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RESEARCH ARTICLE

THE EFFECT OF CEMENT GRINDING ACCELERATORS ON THE PHYSICAL AND MECHANICAL PROPERTIES OF CEMENT STONE

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Abstract. *Given the high energy intensity of the cement grinding process, the development of new and effective intensifiers is a pressing issue. The aim of this work is to develop grinding intensifiers from secondary raw materials produced during carpet manufacturing and gas processing wastes, and to study their effect on the structure and strength of modified cement stone. Methods of physicochemical analysis of raw materials and the obtained grinding intensifier, as well as standard methods for testing cement stone were used in the work. The possibility of obtaining an effective intensifier through the interaction of HYPAN (Hydrolyzed polyacrylonitrile) and diethanolamine was established. The optimal dosage of the grinding intensifier was determined to be 0.1%, which allows increasing the grade strength of modified cement stone by 31.2% and reducing the water consumption by 11%, which is explained by hydration due to the additional effect of reducing the electrokinetic potential between cement particles and increasing the fineness of cement particle grinding. Physicochemical analysis methods established that there is practically no free water in the modified cement stone sample and that the formation of the structure in the cement stone was achieved to a much greater extent. It has been established that, over time, the amount of C-S-H hydration products and calcium sulfoaluminate in the cement matrix of modified cement stone increases, which leads to an increase in the strength of the cement.*

Keywords: *grinding intensifiers, diethanolamine, HYPAN, cement stone, strength, structure*

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ҒЫЛЫМИ МАҚАЛА

ҰНТАҚТАУ ЖЕДЕЛДЕТКІШТЕРІНІҢ ЦЕМЕНТ ТАСЫНЫҢ ФИЗИКА-МЕХАНИКАЛЫҚ ҚАСИЕТТЕРІНЕ ӘСЕРІ

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Аңдатпа. *Цементті ұнтақтау процесінің энергетикалық шығынының жоғары екенін ескере отырып, жаңа және тиімді жеделдеткіштерді әзірлеу өзекті мәселе болып табылады. Бұл жұмыстың мақсаты – кілем өндіру және газ өңдеу қалдықтарынан алынған екінші реттік шикізаттан ұнтақтау жеделдеткіштерін әзірлеу және олардың модификацияланған цемент тасының құрылымы мен беріктігіне әсерін зерттеу болып табылады. Жұмыста шикізат пен алынған ұнтақтау жеделдеткіштерін физика-химиялық талдау әдістері, сондай-ақ цемент тасын сынаудың стандартты әдістері қолданылды. ГИПАН (гидролизделген полиакрилонитрил) мен диэтаноламиннің өзара әрекеттесуі арқылы тиімді жеделдеткіш алу мүмкіндігі анықталды. Ұнтақтау жеделдеткіштерінің оңтайлы мөлшері 0,1% деп анықталды, бұл модификацияланған цемент тасының беріктігін 31,2%-ға арттыруға және сусұранысын 11%-ға азайтуға мүмкіндік береді, бұл эффект цемент бөлшектері арасындағы электрокинетикалық потенциалды төмендетудің және цемент бөлшектерінің ұнтақтылығын арттырудың қосымша әсерінен болатын гидратациямен түсіндіріледі. Физика-химиялық талдау әдістері модификацияланған цемент тасы үлгісінде бос күйіндегі судың іс жүзінде болмайтындығын және цемент тасының құрылымын қалыптастыру әлдеқайда жоғары дәрежеде жүзеге асқанын анықтады. Уақыт өте келе модификацияланған цемент тасының цемент матрицасындағы C-S-H гидратация өнімдері мен кальций сульфоалюминатының мөлшері артып, бұл цементтің беріктігін арттыратыны анықталды.*

Түйін сөздер: *ұнтақтау жеделдеткіштері, диэтанолами, ГИПАН, цемент тасы, беріктік, құрылым*

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НАУЧНАЯ СТАТЬЯ

ВЛИЯНИЕ УСКОРИТЕЛЕЙ ПОМОЛА ЦЕМЕНТА НА ФИЗИКО-МЕХАНИЧЕСКИЕ СВОЙСТВА ЦЕМЕНТНОГО КАМНЯ

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Аннотация. *При условиях высокой энергоёмкости процесса помола цемента актуальной является разработка новых и эффективных ускорителей помола. Целью данной работы является разработка ускорителей помола из вторичного сырья производства ковров и отходов газопереработки и исследования влияния их на структуру и прочность модифицированного цементного камня. В работе использованы методы физико-химического анализа сырьевых материалов и полученной добавки, стандартные методы испытания цементного камня. Установлено, возможность получения эффективных ускорителей помола взаимодействием гидролизованного полиакрилонитрила и диэтаноламина. Определена оптимальная дозировка добавки 0,1% которая позволяет повысить марочную прочность модифицированного цементного камня на 31,2%, снизить расход воды затворения на 11%, которая объясняется гидратации за счет дополнительного эффекта снижения электрокинетического потенциала между частицами цемента и повышения тонкости помола частиц цемента. Методами физико-химического анализа анализа установлено, что в образце модифицированного цементного камня практически отсутствует свободная вода и формирование структуры в цементном камне достигнуто в гораздо большей степени. Установлено что, в модифицированном цементном камне со временем увеличивается количества продуктов гидратации C-S-H и сульфоалюмината кальция в цементной матрице которое обеспечивает повышение прочности цемента.*

Ключевые слова: *интенсификаторы помола, диэтаноламин, гидролизованный полиакрилонитрил, цементная камень, прочность, структура*

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1 INTRODUCTION

The building materials sector is one of the industries that has a significant impact on the development and growth of our country's economy. One of the primary challenges that must be addressed in the production of building materials is improving the efficiency of equipment and the processes it involves—that is, enhancing the energy efficiency of energy-intensive processes during production. It is well known that in cement production, 20% of the total energy consumed goes toward grinding raw materials, 25% toward clinker calcination, and 40% toward final grinding.

