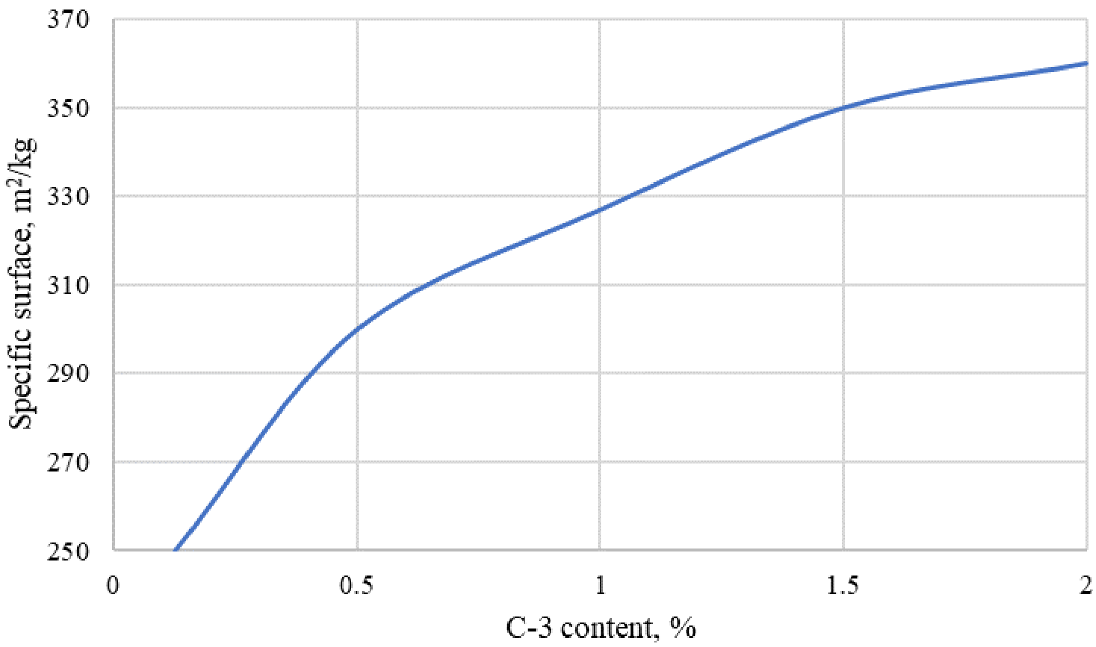

Figure 1 – Graph of dependence of specific surface after grinding on the content of C-3 in the composition of the raw material mixture

To determine the activity of the investigated binders, samples of beams with the size of 40x40x160 mm were prepared. The samples were made using Volsk sand of composition 1/3. After manufacturing the samples in molds were stored (24±1) h in a bath with a hydraulic seal, then the samples were carefully unformed and placed in a bath with water in a horizontal position. Samples for determining the strength of cement during steaming were placed in the steaming chamber. Steaming took place according to the following regime: 2 hours of holding the samples in the chamber at a temperature of 20°C, 3 hours for a uniform rise in temperature to 90°C, isothermal heating at the temperature was held for 12 hours, the process of cooling the samples 2 hours. Further in accordance with [28] the strength characteristics of the considered binders were tested under steaming conditions and after 28 days.

The obtained results of laboratory studies of the properties of the developed binder showed that the binder made by joint grinding of lime, gypsum, blast furnace granulated slag, microsilica and superplasticizer C-3 has higher compressive flexural strength. Also, the flexural and compressive strength of this binder increases significantly after treatment in a steaming chamber (Figures 2, 3, 4).

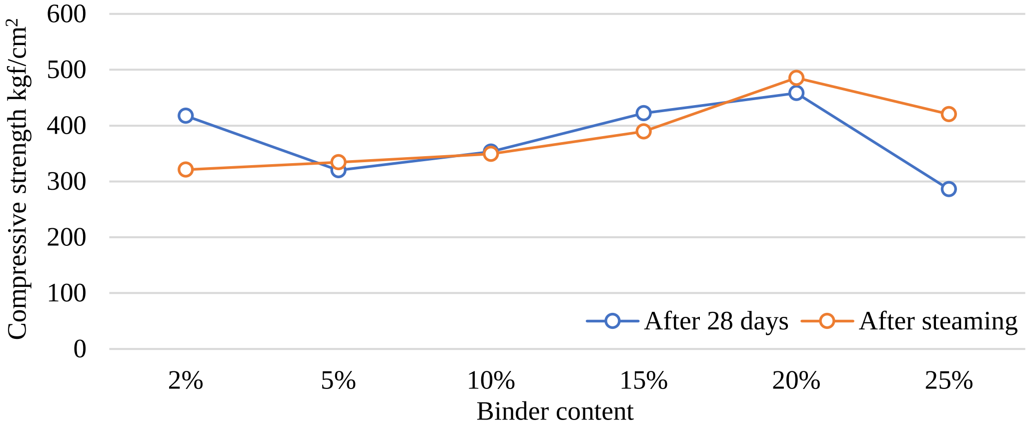

Figure 2 – Dependence of compressive strength on binder composition

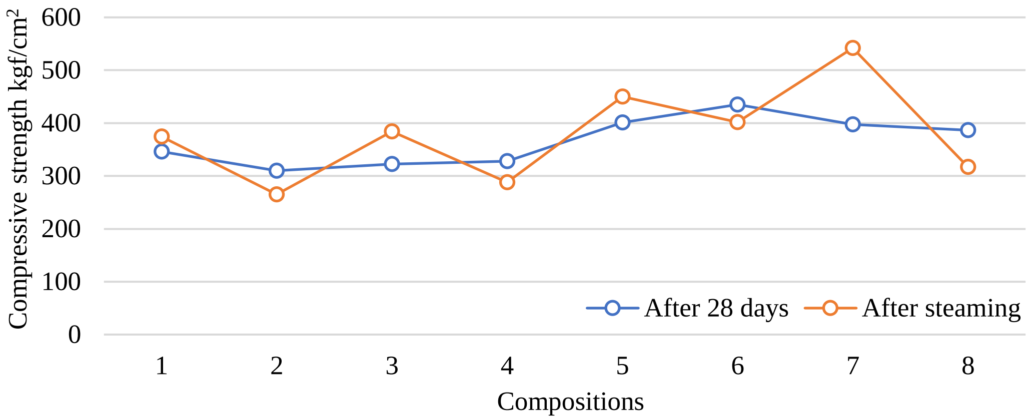

Figure 3 – Compressive strength of clinkerless compositions

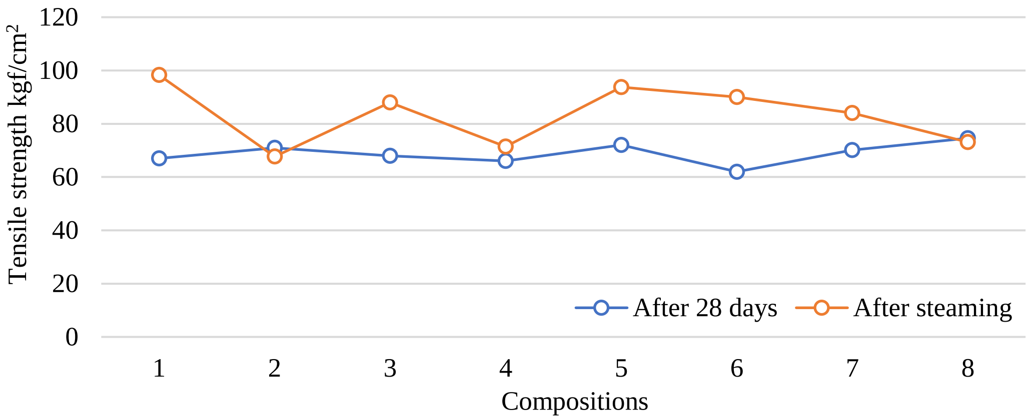

Figure 4 – Tensile strength of clinkerless compositions

Also, the presence of superplasticiser C-3 reduced the water requirements during mixing. It also draws attention to the fact that the water-cement ratio of the studied binders decreases in the presence of gypsum additive in the raw mix. Gypsum content also increases the fineness of grinding.

The content of C-3 additive in binders increases the setting time, while the content of gypsum in the raw mix does not affect the beginning and end of setting of the studied binders.

Technological scheme of binder production using industrial wastes consists of the following main operations: dosing of raw material components, joint fine grinding, packaging and warehousing of finished products.

4. Conclusions

In the course of laboratory tests, raw materials meeting all requirements of state standards were used.

Laboratory research work was carried out in accordance with the requirements of state standards.

Two binder compositions were selected: 1) 14% lime, 2% gypsum, 1.5-2% C-3 additive, 82% blast furnace granulated slag; 2) 14% lime, 1.5% C-3 additive, 2-25% microsilica, 63-80% blast furnace granulated slag.

The tensile and compressive strengths of the specimens were 62-74 kgf/cm^2 and 310-435 kgf/cm^2 for the first and second compositions, respectively.

The production process involves sulphate-alkali activation of potential hydraulic properties, binder modification as well as mechanical activation through fine grinding.

The obtained binders in the research work need further study of the properties of frost resistance, water resistance.