Cement is produced worldwide at an astonishing rate of approximately 150 tonnes per second and is an indispensable material for social and technological development [1]. Research [2] shows that for every tonne of cement clinker produced, approximately one tonne of CO2 is emitted, which actually far exceeds the theoretical decarbonisation content of limestone. This is because the enormous energy consumption involved in cement production ultimately leads to CO_2 emissions exceeding the expected level. At the same time, electricity consumption in the cement clinker grinding process accounts for 60-70% of the total energy consumption in cement production, but only a very low energy utilisation factor, typically less than 15%, is used for effective clinker grinding, with the rest of the energy being lost as heat [3]. Improving the efficiency of cement clinker grinding can be achieved in two key ways: modernising grinding equipment and introducing auxiliary means for cement grinding. In practice, however, it is the auxiliary agents that have found widespread use due to characteristics such as minimal dosage, cost-effectiveness and significant improvement of the grinding process [4-6].

An analysis of scientific literature has shown that several groups of compounds are used in the synthesis of grinding intensifiers, namely surfactants, organic amines, polyhydric alcohols, oligomers, and complex additives [7-10], but the most studied of these are polycarboxylate ester (PCE)-based intensifiers, additives that are commonly used to improve the workability of cement systems as a grinding intensifier in clinker mills [11-14]. These studies have shown that PCE can increase grinding efficiency by reducing cement particle agglomeration through the formation of adsorption coatings on them. Moreover, the use of such a polymer can also improve the fluidity or reduce the water demand of such cements.

PCE - based additives are very diverse, according to B. Lothenbach, Ben Haha, R. Figi [15-17], the weakening of the plasticising effect and cement hydration under the influence of PCE additives is explained not by the chemical interaction of these grinding intensifier with Ca^{2+} ions, but by the electrostatic-steric mechanisms of their action. Koizumi [18], on the contrary, believes that PCE molecules form metastable complexes with Ca^{2+} ions, reducing the basicity of hydrosilicate phases. S. Moothedath and I. Teoreanu propose a theory of neutralisation of static charges on the surface of solid particles in the presence of organic molecules to explain the role of surfactants in grinding intensifier during grinding [19-20]. According to the works of J. Plank et al. [21], PCE react with C3A and are incorporated into the structure of the hydrates formed, creating stable organic mineral phases.

Currently, research is being conducted worldwide in a number of priority areas with the aim of developing new organic chemical additives and applying them in cement composites, including the following: the development of chemical additives with complex mechanisms of action; the production of plasticizing additives based on renewable resources; the development of technologies for producing plasticizing additives using carriers such as zeolite and silica gel; and the production of new, effective additives through the chemical modification of existing superplasticizers[22-23].

However, to date, there has been no systematic study of the relationship between the structure and properties of polyacrylate feedstock as they relate to grinding efficiency. Only limited information can be gleaned from the molecular dynamics simulation study conducted by R. K. Mishra et al. [24], and this information still needs to be verified through experimental work. Furthermore, there are no studies on the possibility of using oil and gas refining waste as secondary alkonalamines in the synthesis of accelerators.

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From the above, it can be concluded that there is no comprehensive information in the literature on the mechanisms of influence of PCE as grinding intensifiers on the properties of cement. In addition, analysis of the literature has shown that information on research into the synthesis of grinding intensifiers based on secondary raw materials, waste from various industries, and the effect of the resulting intensifiers on the cement hydration process is limited.

Kazakhstan is one of the world's leading countries in terms of hydrocarbon reserves, production, and processing. According to statistical data, Kazakhstan has proven natural gas reserves of 3.8 trillion cubic meters, of which 2.2 trillion cubic meters are associated gas and 1.6 trillion cubic meters are natural gas. In the first six months of 2025, natural gas and associated gas production in the republic increased by 18.3%, reached 5.73 billion cubic meters, and aqueous solutions of diethanolamine (DEA) and methyldiethanolamine (MDEA) absorbents are widely used in natural gas and NGL processing plants. The average MDA consumption for purifying one cubic meter of gas depends on the gas composition, the concentration of harmful substances, and the specific purification technologies.

Typically, about 0.1–0.5 kg of MDEA is used for neutral and moderately contaminated gases. Open sources contain no published data on the volume of saturated MDEA residues in Kazakhstan. However, given the active use of this chemical in the oil and chemical industries for producing acid inhibitors, anti-corrosion compounds, and other products, it can be assumed that its residues are generated in significant quantities. Interestingly, MDEA is a substance with absorbent and purifying properties, and its waste requires strict environmental monitoring due to its potential toxicity and the complexity of its disposal. It has been determined that these residues can currently serve as a significant raw material for the production of grinding catalysts.

Thus, the development of new grinding intensifiers is a pressing scientific and technical task. Of particular interest are studies aimed at obtaining effective and environmentally safe intensifiers based on secondary raw materials capable of increasing the energy efficiency of the grinding process without compromising the basic characteristics of the resulting cements.

In this regard, the aim of this study is to develop grinding intensifiers from secondary raw materials produced during carpet manufacturing and gas processing wastes, and to investigate the effect of the obtained grinding intensifier on the structure and strength of the modified cement stone.

2 MATERIALS AND METHODS

Secondary nitronic fiber (PAN, waste from carpet production), secondary diethanolamine (DEA) (waste from gas processing by PetroKazakhstan Oil Products LLP), 8% sodium hydroxide solution, methanol, and hydrochloric acid were used as raw materials for the synthesis of cement grinding intensifiers.

The synthesis of PCE was carried out by the hydrolysis of nitrile groups, i.e., the treatment of PAN with strong alkalis at elevated temperature and pressure and esterification, in which the resulting PCE (or its salt) reacts with diethanolamine in the presence of an acid catalyst to form ester groups (PCE).

The raw materials and grinding intensifier obtained were studied by IR spectroscopy, thermal analysis and X-ray phase analysis.

The IR spectrum of the synthesised grinding intensifier, was recorded on an IRAffinity-1S spectrometer (SHIMADZU CORP., Japan), a high-sensitivity spectrometer (noise ratio 60,000:1) that allows the analysis of wave numbers of various samples, despite the low intensity of spectral bands, in the wave number range of 4000÷400 cm^{-1}. The interferometer optimisation system, along with built-in self-diagnostics and a built-in automatic drying device, significantly improves ease of use and ensures long-term stability of the instrument. The high-speed scanning mode (20 spectra per second) allows reactions lasting several seconds to be monitored [1].