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Article

Research on clay shear strength anisotropy at Šenkovec clay pit

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Abstract. The paper deals with influence anisotropy to shear strength of clay and differences in test results of shear strength parameters, cohesion (*c*) and internal friction angle (*φ*) considering the direction of testing. Clay is very often the foundation soil of many buildings. There were performed three series of direct shear experiments for each of two different directions in relation to the horizontal, 0° and 90° (18 direct shear experiments in total). The results showed significant differences in the values of the shear strength parameters and to shear strength ultimately with considering to the test direction. Angle of internal friction (*φ*) is higher by 3.0° or 11.81% in the test at an angle of 0° in relation to the horizontal. A much more significant difference is visible in cohesion (*c*). The results showed that the cohesion (*c*) in the 90° test was higher by 14.92 kN/m² or 106.04%.

Keywords: anisotropy, cohesion, direct shear experiment, internal friction angle, shear strength.

1. Introduction

In recent times, the rapid development of cities, industry and transport, and an increasingly common occurrence redevelopment leads to a lack of land suitable for construction leading to situations of not choosing a place to build large and demanding buildings. That is why it is becoming more common such buildings are built in extremely complex geological conditions. Clay soil belongs to the complex engineering geological conditions of construction in the construction of various facilities in construction such as underground structures, underground garages, underground railways and the foundation of all buildings, especially indented buildings of irregular form.

When designing buildings and dimensioning load-bearing structures, using Mohr-Coulomb, is required determine the parameters of shear strength of the soil from which according to known methods and accordingly prescribed norms can calculate the bearing capacity of the foundation soil, active pressure, passive resistance, slope stability and more.

Most calculation models state that the soil is homogeneous and isotropic. Natural soil is in most cases very heterogeneous and anisotropic. In work of Shkola [1], based on calculation and analysis, it is stated that the anisotropic properties must be taken into account in differences in the shear strength properties of the soil with directions of at least 5% in the angle of internal friction and 10% in cohesion. Actually, number of soil properties involved in the formation of its discrete model, determines the number of isotropies, i.e., anisotropies in its qualitative and quantitative characteristics being studied.

Zaretsky [2] stated in his paper that the influence of the orientation of structural elements on the shear strength of clay soils and grain orientation in non-cohesive soils is qualitatively similar. This theme was also considered by many scientists such as Ž.E. Rogatkina [3], A.K. Loh – R.T. Holt [4], Z. Ewertowska-Madej [5], K.Y. Lo – V. Milligan [6] and A.V. Shkola – A. Kheydar [7], A. Aniskin and others [8]. Many of them confirmed the influence of clay anisotropy on shear strength parameters.

According to some papers, there are two basic types of soil anisotropy. The first refers to the layering of textural elements consisting of soil layers with different granulometric composition, structure and physical-mechanical properties Ornatskyi [9], and Harr [10]. The deviation of the soil from the isotropy in this case is defined by natural or artificial stratification. The process of sedimentation of rocks that form natural heterogeneous soil deposits are characterized by natural stratification while artificial stratification is realized in newly formed massifs through the technological specifics of construction. The second type of anisotropy is determined to be predominant by the orientation of anisometric particles in space. Soil particles are considered to be asymmetric and yes are oriented sedimentation and fit into layers under the action of gravitational forces predominantly horizontally with a larger area Ornatskyi [9]; Geniev [11] and Kandaurov [12].

The works of the Shkola [13] and Voitenko [14] provide a detailed review of the literature on experimental and theoretical investigations of shear strength anisotropy of natural and artificial soils.

An analysis of many papers concludes that the anisotropy of the shear strength of clay has not been sufficiently studied. Through this work it is wanted by laboratory testing of a series of undisturbed clay samples and by processing and analyzing the obtained results, investigate the difference in the shear strength parameters given the direction of the test in relation to the orientation of the samples in nature.

2. Methods

2.1 Materials

In this study, 18 clay test samples were investigated. The samples were taken from a clay pit to ensure they were as homogeneous as possible. The location of the clay pit is in Šenkovec (46.410704N, 16.407906E), in the northern region of Croatia (Figure 1). From this clay pit, clay is extracted to produce bricks.

Figure 1 – Šenkovec clay pit

Upon choosing the site within the clay pit, we removed the visibly disturbed surface layer of soil, which was 10.0 to 15.0 cm thick due to atmospheric influences. Subsequently, we excavated a rectangular ditch, 40.0 cm deep, enabling the extraction of a clay sample (Figure 2). To maintain the integrity of the sample, it was carefully wrapped in plastic to prevent moisture fluctuations. Emphasizing the study's objective, we took special care to preserve the natural orientation of the sample in space during both extraction and transport.

Figure 2 – Sample prepared for extraction (left) and sample with top mark (right)

2.2 Investigating physical characteristics of clay

A series of laboratory tests were performed to determine the physical characteristics of clay. Physical characteristics are essential to determine the uniformity of test samples. All experiments were performed in accordance with the prescribed standards for laboratory tests. The physical characteristics for each tested sample of clay (Table 1 and 2) and the particle-size distribution of clay (Figure 3) obtained by soil hydrometry are given below.

Table 1 – The physical characteristics of clay samples

Mark	Moisture w [%]	Density ρ $[g/cm^3]$	Dry density ρ_d $[g/cm^3]$	Particle density ρ_s $[g/cm^3]$	Porosity n [%]	Void ratio e [1]	Saturation S_r [%]
1a 0°	24.3	1.83	1.47	2.747	46.48	0.8683	76.88
1b 0°	23.3	1.85	1.50		45.25	0.8264	77.45
1c 0°	22.6	1.87	1.52		44.58	0.8043	77.19
2a 0°	22.7	1.88	1.53		44.18	0.7915	78.78
2b 0°	21.8	1.89	1.55		43.49	0.7695	77.82
2c 0°	25.4	1.93	1.54		43.90	0.7825	89.16
3a 0°	25.2	1.88	1.50		45.36	0.8300	83.40
3b 0°	24.9	1.92	1.54		43.95	0.7841	87.23
3c 0°	25.3	1.84	1.47		46.59	0.8722	79.68
1a 90°	24.2	1.89	1.52		44.66	0.8070	82.38
1b 90°	26.7	1.88	1.48		46.06	0.8539	85.89
1c 90°	24.7	1.88	1.51		45.12	0.8220	82.54
2a 90°	25.6	1.86	1.48		46.13	0.8564	82.11
2b 90°	26.3	1.91	1.52		44.84	0.8130	88.86
2c 90°	25.4	1.87	1.49		45.66	0.8402	83.05
3a 90°	226	1.87	1.52		44.54	0.8030	77.32
3b 90°	24.7	1.90	1.53		44.41	0.7989	84.93
3c 90°	26.6	1.93	1.52		44.59	0.8046	90.81

Table 2 – The mean values of physical characteristics for samples in 0° and 90°

Test direction	Moisture w [%]	Density ρ $[g/cm^3]$	Dry density ρ_d $[g/cm^3]$	Particle density ρ_s $[g/cm^3]$	Porosity n [%]	Void ratio e [1]	Saturation S_r [%]
0°	23.9	1.88	1.51	2.747	44.86	0.8129	80.84
90°	25.2	1.89	1.51	2.747	45.11	0.8221	84.21
Differences	1.30	0.01	0	0	0.25	0.0092	3.37

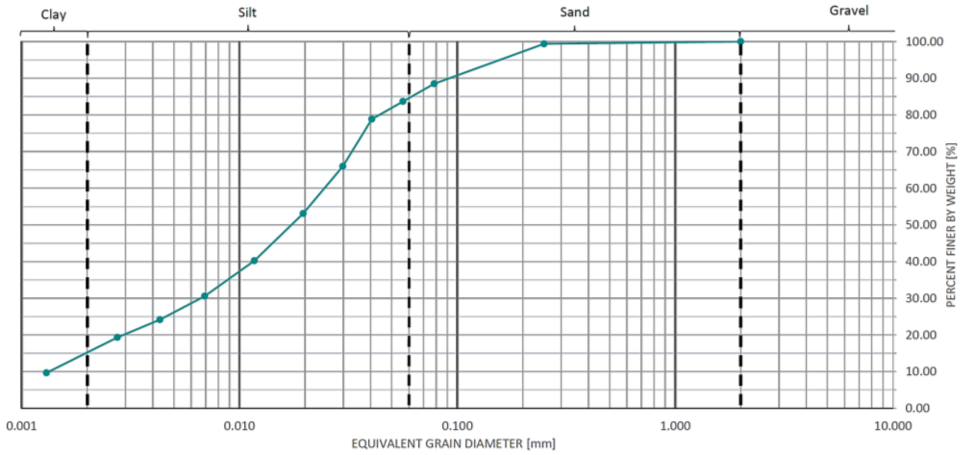

Figure 3 – Particle-size distribution of the clay

From the obtained results of the physical characteristics of the clay samples, we can conclude that the samples are enough uniform and they are suitable for direct shear testing. Considering on the long-time duration of the experiments, the moisture did not change significantly.

2.3 Methodology of experimental research

A commonly used device for laboratory determination of shear strength parameters is the device for direct shear.

In this case, for determination of the shear strength parameters it was used an automatic direct shear apparatus “27-WF21E80 Shearmatic EmS” manufactured by Controls Group and Wykeham Farrance (Figure 4).

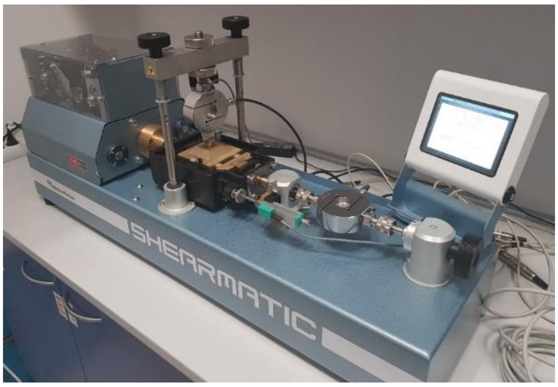

Figure 4 – Direct shear apparatus “Shearmatic” during testing

Shearmatic is a standalone automatic apparatus with electro mechanic servo actuation for direct/residual shear testing. It incorporates two high resolution stepper motors with high precision transmissions for applying and retaining forces. It also contains horizontal and vertical displacement transducers for displacement measurement. We control the device using software via a touch screen that allows us to adjust the test settings. We use the screen to run, pause and stop the experiment, and numerically and graphically monitor the readings during experiments execution. The big advantage of this device is that, depending on the settings, it starts automatically direct shear experiment after completed consolidation. The device saves all read data to a external memory in TXT format.

There were performed three series of direct shear experiments for each of two different directions in relation to the horizontal, 0° and 90° (Figure 6). Each series included three direct shear tests at different normal stress – 50.0 kPa, 100.0 kPa and 200.0 kPa at shear rate velocity of 0.01 mm/min. In total it is 18 direct shear tests (2 directions×3 series×3 tests). All tests were performed in accordance to British Standard BS 1377-7:1990 clause 4 [15].

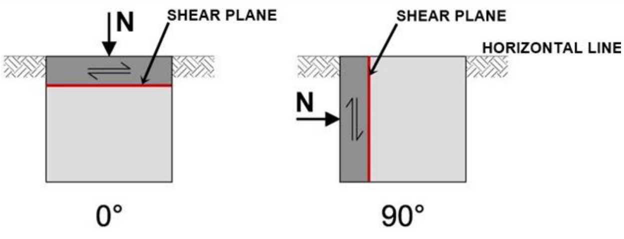

Figure 5 – Direction of sampling and shear (N- normal stress)

The samples are shaped with a mold to dimension 6.0×6.0×2.0 cm with special attention to the natural orientation of the samples in space (Figure 6).

a) Shear direction 0°

b) Shear direction 90°

Figure 6 – Sample shaping

These experiments will allow an assessment of the shear direction influence on the values of the shear strength parameters, angle of internal friction (φ) and cohesion (c).

3. Results and Discussion

All experimental data were obtained from Shearmatic in TXT format. Data were processed in Microsoft Excel and interpretated in figures (Figures 7-12).

Peak value of tangential stress was determined in curve maximum according to standard method [15]. In each series of tests, the result is three peak values of τ for each vertical stress σ. Shear strength parameters were calculated with linear regression.