The thermal stability of the synthesized grinding intensifier and cement mixtures was analyzed using differential thermal and thermogravimetric methods on a DTG-60 device

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manufactured by the Japanese company SHIMADZU. SHIMADZU's TGA (simultaneous thermal analysis) and simultaneous TGA-DTA and TGA-DSC analysis methods provide an easy-to-use, reliable and highly efficient platform for thermal analysis. The derivatogram was studied on a derivatograph at a speed of 10 degrees/min, with the sensitivity of a T-900, TG-200, DTG-1/10, DTA-1/10 galvanometer, with automatic recording of the derivatogram on photographic paper. A sample of the pigments under study weighing 35-46 mg was placed in a 10 mm diameter aluminium oxide and platinum crucible without a lid, capable of withstanding temperatures up to 165 °C. Differential heating was carried out under atmospheric conditions. During the analysis, the synthesized pigments were subjected to thermal analysis at temperatures ranging from 20 to 1000 °C [1].

X-ray phase analysis cement stone added grinding intensifier was performed using a modern Rigaku MiniFlex 600 X-ray (Rigaku CORP., Japan) device, which combines various research methods that typically use X-ray radiation. In the equipment used for the analysis, X-ray radiation uses transverse electromagnetic oscillations with a wavelength of 10^{-2}-10^{2} Å. In the process of generating X-rays, radiation is formed as a result of the collision of fast-moving electrons with a metal cathode under the influence of high voltage in X-ray tubes.

The distance between surfaces *(d)* was calculated based on the wavelength of X-ray radiation and the Bragg angle *(θ)*. The values of *d* for each sector were calculated, and the values of the distance *d* between each surface were determined using special programmes and calculators [1].

The water requirements of cement systems were determined using the methods of GOST 301.6-2020 and the Vika apparatus.

The results of HYPAN IR spectroscopy showed that there are two strong carbonyl peaks at 1697 cm^{-1} and 1653 cm^{-1} in the spectrum. This indicates the presence of both a carboxylic acid (1697 cm^{-1}) and an amide (1653 cm^{-1}) group, i.e. a compound containing both acidic and amide groups in its molecule (Figure 1).

Currently, along with methyldiethanolamine, diethanolamine is also actively used in the oil and gas industry (albeit to a lesser extent than methyldiethanolamine). Therefore, the use of diethanolamine as a secondary raw material is of great importance.

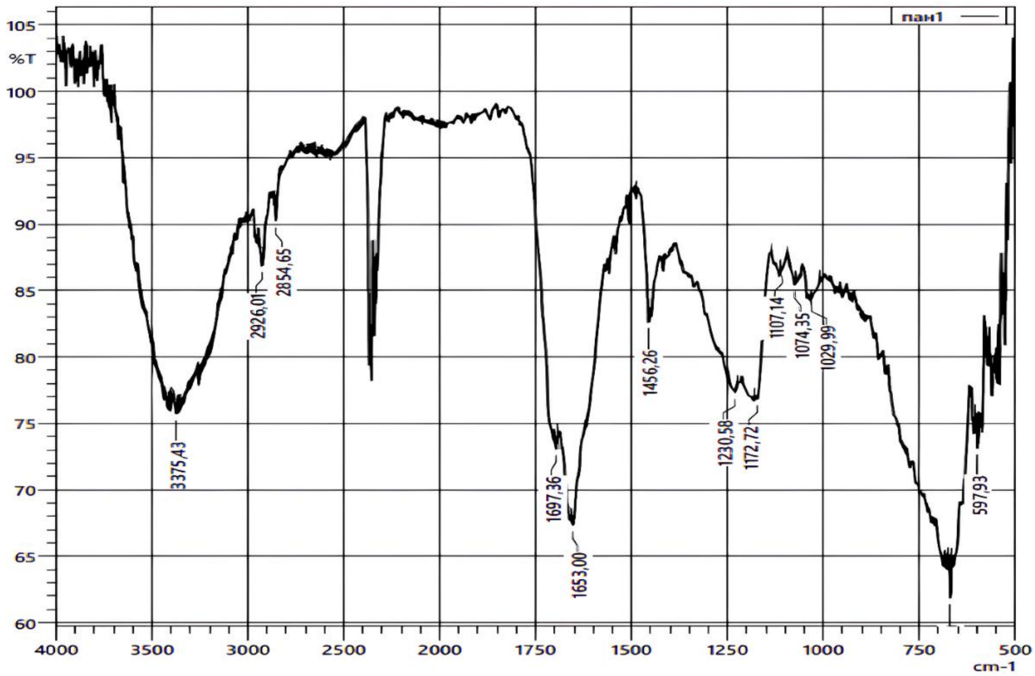

Figure 1 – IR spectra of HYPAN

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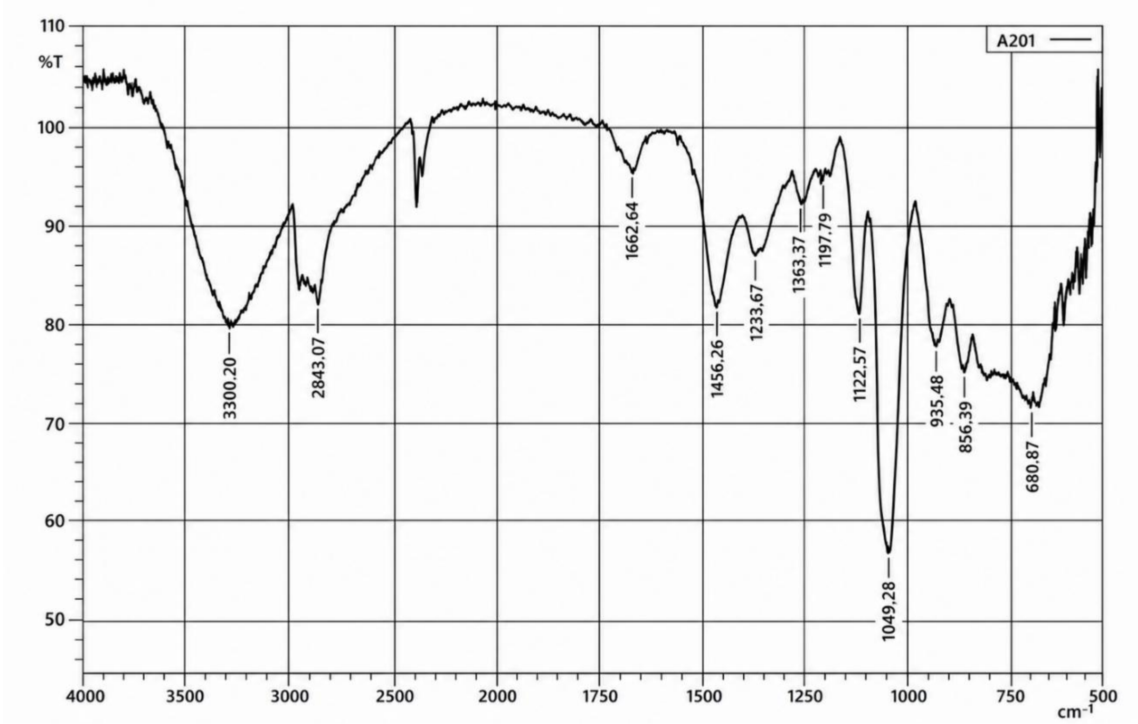

Figure 2 – IR spectra of diethanolamine (DEA)

The results of DEA IR spectroscopy showed that the spectrum has a very strong peak at 1662 cm-1 and C=O (amide) at 3300 cm-1: a broad N-H stretching peak at 1236 cm-1: strong C-N stretching (amide III). These three peaks together confirm the clear presence of an amide group (-CONH-) (Figure 2).

The synthesis of the grinding intensifier based on HYPAN and diethanolamine was carried out in a 5-litre reactor, into which the calculated amount of HYPAN was placed. The temperature of the mass in the reactor was brought to 50 °C and the calculated amount of diethanolamine was slowly added over the course of 1 hour. After that, the reaction mass was cooled to room temperature. Unreacted diethanolamines were separated from the cooled reaction mass by vacuum distillation. The resulting product is a viscous liquid whose colour can vary from light yellow to orange.

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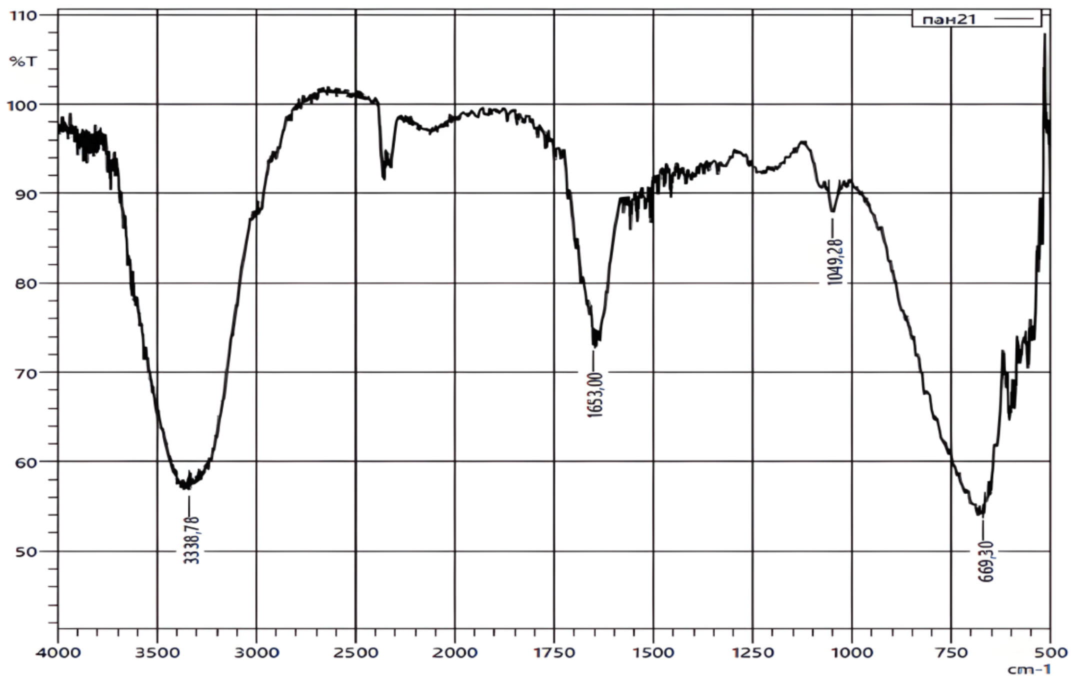

Figure 3 – IR spectra of HYPAN and diethanolamine

As can be seen from Figure 3, absorption bands characteristic of ν(C≡N) – elongation of the nitrile group in acrylonitrile segments – are observed in the 2240-2250 cm-1 range. In the spectrum, this means that a decrease or shift in the peak occurs during the formation of hydrolysis or amide. Absorption bands in the 1730-1740 cm-1 region are characteristic of ν(C=O) – carbonyl stretching. Amides or ester fragments are specific to amides formed during PAN hydrolysis. Absorption bands in the 1650-1670 cm-1 region are characteristic of δ(N-H) and ν(C=O) mixed oscillations in the second-order amide structure. On the spectrum, this appears as a strong or broad peak. Absorption bands in the 1250-1300 cm-1 region are characteristic of ν(C–N) in the structure of amide or amine groups. This is characteristic of hydrolysed PAN. Broad absorption in the range 3400-3500 cm-1 represents oscillations – ν(O-H) or ν(N-H), which indicates an increase in hydrophilic properties.

The strength of cement stone specimens prepared using cement with a grinding accelerator was studied and compared with that of cement stone specimens prepared using a traditional mixture (control specimen). The composition of the control sample for grinding was as follows: cement clinker—1,140 g (95%), gypsum—60 g (5%); the composition for grinding using cement grinding intensifiers was calculated with an additive mass fraction of 0.1% of the total mass, i.e., cement clinker – 1,138.86 g, gypsum – 59.94 g, grinding accelerator – 1.2 g. The mixture was loaded into a ball mill, and the grinding time was 45 minutes. After stopping the grinding process, the mill's contents were discharged into a screen to separate the balls; from the remaining screenings, a 25-gram sample was weighed, and the fineness of grinding was determined by sieving through a No. 0.08 sieve, with the residue on the sieve amounting to 9–14%.

Study of the strength of cement specimens with the addition of a grinding accelerator. The cement specimens were prepared as follows, in accordance with GOST 30744-2001. To do this, a control specimen was mixed in a special mixer, poured into a 3×3×3 mold, and compacted on a vibrating table. The cement specimens in the molds were stored in a special climatic chamber at a temperature of 20°C and a humidity of 98% for 24 hours; after that, the specimens were removed from the molds and placed in water-filled containers in a special climatic chamber at a temperature of 20°C and a humidity of 98%. To test the compressive and flexural strength of the cement samples, samples were taken on the 2nd, 7th, and 28th days and tested in special presses.