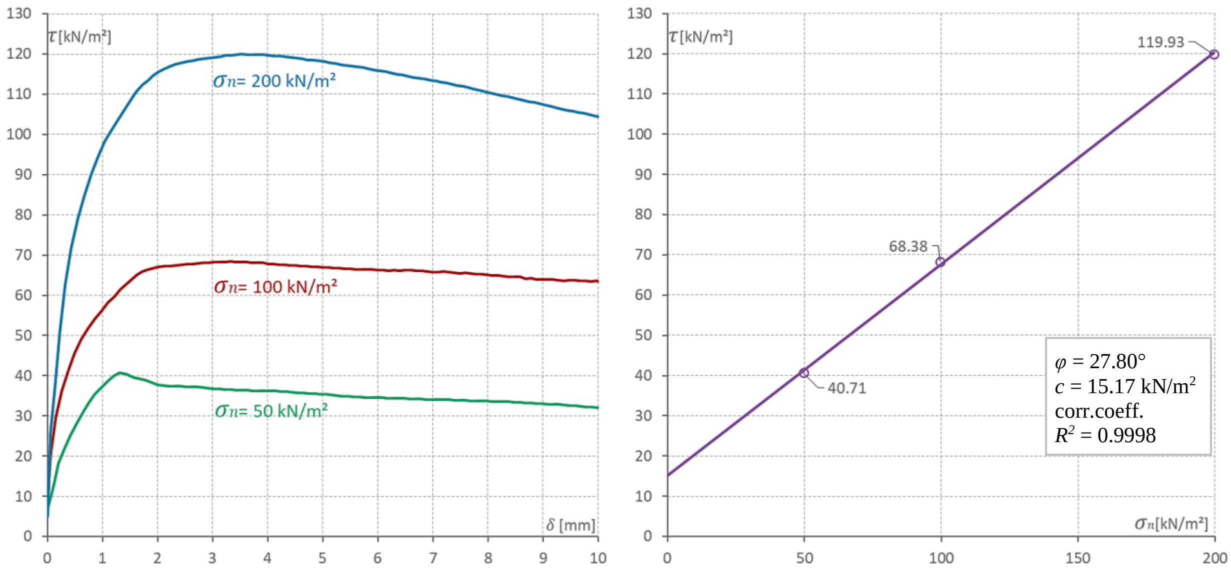

Figure 7 – Analysis of 1 test direct shear data for direction 0°

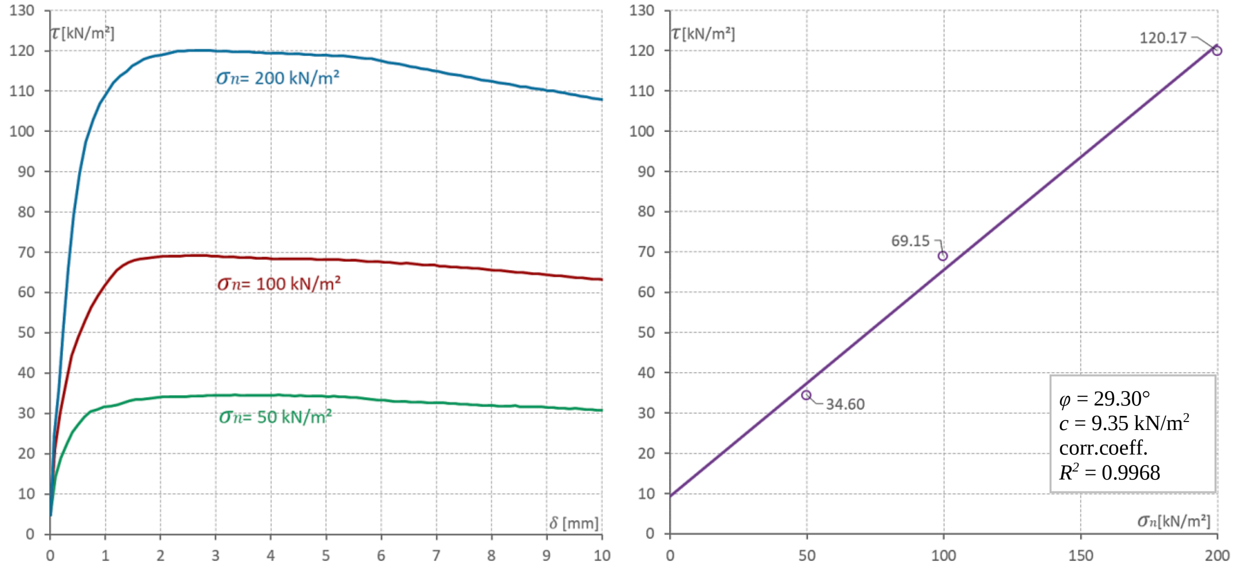

Figure 8 – Analysis of 2 test direct shear data for direction 0°

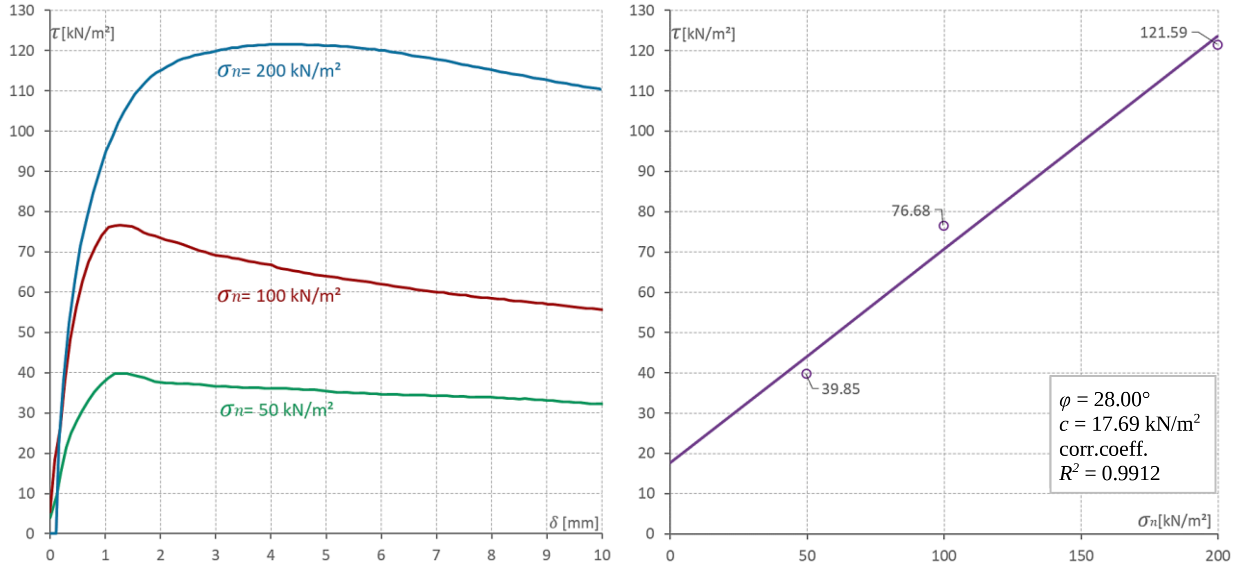

Figure 9 – Analysis of 3 test direct shear data for direction 0°

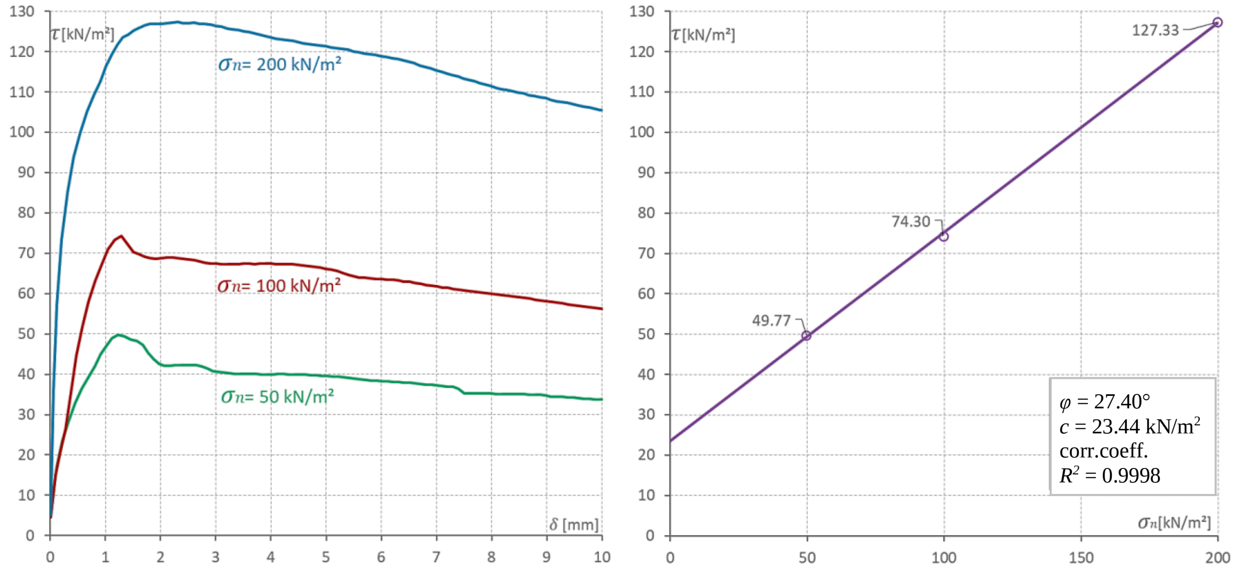

Figure 10 – Analysis of 1 test direct shear data for direction 90°

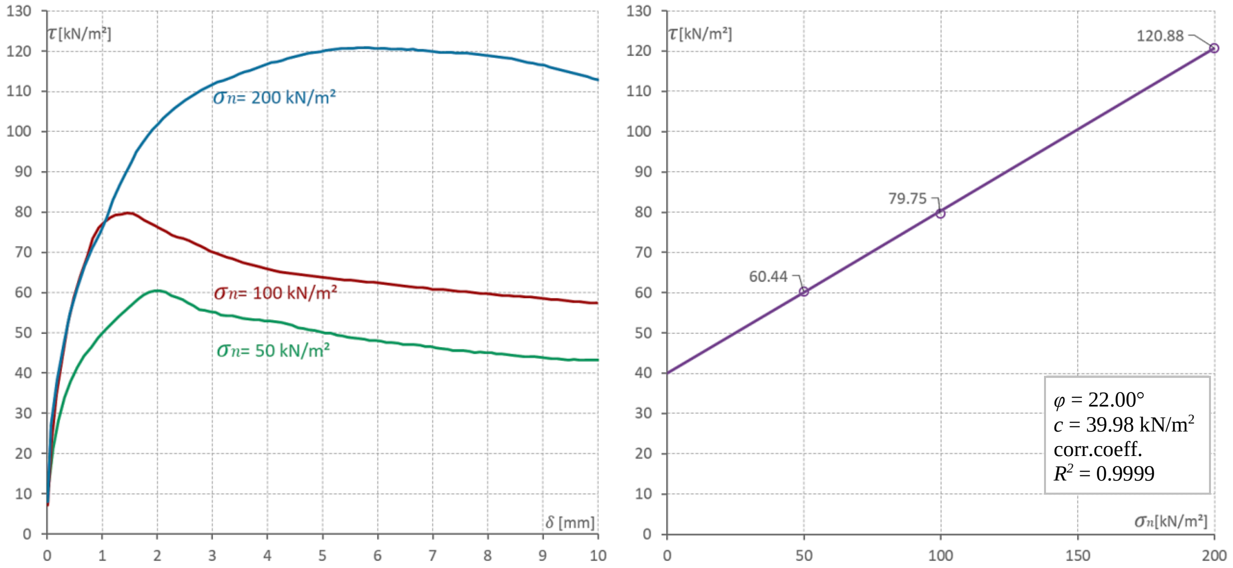

Figure 11 – Analysis of 2 test direct shear data for direction 90°

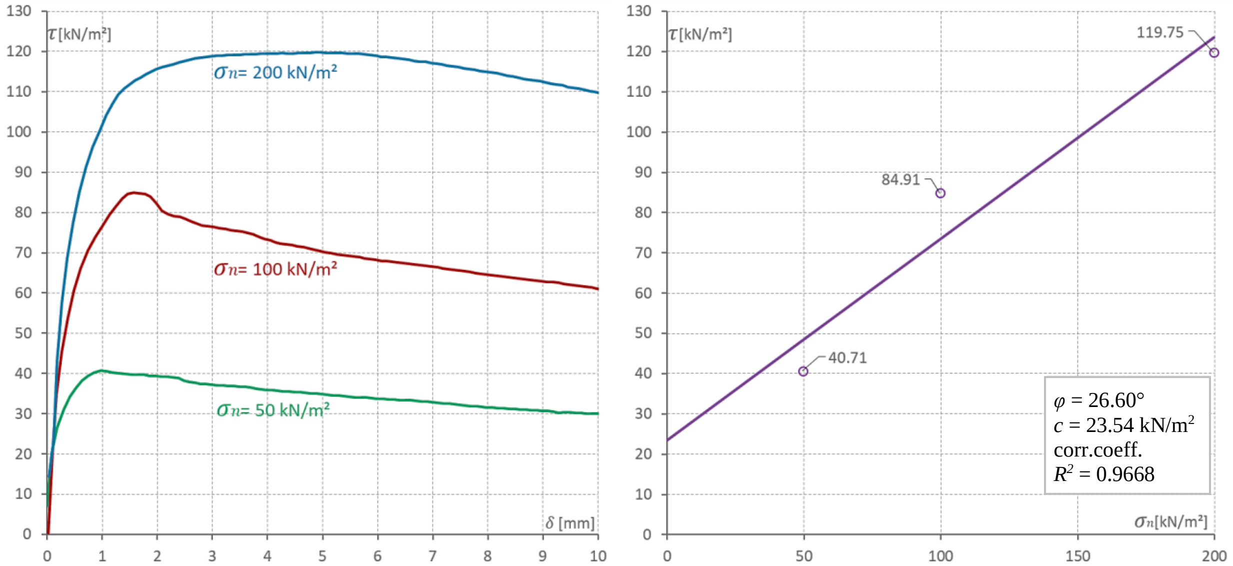

Figure 12 – Analysis of 3 test direct shear data for direction 90°

Considering that three series of direct shear experiments were performed for each of two different directions in relation to the horizontal (0° and 90°), the mean value of the measured data for each of the directions was calculated and the obtained values of shear strength parameters were analyzed (Table 3 and 4).

Table 3 – Mean value of direct shear data for direction 0°

Measured			Linear regression			
σ $[kN/m^2]$	τ $[kN/m^2]$	$\tau_{regres.}$ $[kN/m^2]$	c $[kN/m^2]$	*tg φ* [1]	*φ* [°]	*correl. coeff.* [1]
0.00 49.54 99.52 199.56	0.00 38.39 71.40 120.56	14.07 40.80 67.78 121.77	14.07	0.5397	28.4	0.9970

Table 4 – Mean value of direct shear data for direction 90°

Measured			Linear regression			
σ $[kN/m^2]$	τ $[kN/m^2]$	$\tau_{regres.}$ $[kN/m^2]$	c $[kN/m^2]$	*tg φ* [1]	*φ* [°]	*correl. coeff.* [1]

0.00 49.63 99.56 199.58	0.00 50.31 79.66 122.65	28.99 52.56 76.28 123.78	28.99	0.4750	25.4	0.9966

The analysis of the obtained results of the direct shear test showed significant differences in the values of the shear strength parameters with considering to the test direction. The angle of internal friction (φ) is higher by 3.0° or 11.81% in the test at an angle of 0° in relation to the horizontal. A much more significant difference is visible in cohesion (c). The results showed that the cohesion (c) in the 90° test was higher by 14.92 kN/m² or 106.04%. Significant difference can be explained by particle orientation. The similar result with a less pronounced difference was obtained by authors: Ž.E. Rogatkina [3], A.K. Loh – R.T. Holt [4], Z. Ewertowska-Madej [5], K.Y. Lo – V. Milligan [6] and A.V. Shkola – A. Kheydar [7].

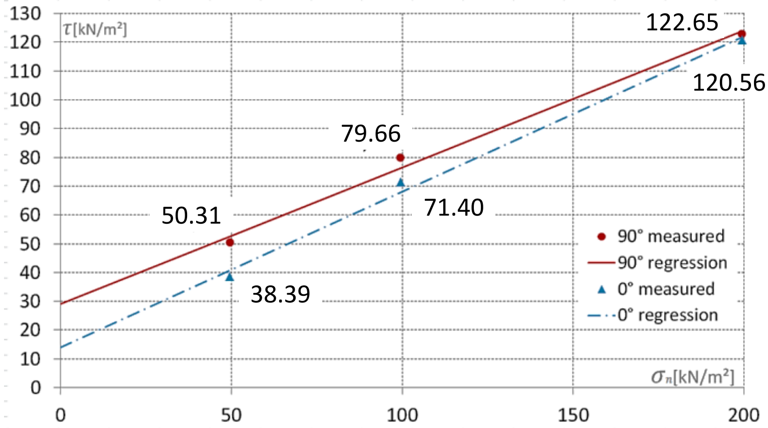

Figure 13 – Analysis of mean values direct shear data for direction 0° and 90°

Table 5 – Analysis of shear strength parameters for direction 0° and 90°

Parameter	0°	90°	Difference	
			[1]	[%]
$c\ [kN/m^2]$	14.07	28.99	14.92	106.04
$\varphi\ [°]$	28.4	25.40	3.00	11.81

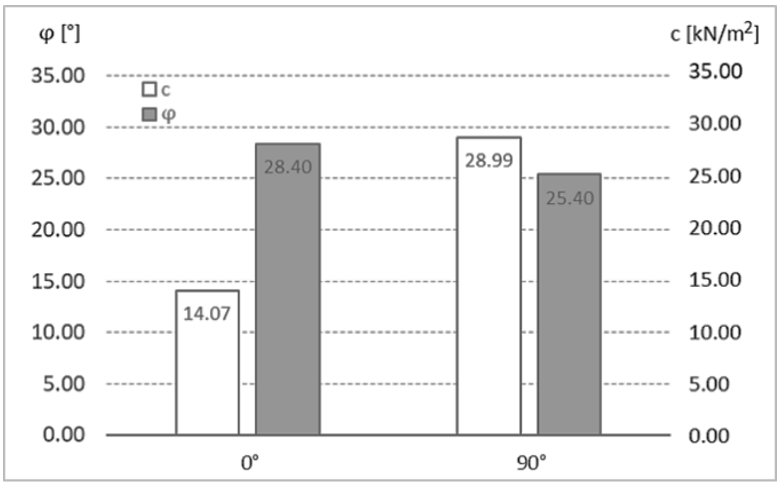

Figure 15 – Shear strength parameters for direction 0° and 90°

It can be concluded that anisotropy of shear strength of clay is not negligible and according Shkola [1], should be considered in practical calculations, designing and dimensioning of structures.

Also, when conducting investigation works on anisotropic soils, the natural orientation of the test specimens and the direction of the tests should be considered as it proposed Shkola in [1].

4. Conclusions

1. Three series of direct shear experiments of clay were performed for each of two different directions, 0° and 90° in relation to the horizontal (18 direct shear experiments). The shear strength parameters (cohesion and internal friction angle) of 0° and 90° were obtained.

2. The results showed that anisotropy in shear strength parameters of clay is significant. Angle of internal friction (φ) is 11.81% higher in the test at an angle of 0° and cohesion (c) is more than twice the value (106.04%) at an angle of 90°. Shear strength anisotropy of clay is significant and should be considered in practical calculations, design and dimensioning of structures.

3. Also, when conducting investigation works on anisotropic soils, the natural orientation of the test specimens and the direction of the tests should be considered.

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Article

Improvement of road infrastructure on the example of the Center-South transport corridor of the Akchatau-Akzhal section

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Abstract. The study investigates the enhancement of road infrastructure in the Center-South transport corridor of the Akchatau-Akzhal section, addressing the challenges posed by rapid road pavement deterioration due to increased traffic flow. By analyzing the natural and climatic conditions of the area, optimal concentrations of additives were determined to improve the properties of bitumen and asphalt concrete, with a focus on increasing strength and durability. Specifically, the addition of monoethanolamine to bitumen at a concentration of 0.08% led to notable improvements in key properties. The needle penetration depth at 25°C decreased from 80 to 71, indicating enhanced consistency. Moreover, the ring and ball softening point increased from 52 to 56, demonstrating increased resistance to temperature variations. Stretchability at 40 improved from 65 to 70, highlighting enhanced flexibility and durability. The study emphasizes the critical importance of quality construction and regular maintenance to ensure the durability and resilience of road networks to various factors. By utilizing innovative technologies and materials, such as modified binders with additives, the study showcases the potential to significantly enhance the performance, safety, and efficiency of road networks while reducing costs and environmental impact. The findings underscore the need for continued research and implementation of optimized solutions to improve road infrastructure sustainability and longevity.
Keywords: road infrastructure, transportation corridor, improvement, innovative technologies, bitumen, asphalt concrete, additives.

1. Introduction

Together with the growth of the transport industry and the increase in traffic flow, the problem of rapid deterioration of pavements arises. Operational stresses, including heavy vehicle traffic, exposure to weather conditions, and inadequate road construction and maintenance, lead to rapid deterioration and damage to the road surface. This not only increases infrastructure repair and maintenance costs, but also creates inconvenience for road users and jeopardizes road safety. Therefore, it is necessary to pay special attention to improving the quality of construction and regular maintenance of the road network to ensure its durability and resistance to various factors.

The introduction of innovative technologies and materials into the construction and maintenance of road infrastructure is essential to improve its durability, safety and efficiency. Research shows that modifying bitumen using various additives such as recycled high-pressure polyethylene, polypropylene, polymers and carbon nanotubes helps to significantly improve its performance and durability of asphalt mixtures [1-2].

The additives effectively affect the rheological properties of bitumen, reducing its stiffness, increasing resistance to low-temperature cracking, increasing fatigue strength and overall resistance to rutting [2-3]. The optimum concentration of these additives plays a key role in achieving the desired results, and exceeding the optimum dosage can negatively affect the improvement of bitumen properties [4-5].

The use of modified bitumen binders with additives of polymer industry wastes, such as recycled high-pressure polyethylene and polypropylene, also makes it possible to significantly improve the performance characteristics of bitumen and increase the strength properties of road pavements [6].

Special attention is given to the geotechnical studies necessary to understand the characteristics and behavior of expansive soils during road construction. This is important to prevent structural problems and premature failure of road infrastructure [7].

Using effective modifications, additives and rejuvenators, the performance, safety and durability of road networks can be significantly improved, while reducing costs and negative environmental impact.

Thus, the main objective of research in this area is to determine the optimum concentrations of additives that can maximize the properties of bitumen and asphalt concrete and provide improved strength and durability of road surfaces.

1. Methods

The road section within the reconstruction of the Center-South corridor on the Akchatau-Akzhal section was selected for the study.

The analysis of natural and climatic conditions of the area of reconstruction of the Center-South corridor section showed the following.

Road and climate zone – IV.

Normative frost depth of soils:

- loams and clays - 158 см;
- sandy loam and fine, dusty sands - 193 см;
- medium coarse, gravelly sands - 207 см;
- coarse clastic - 234 см.

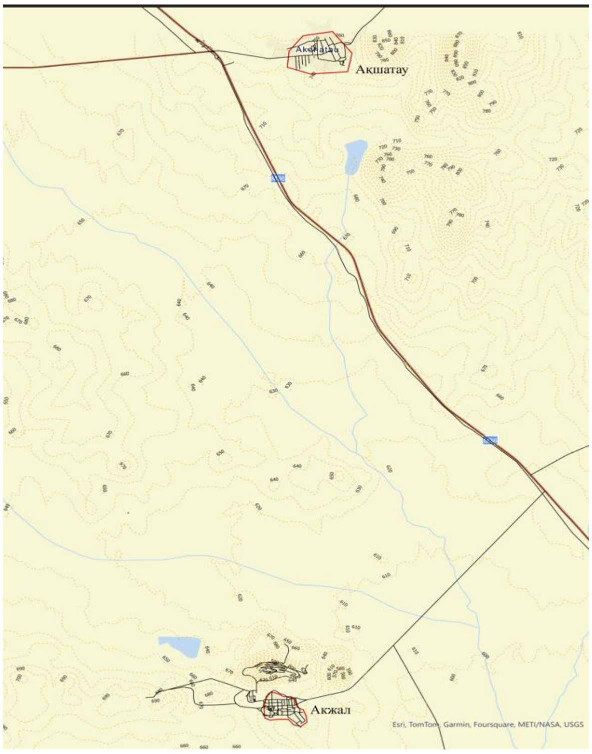

Figure 1 – Situation diagram of the highway

The road section selected for reconstruction and the corridor within the "Center-South" transport corridor is characterized by special natural and climatic conditions that need to be taken into account in the design and construction of the road.

The road corridor is located in a weakly hilly flat terrain within the Central Kazakhstan fine-grained sedimentary basin. The geological structure includes coal-bearing deposits, coarse-grained granites, alluvial deposits, dealluvial-proluvial deposits and eluvial Quaternary deposits.

Adverse physical and geologic processes observed in the area include salinization, weathering, waterlogging, lateral and bottom erosion. As a result, the existing road surface is damaged, with potholes, cracks and eroded edges.

Existing small man-made structures such as culverts are mostly in poor condition and require complete replacement. In addition, three bridges over the Zhamshi River are in an emergency condition and need to be replaced with new structures.