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3 RESULTS AND DISCUSSION

The study of the influence of grinding intensifier on the main characteristics of modified cement was conducted by many authors [25-31], who established that particle size distribution, uniformity of distribution, and specific surface area (SSA) have a significant impact on the performance properties of cement, especially its strength.

The optimal amount of grinding intensifier was selected based on experiments and literature data. Typically, PCE are added to cement systems in amounts no greater than 0.1-0.2%. Exceeding these amounts typically results in the cement and water separating into two layers. However, all results presented were obtained by averaging multiple analyses.

The authors of this article conducted experimental studies to determine the effect of the obtained grinding intensifier on the strength and structure of cement stone. As a result of the study, when testing the compressive and flexural strength of cement samples with grinding intensifier, it was found that the strength of the sample containing the grinding intensifier additive changed as follows compared to the conventional SEM II/A-I 32.5N cement sample without grinding intensifier (Table 1).

Table 1 - Compressive strength (a) and flexural strength (b) of cement stone samples of grade SEM II/A-I 32.5N with the addition of a grinding intensifier

№	SEM II/A-I 32.5N cement (g)	Water (ml)	Grinding intensifier (g)	Compressive and flexural strength of cement samples					
				2 days (N/mm^2)		7 days (N/mm^2)		28 days (N/mm^2)	
				a	b	a	b	a	b
1	2	3	4	5		6		7	
2	1000	250	-	16.4	3.5	25.1	4.6	37.7	6.3
3	1000	225	1	21.2	3.9	32.8	4.9	46.9	6.6
4	1000	225	5	23.2	4.2	36.5	4.8	48.2	7.5
5	1000	225	10	22.8	4.5	38.8	4.8	49.5	7.8

The results in Table 1 show that the compressive strength of the cement sample with 1 grams of grinding intensifier was 29.3% higher after 2 days, 31% higher after 7 days, and 24.4% higher after 28 days than that of cement stone samples obtained from SEM II/A-I 32.5N cement samples. The flexural strength of the samples was 11.2% higher after 2 days, 6.5% higher after 7 days and 4.7% higher after 28 days. When studying the compressive strength of cement samples obtained with the addition of 5 g of a grinding intensifier, it was found that after 2 days it was 41.4% higher, after 7 days – 45.4% higher, and after 28 days – 31.2% higher. The flexural strength of these samples was 10% higher after 2 days, 4.3% higher after 7 days, and 23.8% higher after 28 days. This indicates that the grinding intensifier plays a very important role in increasing the strength of cement stone by actively participating in the primary and secondary hydration of the cement mixture.

Usually, when adding grinding intensifier to cement (and concrete), the need for water is first determined, so experiments are carried out when the water and cement are in the same ratio without defining this parameter, the actual effectiveness of the grinding intensifier cannot be estimated due to the negative consequences associated with the increase in the amount of free water. A reduction in water consumption may only indicate that the supplement has other positive properties.

Effect of grinding intensifier on the Blaine specific surface area of cement. The grinding process in cement production is an important step that determines the main physicochemical properties of the product. In particular, the Blaine specific surface area (m²/kg) of cement directly affects its hydration rate, strength-building properties, and overall reactivity.

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Table 2 - Time dependence of the specific surface area of cement with and without the addition of a grinding intensifier

№	Time (min)	Without grinding intensifier (m²/kg)	With grinding intensifier (m²/kg)	Efficiency (%)
1	20	222	263	+18%
2	40	284	337	+18%
3	60	326	390	+19%
4	80	358	493	+38%
5	100	380	456	+20%

The conducted analyses show that the use of special grinding intensifier — in the grinding process significantly increases the dispersion level of cement. The graph, compiled based on the experimental results, shows an increase in the Blaine specific surface area with increasing grinding time. However, in the case where the intensifier is not used, this increase is relatively slow.

In the case of grinding without an intensifier, the specific surface area of cement in 20 minutes was approximately 222 m²/kg, while in 100 minutes this indicator increases to 380 m²/kg. During this process, agglomeration (sticking) between particles can be observed, which reduces the grinding efficiency.

On the contrary, under the conditions of using a grinding intensifier, the growth rate of the Blaine specific surface area is much higher. In particular, if 263 m²/kg is achieved in 20 minutes, then in 100 minutes this indicator reaches 456 m²/kg (Table-2). This is an average result of 15–25% higher. The main reason for this is that the intensifier adsorbs on the surface of the particles, reducing their adhesion and improving the dispersion process.

Also, when grinding intensifier are used:

energy consumption is reduced;

mill productivity increases;

a uniform granulometric composition of the cement is ensured.

Cements with a high Blaine specific surface area usually hydrate faster and develop early strength faster. However, excessively high dispersion can increase water demand and cause some technological inconveniences. Therefore, choosing the optimal grinding mode is important.

In conclusion, the use of grinding intensifier significantly increases the Blaine specific surface area of cement and improves production efficiency, which justifies their widespread use in modern cement production technologies.

The effect of grinding intensifiers on the fineness of cement particles. In cement production technology, the grinding process is one of the main stages that form the granulometric composition of the product. The size distribution of particles directly affects the physicochemical properties of cement, in particular, the hydration rate, water demand and strength indicators. Therefore, increasing the efficiency of the grinding process is of great scientific and practical importance.

In modern technologies, various grinding intensifiers are used to increase the efficiency of grinding - grinding intensifier s. The main function of these substances is to reduce the adhesion (agglomeration) forces between particles and increase their dispersion.

Table 3 - The dependence of the fineness of cement particles with and without the addition of a grinding intensifier

Faction (µm)	Without intensifier (%)	With intensifier (%)	Eff iciency
>80	14	7	−50%
45–80	28	21	−33%
20–45	27	29	+7%
<20	31	42	+35%

According to the results of experimental analyses, in the absence of a grinding intensifier, the proportion of large fractions in the granulometric composition of cement particles remains relatively

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high. In particular, the amount of particles larger than 80 μm is significant, which indicates that the grinding process is not fully effective. In this case, the electrostatic and molecular attraction forces between the particles lead to their adhesion to each other, as a result of which the grinding process slows down and energy consumption increases.