The road rehabilitation project aims to meet the technical characteristics of a Category I-b road, taking into account factors such as road category, speed limits, number of lanes, road width, shoulder width, alignment radius and visibility requirements.

The detailed design provides for the reconstruction of the road section according to I-b category standards.

Table 1 – Technical parameters of the highway

No. n/a	Name of parameters	Parameters	
		according to [8]	Adopted in the draft
1	Road category	I-b	I-b
2	Estimated speed of traffic, km/hour	120	120
3	Number of traffic lanes, pcs.	4	4
4	Lane width, m	3.75	3.75
5	Carriageway width, m	2x(3.75x2)	2x(3.75x2)
6	Shoulder width, m	3.75	3.75
7	Smallest width of the shoulder reinforcement strip, m	0.75	0.75
8	Width of separating strip between different directions of traffic Bss, m	2 м + fence width	3.0
9	Smallest width of the reinforcement strip on the dividing strip, m	2x1.0	2x1.0
10	Width of subgrade, m	2x(3.75x2)+7.5+ Bss	25.5
11	Transverse slope of roadway, ‰	20	20
12	Transverse slope of shoulder, ‰	40	40
13	Highest longitudinal gradient, ‰	40	21
14	The shortest visibility distance for stopping an oncoming vehicle, m	250 450	250 450
15	Smallest radii of curves in the plan, m in longitudinal profile: convex, m concave, m	 800 15000 5000	 1020 15000 5000

The use of bitumen as a road binder requires careful consideration of its properties, including penetration depth, softening point, adhesion, stability and temperature sensitivity.

Various tests and measurements of bitumen have been carried out to evaluate its suitability for road construction.

The introduction of additives and modifiers such as polymers, carbon nanotubes and rejuvenators can improve the properties and performance of bitumen and asphalt mixtures. These modifications can improve viscosity, elasticity, rutting resistance, fatigue resistance, and low-temperature performance.

The study identified specific optimum dosages and concentrations of the additives and rejuvenators used to achieve the desired improvements without degrading the overall performance of the asphalt concrete mixtures.

To improve the properties of bitumen, the effects of various plasticizers that enrich the dispersion medium of bitumen, lower its softening point and increase penetration were investigated. Laboratory experiments were carried out with samples of bitumen grade BND 100/130 weighing 100 grams (Table 2).

Table 2 – Results of laboratory tests on determination of bitumen parameters

Indicators	BND 100/130 grade
Needle penetration depth at:	
25°C	80
0°C, not less than	20
Softening temperature by ring and ball, °C, not lower	100
Stretchability, cm,not less:	
at 25°C	2
0°C	1
Brittleness temperature, °C, not higher	40
Flash point, °C, not lower	220

The following methodology was used to determine the physical and mechanical properties of bitumen, such as needle penetration depth, softening point, extensibility and brittleness temperature.

In determining the depth of needle penetration at 25°C and 0°C, the standard test method according to [9] was used, using a test bench with adjustable needle weight and a marker to measure the penetration of the needle into the bitumen (Figure 2). Softening temperature by ring and ball was determined using the test method according to [10], using a special device where bitumen is heated and its softening temperature is determined by the device readings at penetration of a cone-shaped indenter (ring) and ball into the heated bitumen sample (Figure 3). Tensile strength at 25°C and 0°C was measured in accordance with the test procedure [11], where the bitumen sample was heated to the required temperature, then measured its tensile strength in a special testing device (Figure 4). To determine the brittleness temperature, the test methodology was used in accordance with the requirements of [12], where a specialized test apparatus was used, in which the bitumen was heated and the temperature at which the bitumen becomes brittle was determined (Figure 5).

The amino alcohol monoethanolamine was added to these samples at concentrations of 0.02%, 0.05%, and 0.08% at 180°C. Using a laboratory dispersant, the samples were mixed. Then physical and mechanical properties of the newly obtained mixture were determined.

Figure 2 – Determination of bitumen viscosity on penetrometer

Figure 3 – Determination of bitumen softening temperature on the "ring and ball" device

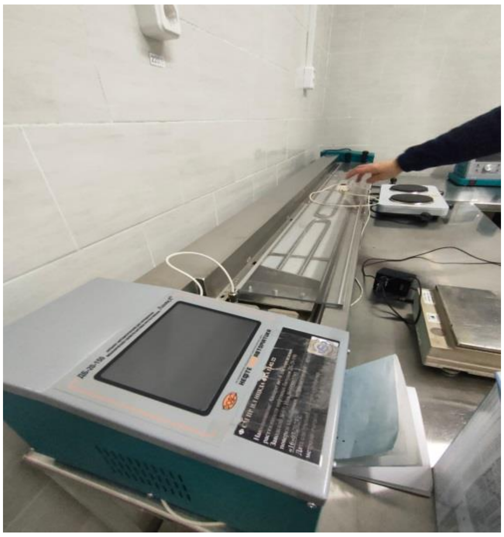

Figure 4 – Determination of bitumen extensibility on a ductilometer

Figure 5 – Bitumen heater

3. Results and Discussion

The performance of bitumen with monoethanolamine concentrations is presented in Table 3.

Table 3 – Performance comparisons

Indicators	BND 100/130	Monoethanolamine 0.02%	Monoethanolamine 0.05%	Monoethanolamine 0.08%
Needle penetration depth at 25°C	80	73	75	71
Needle penetration depth at 0°C	20	23	25	28
Ring and ball softening point	100	52	56	53
Stretchability at 25°C	40	65	95	70
Stretchability at 0°C	1	3.2	3.8	3.1
Brittleness temperature	40	18	22	19

From the table it can be seen that the concentration of monoethanolamine 0.05% provides optimal physical and mechanical properties of bitumen grade BND 100/130, such as increased needle penetration depth at 25°C, increased extensibility at 0°C and increased brittleness temperature. These results indicate that this additive concentration is effective in improving bitumen properties and can be recommended for use in road construction practice.

The mass density of oxygen molecules in the reference bitumen film after 5-min diffusion at different temperatures (25°C, 50°C and 100°C) was also investigated. The study revealed that the best ratio of oxygen molecule mass density in the bitumen film was observed at 50°C, indicating that more desirable bitumen properties were obtained at this temperature (Figure 6).

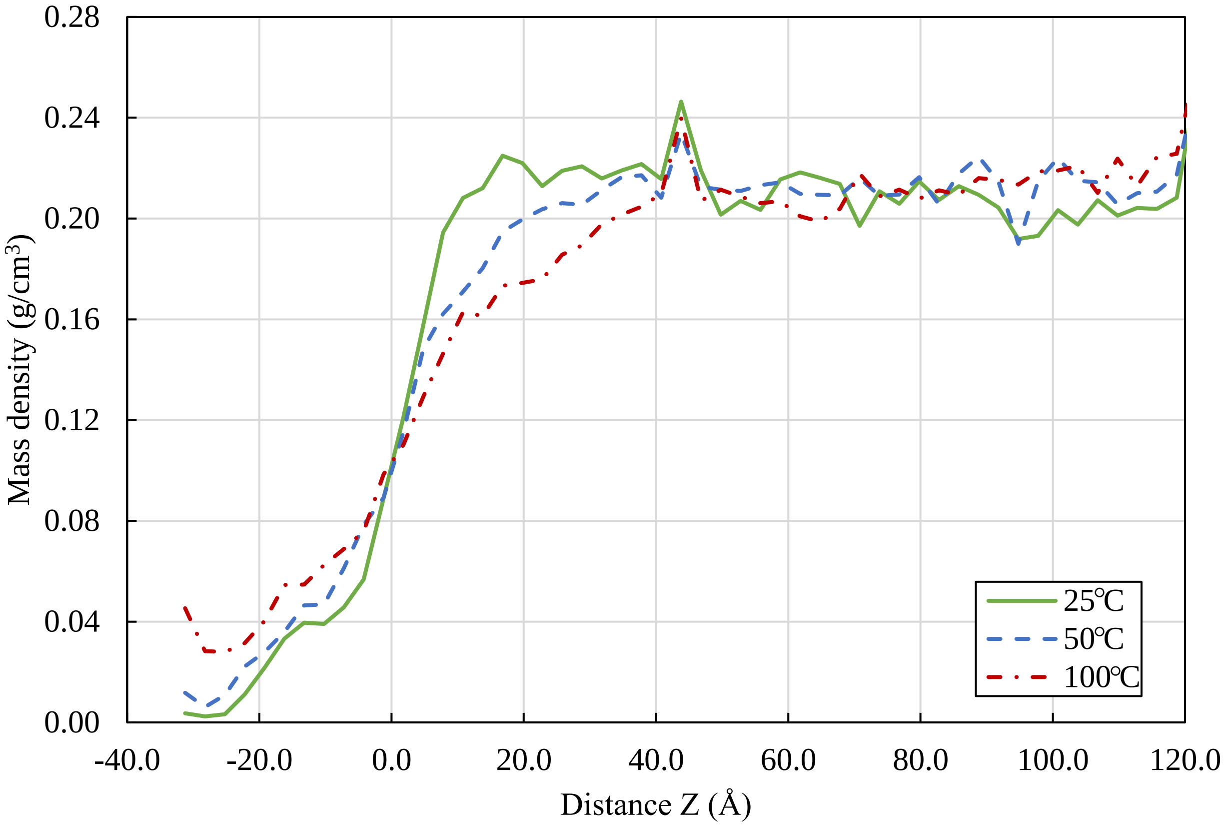

Figure 6 – Dependence of mass density of oxygen molecules in bitumen film on distance at different temperatures

Thus, the results of the study confirm the effectiveness of monoethanolamine concentration of 0.05% to improve the properties of bitumen and indicate the importance of taking into account the temperature conditions when working with bituminous materials to achieve optimal characteristics of road surfaces.