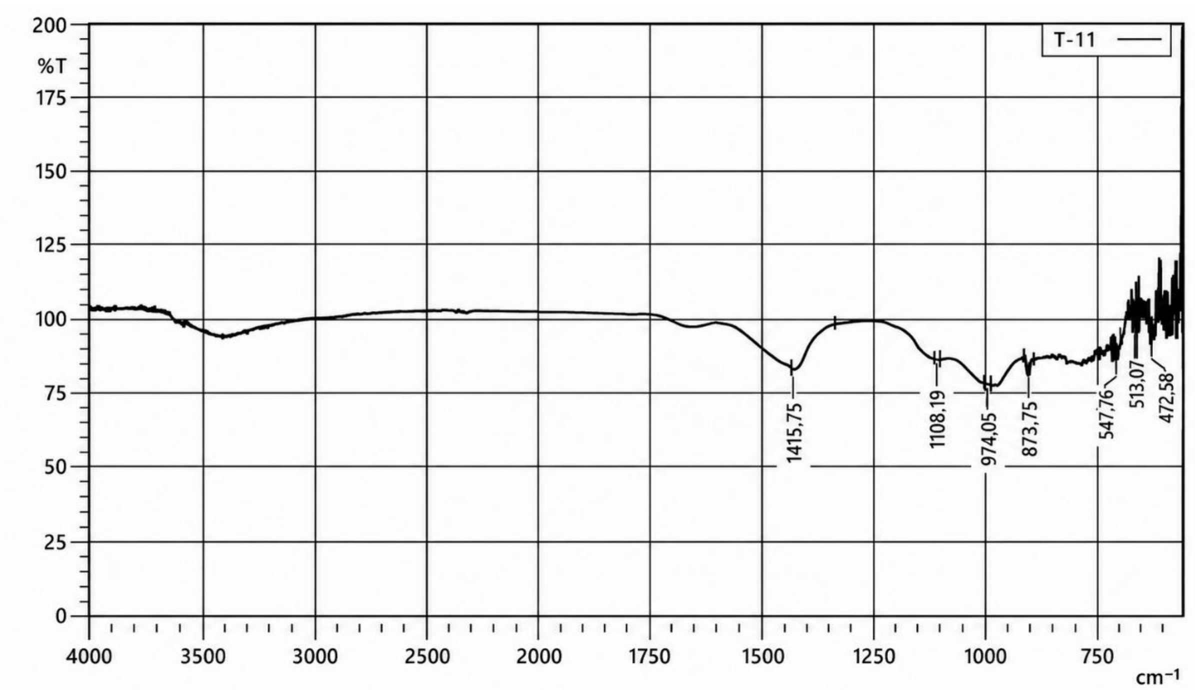
When a grinding intensifier is used, the size distribution of the particles changes radically. First of all, the proportion of large particles decreases sharply, while the proportion of small (<20 μm) (Table 3) fractions increases significantly. This is explained by the adsorption of intensifier molecules on the particle surface. As a result, the adhesion forces between the particles decrease, they are easily separated from each other, and the grinding process is more efficient.

At the same time, the use of grinding intensifiers not only improves the granulometric composition, but also increases the economic efficiency of the technological process. In particular, energy consumption is reduced, mill productivity is increased, and production costs are reduced.

However, excessive particle size can also lead to some negative consequences. For example, the water requirement of cement increases, which can affect the ease of processing concrete mixtures. Therefore, ensuring optimal granulometric composition during the grinding process is an important task.

In conclusion, the use of grinding intensifiers significantly increases the degree of fineness of cement particles, reduces the proportion of large fractions, and increases the amount of fine fractions. This serves to improve the reactivity and technological properties of cement and scientifically justifies the use of such additives in modern cement production.

During IR spectroscopic analysis of modified cement stone, absorption lines were observed in the range of 873.75-1080.31 cm^{-1}. It is known from the literature that the range of 1100-750 cm^{-1} corresponds to symmetric and asymmetric absorption lines of Si-O-Si and Si-O bonds, as well as Si-O-Al bonds (Figure 4b).



a)

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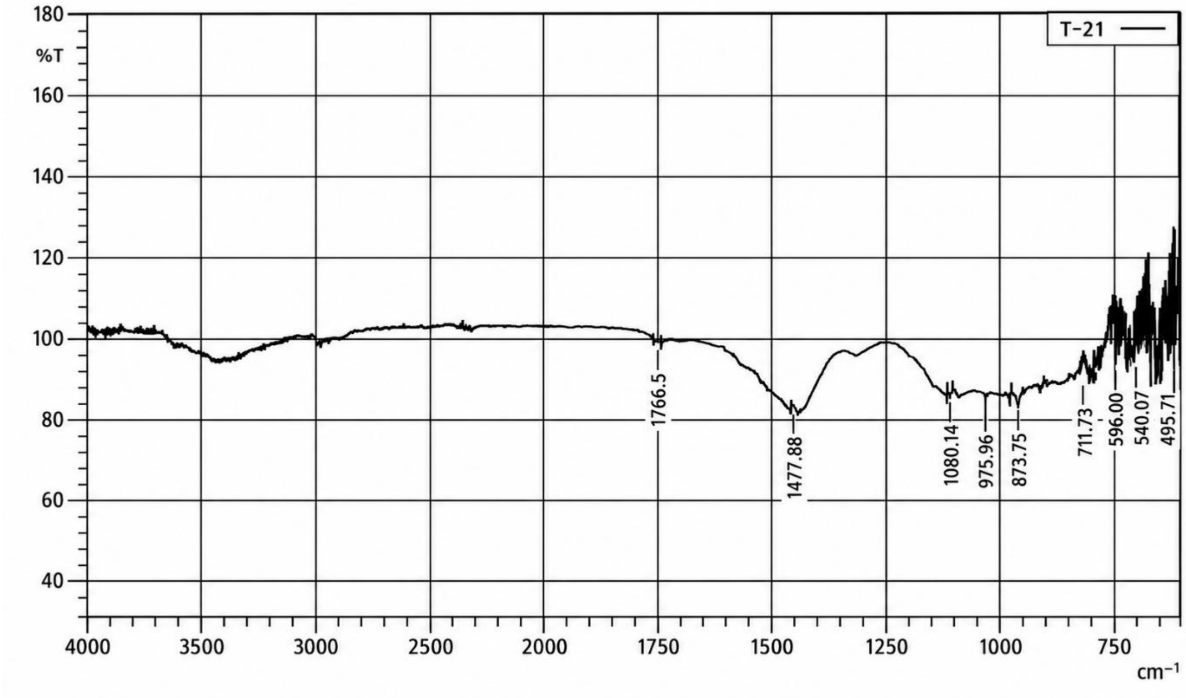

b)