Based on the results of experiments and calculations in accordance with the requirements of standards [8] and [13] the following design of pavement for the road surface of the transport corridor "Center-South" section Akchatau-Akzhal was adopted (Figure 7):

- the top layer of the pavement is represented by crushed stone-mastic asphalt concrete ShchMA-20 in accordance with [14], with a thickness of 0.05 m, containing polymer additives;
- the bottom layer of the pavement consists of hot dense coarse-grained asphalt concrete mixture of type B of mark I according to [1]on bitumen of mark BND-100/130, with a thickness of 0.10 m and a new binder containing monoethanolamine at a concentration of 0.05%;
- the top layer of the base is made of hot porous coarse-grained asphalt concrete mixture of II grade on bitumen BND 100/130 according to [15], with a thickness of 0.12 m;
- the bottom layer of the base consists of black crushed stone, laid by the method of wedging in accordance with the standard [15], with a thickness of 0.10 m;
- the additional base layer is represented by the soil reinforced with a complex binder (composition: soil - 58%, gravel and woody soil - 38%, cement - 4%, "Roadzyme" - 0.002%), with the grade M20 and strength class F25, with a thickness of 0.20 m;
- on the dividing strip of the administrative and dividing lane the pavement is made of fine-grained dense asphalt concrete of type B - mark II on bitumen BND 100/130, with a thickness of 0.04 m.

Shoulder reinforcement is carried out in two stages: the first stage uses a mixture of crushed stone of 20-40 mm fraction and gravel and woody soil, with a thickness of 0.15 m; the second stage uses material from the dismantling of the existing pavement, with a thickness of 0.15 m.

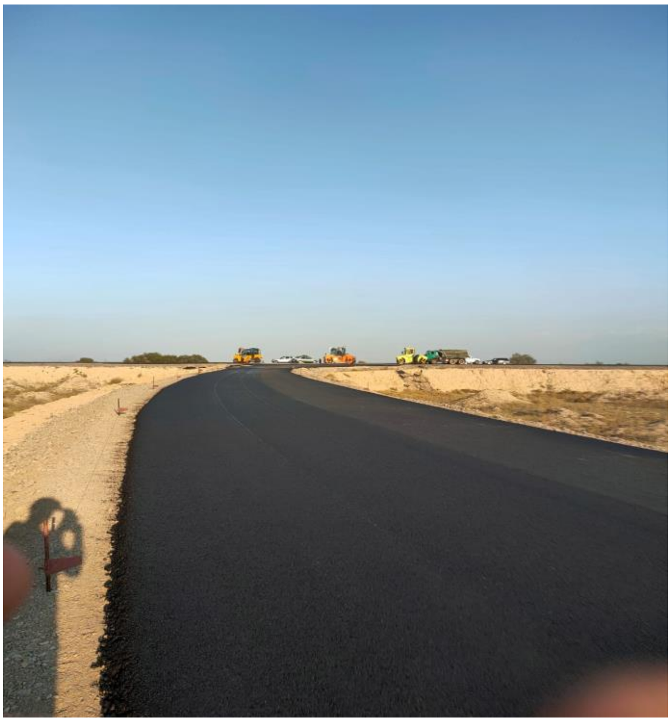

Figure 7 – General view of the highway after reconstruction

4. Conclusions

Based on the results of the experiments, the following conclusions can be drawn:

1. Addition of monoethanolamine to bitumen leads to the improvement of penetration depth, softening temperature, elongation and brittleness temperature;

2. Mass density of oxygen molecules in bitumen film shows the best ratio at 50°C, indicating desirable properties of bitumen at this temperature;

3. The use of innovative technologies and materials, such as modified binders with the addition of spent polymers and concentration optimization, can significantly improve the durability, safety and efficiency of road networks while reducing costs and environmental impact;

4. Geotechnical research is critical to understand the characteristics and behavior of expansive soils during road construction to prevent structural problems and premature deterioration of road infrastructure;

5. Adoption of innovative technologies and materials in the construction and maintenance of road infrastructure is necessary to improve its durability, safety and efficiency;

6. Attention should be paid to improving the quality of road construction and regular maintenance to ensure the durability and resilience of road networks to various factors.

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Article

Main problems in the operation of metal gas discharge pipes

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Abstract. This paper considers the main problems of operation of metal gas discharge pipes on the example of research and survey work on the examination of building structures of the exhaust tower with three gas discharge trunks 180 m high, flue gas purification unit of the sintering shop of LLP "NDFZ" in Zhambyl region. Analysis of the actual technical condition, considered in this article exhaust tower with three gas discharge shafts, according to the results of the survey, its volume-planning and structural solutions, showed its generally unrepairable, due to the mass of characteristic critical and unacceptable damage to the load-bearing elements of the frame, physical fatigue of materials, significant corrosion wear of metal structures, which will require a significant amount of proposed repair and maintenance work to eliminate them. The conducted complex of researches has shown that the service life of chimneys built before the 1960s and after has practically expired. Repair or reconstruction of chimneys using previously mastered technologies and materials does not solve the issues of reliability improvement. Rational solutions to these problems are periodic technical expertise by highly specialized organizations and implementation on its basis of methods of overhaul of both gas-exhausting trunks and building structures and interface units, wide implementation of which will solve the problem of extending the life of chimneys.
Keywords: structure, exhaust tower with gas exhaust shafts, technical inspection, defects, corrosion, experiments, research.

1. Introduction

The industry of Kazakhstan has received the development in 50-60th years of XX century, thus in the Republic, owing to the pronounced raw material character of its economy, the branches of extractive industry have received the predominant development. And though existence and development of the basic branches of industry were supported not by intensification of production, but mainly at the expense of increase of capital investments, input of new capacities, nevertheless, in basic, especially in raw material branches of the Republic there was no stagnation. In 1961-1965 alone, more capital investments were utilized in the national economy of the Republic than in all previous years of Soviet power, thanks to which the industrial potential of the Republic doubled. 729 large industrial enterprises and 535 workshops were put into operation. In the second half of the 1960s, another 445 large enterprises and workshops were put into operation, hundreds of plants and factories were reconstructed and technically re-equipped [1-2].

Many of these enterprises became city-forming enterprises and, accordingly, the cities had to be provided with electricity and heat/water supply through the construction of CHPPs [3].

Today, many of the industrial enterprises, including CHPPs, continue to operate. However, most of them have a large physical and moral deterioration of both bearing and enclosing building structures of buildings and structures, and engineering networks. Various topical problems of the technical condition of industrial buildings and structures in Kazakhstan are identified below [4-5].

Lack of regular maintenance: Many enterprises suffer from a lack of systematic maintenance of their buildings and facilities, which can lead to an accumulation of faults that can become serious problems over time [6].

Infrastructure deterioration: Many industrial buildings and facilities were built decades ago and are nearing the end of their useful life or have long since expired. This includes not only physical deterioration of materials, but also outdated HVAC systems, electrical networks, etc [7].

Environmental and health and safety issues: Unmaintained or improperly maintained facilities can become hazardous to workers and the environment. This can include the risk of collapse of old structures, leakage of hazardous substances, fires due to electrical faults due to accidents, and interruption of the city's life support [8].

Lack of adaptation to new technologies and standards: many industrial facilities are lagging behind in terms of technological innovation and safety standards. For example, lack of automated control systems or low energy efficiency can reduce the competitiveness of enterprises [9].

Environmental issues: outdated equipment and technologies are environmentally unsafe and lead to air, water and soil pollution. These problems require serious attention from both the owners and managers of enterprises, as well as from government and regulatory authorities, to ensure the sustainable development of Kazakhstan's industry [10].

Chimneys in industrial complexes play an important role in the removal of exhaust gases, vapors and other emissions from production facilities and operated under the continuous action of high-temperature aggressive gas flows and external natural factors that reduce the durability of the structure in connection with what requires periodic inspection to determine the actual technical condition of chimneys, which has certain specifics [11].

This article will consider one of the examples of technical inspection of bearing and enclosing structures of a chimney with violation of modes during their operation, almost complete absence of technical supervision, underestimation of the importance of technical diagnostic measures.

The purpose of this article is to consider an example of technical inspection of bearing and enclosing structures of a chimney with violations of modes during their operation. The main emphasis is made on the analysis of almost complete absence of technical supervision and underestimation of the importance of technical diagnostic measures. By considering this example, the article aims to identify current problems of the technical condition of industrial facilities in Kazakhstan and discuss the need for systematic maintenance and control to ensure the safety and sustainable development of the country's industry.

2. Methods

In 2023, specialists of the Research, Expertise and Design and Survey Kazakhstan Multidisciplinary Institute of Reconstruction and Development (KazMIRD) at the "Karaganda Technical University named after A. Saginov" carried out comprehensive research and survey works on the examination of building structures of the structure "Exhaust tower with three gas discharge trunks H=180m" of the flue gas purification unit of the sintering shop of "NDFZ" LLP in Zhambyl region.

Complex research and development work on examination of the object defined by the Customer's technical task in accordance with [12–16].

The year of construction and commissioning of the Object - 1978. According to [13] the service life of such structures should not exceed 30 years, moreover, the object at the time of the survey is operated for more than 45 years in the absence of capital repairs required by the norms.