Figure 4 – Results of IR spectroscopic analysis:
a) conventional cement stone b) modified cement stone

According to the analysis of IR spectra of the modified cement stone sample and the conventional cement sample, wavelengths in the ranges of 694-779 and 873 cm^{-1} correspond to symmetric and asymmetric oscillations of Si-O-Si and Si-O bonds. At wavelengths of 975.8 and 1080 cm^{-1}, oscillations of Si-O-Al bonds and better crystallisation of calcium hydrosulfoaluminate are observed. At a wavelength of 1417.68 cm^{-1}, the presence of carbonate, bicarbonate and sulfite groups is indicated, resulting in the formation of hydrocarbonaluminates and hydrosulfocarbonates, which increases the strength of the cement stone. At a wavelength of 2926-2976 cm^{-1}, the presence of free water molecules is indicated. Unlike a conventional cement sample, the wavelength of 3415.93 cm^{-1} is associated with the oscillations of the SiO_4 tetrahedron bound by OH groups, indicating a high content of $Si(OH)_4$ hydrosilicates and submicron crystals. This increases the strength and water resistance of the cement sample.

In infrared spectra, absorption lines in the region of 3200-3600 cm^{-1} usually belong to hydroxyl groups, so it is difficult to see amines and amides against the background of hydroxyl groups, but in diethanolamine we can see that the absorption lines in this region are not as broad as those characteristic of -OH groups, but rather narrow. This means that the amount of $-NH_2$ and -OH groups in diethanolamine is equal. Another absorption line at 1620-1680 cm^{-1}, characteristic of $-NH_2$ groups, is lower in the spectra of ethanolamine, which can be explained by the hydrogen bonds in the ethanolamine molecule.

Thermogravimetric analysis showed that the experiment was conducted for 90 minutes at temperatures up to 900 °C. During this time, three intense mass losses were observed on the TGA of the conventional cement sample. During the experiment on intense mass loss 1, a mass loss of 9.526% was observed at a temperature of 59.77-426.82 °C due to excess moisture and water in the gypsum. In the intensive mass loss experiment 2, it can be seen that the mass loss of 31.511% is due to the dehydration of C-S-H crystals and the decomposition of $Ca(OH)_2$ at a temperature of 426.82-675.82 °C, and in the intensive mass loss experiment 3, it can be seen that the mass loss of 41.150% is due to the decomposition of $CaCO_3$ at a temperature of 675.82-901.75 °C. During differential

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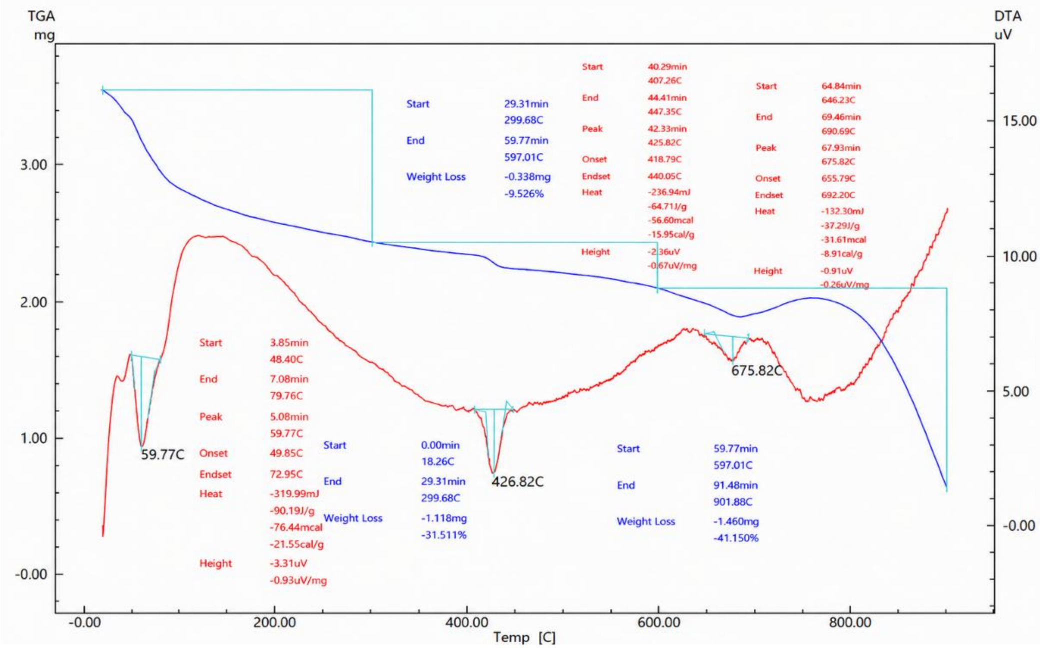
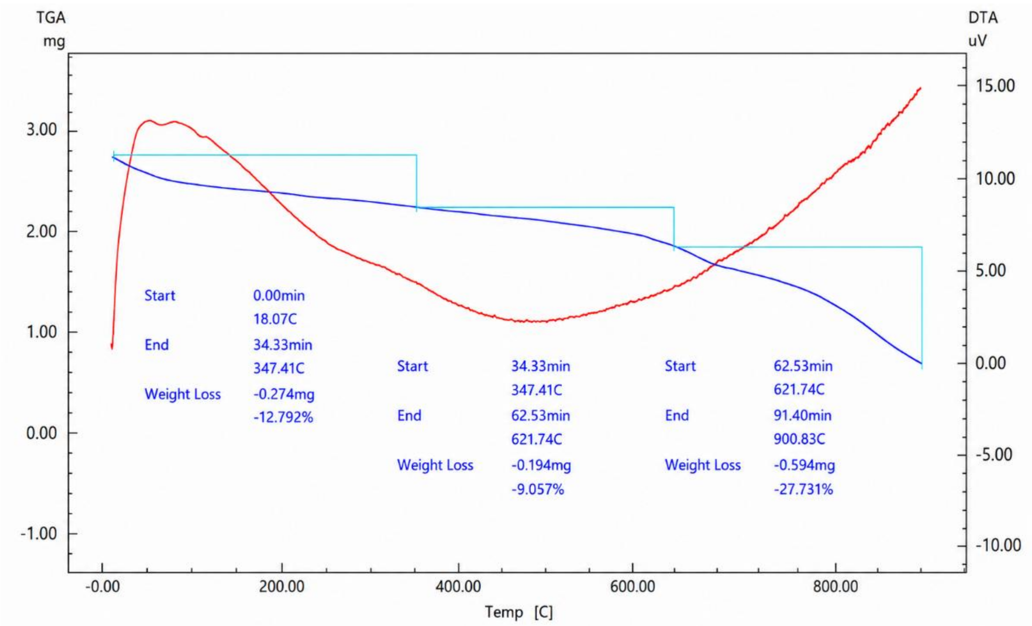
thermal analysis, energy absorption was observed in the temperature range of 59.77, 675.82, 901.75 °C, with the maximum heat absorption recorded at 901.75 °C (Figure 5a).