The preliminary survey determined the volume-planning and structural solution of the object.

The foundation for the main load-bearing tower is a monolithic reinforced concrete strip foundation (ring-shaped in plan) made of M200 grade concrete. The foundation for each of the tower pyramidal base struts is a monolithic reinforced concrete freestanding foundation made of M200 grade concrete.

The structural scheme of the Facility is of the tower type, which consists of a load-bearing tower and three gas discharge trunks designed from steel structures; in terms of the design scheme, the Facility is designed as a cantilevered rod rigidly fixed in the base. In this case, the supporting tower is a hexagonal prism (hereinafter referred to as the main supporting tower) with a height of 169.2m (relative elevation +169.200), which is pinched in the base and at the levels of elevations +19.200 and +49.200 is reinforced by a system of underpinnings (hereinafter referred to as the pyramidal base of the tower). The geometric invariability of the tower cross-section is ensured by horizontal ties located between the tower belts in the form of a triangle. The 180-meter-high gas discharge trunks are located outside the tower on remote cantilevered platforms. The absolute mark of 550.90 is taken as the relative mark ±0.000.

Figure 1 – General view of the Object

In order to reinforce the main load-bearing tower during its erection, the pyramidal base of the tower is designed as a spatial structure, which includes additional struts and guide beams, supported by a system of vertical and horizontal connections. The designed system of connections ensures spatial invariability of the pyramidal base of the tower at all stages of installation.

The outrigger cantilever platforms are designed for fastening the gas discharge trunks to them and transferring the loads from the wind and own weight of the trunk sections between the expansion joints to the supporting tower.

For climbing the tower, its maintenance and structural inspection, walking ladders and transition platforms were designed.

Continued monitoring and inspections will be crucial to ensure the structural integrity and safety of the tower over time.

3. Results

The technical condition of the object at the time of the survey is generally assessed by the category of significant damage, due to the presence of critical and inadmissible identified damage caused by long-term operation in conditions of medium and highly aggressive gas-air environment, as well as the impact of electrochemical corrosion. At the same time, it is necessary to take into account the impact of significant wind loads in this climatic region, as well as the location of the object under consideration in an earthquake-prone zone, which creates significant dynamic processes during operation in the form of chaotic vibrations of structures and their components, causing fatigue of materials. In addition, the above factors have radically changed the design scheme of the structure, which significantly reduces the load-bearing capacity of the frame of the extraction tower, due to the violation of the strength conditions of load-bearing steel structures, and also creates conditions for the possible loss of overall stability, in the form of its overturning.

The detailed instrumental inspection revealed significant defects and damages that reduce the load-bearing capacity and affect the serviceability, namely:

1) inspection of the foundations in the opened pits showed that the structures were made with deviation from the geometric parameters regulated by the album of the project drawings, in particular, the foundation for the load-bearing tower is made as a continuous slab, while the project provides for a strip foundation (in the plan in the form of a ring), also, the bottom (sole) of the foundation is actually located at the level of relative elevation -3.300, but the project specifies elevation -3.500. The geometric parameters of the foundation for the tower's base struts also do not correspond to those given in the project. According to the project, the specified free-standing foundations should have been made of pyramidal shape with one vertical face without ledges with a gentle (at an acute angle) extension to the bottom, but in fact the foundation structure is made in the form of a triangle with two sloping (when viewed in profile as in the drawing) and two vertical side faces with a developed bottom part (see Figure 2).

Figure 2 – General view of the opened test pits

2) characteristic critical damage to the supporting foundation base of the load-bearing tower belt: the foundation bolts are broken, a rattling sound is heard when tapping - the damage was found in 3 bolts out of 12, which is 25% of the total number of bolts (see Figure 3);

3) significant damage characteristic for all foundation bolts of the support base (see Figure 4): continuous irregular corrosion of bolts with damage of up to 14% of the area of the design cross-section, the residual diameter of bolts in localized areas of the non-threaded part is 69mm (M80 bolts are regulated by the project);

Figure 3 – Breakage of foundation bolts

Figure 4 – Continuous irregular corrosion of foundation bolts

4) critical damage to all the chords of the load-bearing tower, due to the presence of characteristic closing nodes at the levels of +19,200 and +49,200, the presence of which changes the design scheme of the main load-bearing tower, thus significantly reducing its load-bearing capacity and creating conditions of unsuitability of the load-bearing tower as a whole under the action of design (project) loads (see Figure 5);

Figure 5 – Characteristic critical defect: weld rupture in the connection between the strut attachment plate and the fascia

5) the presence of characteristic critical damage in the form of ruptures and cracks in the welded joints of girder strut attachment assemblies, as well as due to the presence of irregular corrosion of girder walls and flanges in the support and span sections with up to 30% of the cross-section of the elements, In addition, there are deformations of overlays (bulging), due to the development of crevice corrosion in the gaps, the size of corrosion products in some places reaches a thickness of 8 mm, indicating a significant reduction in load-bearing capacity and threatening, if no action is taken, the collapse of structures (Figure 6);

- the presence of gaps and cracks in welded joints in the nodes of fixing elements on beams and links, indicating the loss of their load-bearing capacity and threatening their collapse (Figure 7);

Figure 6 – Fracture of the weld along the entire length of the joint

Figure 7 – Fracture of the weld at the fusion boundary along the entire length of the joint

6) a set of critical defects and damages of the gas exhaust trunks No.1, No.2 and No.3, namely (Figures 8, 9):

- deviations from the original design in terms of reduction of the thickness of the shell sheets and trunk support rings in comparison with the original design;
- deviations from the design in the form of non-compliance of the support units of trunk support beams;
- ruptures of shaft shells in the places where the support ring ribs meet;

- critical damage typical for the majority of similar connections of support beams: breaks and cracks in welded joints in the areas of support of elements; in addition, significant damage typical for the majority of similar assembly overlap welded joints of beam support assemblies: development of crevice corrosion, thickness of corrosion products is 5...10 mm;
- critical damage typical for all elements of sliding supports: ruptures of welded joints of guide angles with the beam, ruptures of welded joints of support plates of sliding element (channels) with ring ribs; in addition, development of crevice corrosion between contact surfaces of elements, thickness of corrosion products reaches 30 mm;
- cracks along the entire length of the butt-welded joints of the butt-welded assembly of the support ring ribs, as well as the ring support ribs are welded to the barrel shell with a one-sided weld; butt welded joints of the ring ribs are made with incomplete welds, there are also metal inclusions in the joints;
- gas-diverting trunks #1 and #3 have deviation from the vertical plane (roll), the values of which exceed the values allowed by the burrows, trunk #1 - deviation of 540 mm, trunk #3 - deviation of 550 mm [the permissible value of the line of intersection planes from the vertical at a height of h≈140m is 420mm according to [17];
- the results of the performed works on thickness measurement of gas-venting trunks have shown that at the whole height of trunks there is a significant wear of the trunk shell, with damage of up to 20% of the thickness of the sheets; at the same time, in some areas, at the level of the heads, the wear reaches 65%;
- in localized areas, replacement of the gas venting shaft sheathing sheets with carbon structural steel sheets is observed.

Figure 8 – Support ring of gas outlet shaft No.1 at the level of site level at level +49.200

Figure 9 – Rolls and loss of local stability of the walls of the support beams of gas outlet shafts characteristic for beams at the site level at level +49.200

Corrosive wear of metal structures of the Facility in some areas occurs on average with an intensity of more than 0.22mm/year (i.e., for 45 years of operation of the Facility the amount of corrosion damage of steel structures in some areas reaches 10mm). Based on this, the degree of aggressive impact of the operating environment on the structures is characterized as medium-aggressive, which excludes the possibility of operation of the building structures of the Object without special protective chemical-resistant paint and varnish coatings.

The analysis of the technical condition of the Object according to the results of the performed survey, its volume-planning and structural solutions, showed in general its emergency condition, unrepairable, due to the mass of characteristic critical and unacceptable damage to the load-bearing elements of the framework, physical fatigue of materials, which will require a significant amount of proposed repair and restoration work aimed at ensuring the normative load-bearing capacity and serviceability in the conditions of already

Due to the above-mentioned defects and damages, it was decided to dismantle the extraction tower with three gas discharge trunks (H=180m).

However, taking into account the critical importance of the object for ensuring the continuous nature of the Customer's production, the repair and restoration works on the object are theoretically possible, but technically extremely difficult, associated with high labor costs and associated with significant risks in the work.

Under the current conditions, in the presence of established defects and deviations of mass character in the gas-venting trunks, the development of working technical solutions to restore serviceability, including strengthening and replacement of individual structures, followed by their qualitative implementation was inexpedient. In this regard, KazMIRR Institute gave recommendations for the complete replacement of gas exhaust shafts No. 1, 2 and 3, including their supporting elements.

4. Conclusions

Analyzing the results of technical inspection, we can draw conclusions:

- chimneys in their bulk were built in Soviet times and practically exhausted their operational resource, therefore it is necessary to conduct periodic technical expertise by highly specialized organizations and on its basis perform major repairs, only in this way it is possible to extend the service life of chimneys;
- major overhaul or construction of new chimneys is expedient (high cost price) at present only for large industrial production facilities;
- relatively low cost of installation, as well as the speed of erection make the use of metal chimneys at small enterprises practically non-alternative;
- specialized design and construction organizations with experience in the design and construction of high-rise chimneys and (or) exhaust stacks should be engaged to develop the detailed design and to carry out the works.

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