a)



b)

Figure 5 – Thermogravimetric analysis (TGA) and differential thermal analysis (DTA):
a) sample of conventional cement b) cement stone based on modified cement

According to thermogravimetric analysis of a cement sample with a grinding intensifier, three intense mass losses were observed in TGA. During the first intense mass loss of 12.792% at a temperature of 347.41-621.74 °C, the mass loss was observed due to the excess moisture and the C-S-H dehydration. In the second phase of intense mass loss, the mass loss of 9.057% was observed at a temperature of 621.74-900.83 °C due to the partial dehydration of C-S-H and the decomposition

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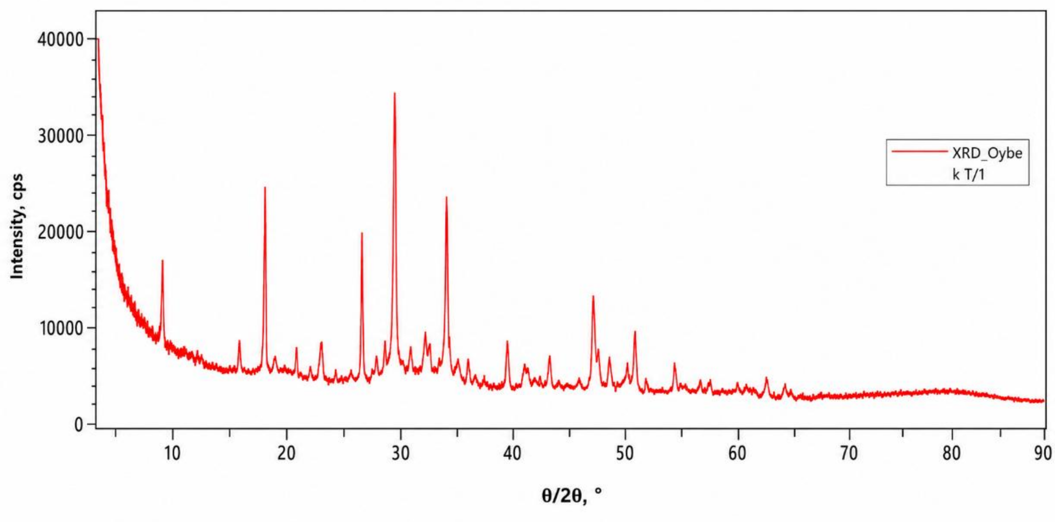
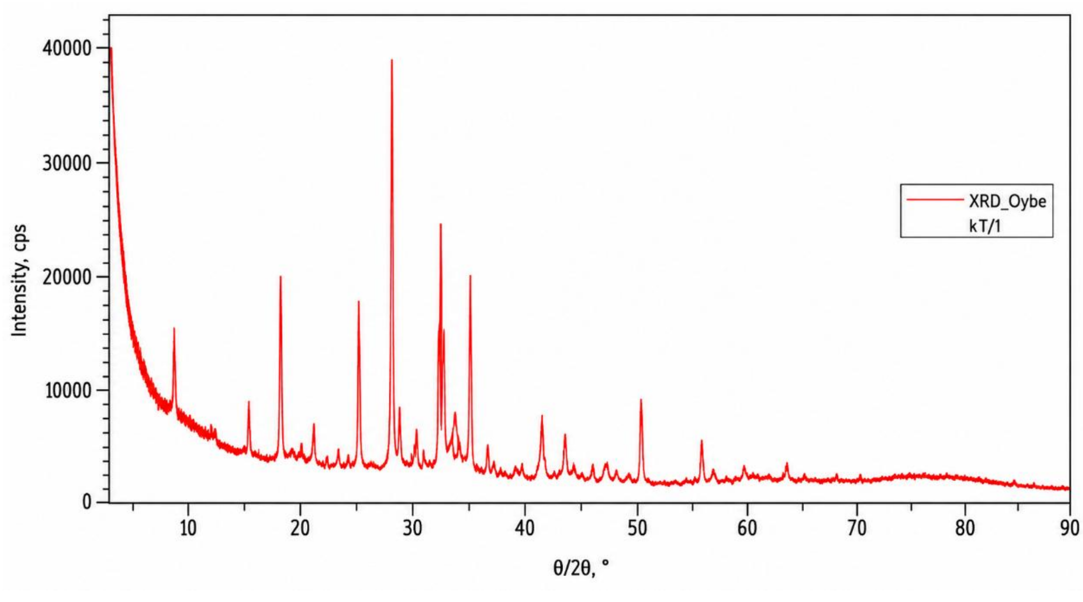
of Ca(OH)2. In the zone of intense mass loss 3, it can be seen that the mass loss was 27.731% at a temperature of 621.74-900.83 °C, mainly due to the decomposition of CaCO3 (Figure 5).

Differential thermal analysis of a cement sample with a grinding intensifier showed that energy absorption was observed in the temperature range from 347.41 to 621.74 °C, with the maximum heat of absorption recorded at 621.74 °C. (Figure 5b).



a)



b)

Figure 6 – Results of X-ray phase analysis:
a) cement stone sample obtained from conventional cement. b) cement stone sample obtained from modified cement

Figure 6b, illustrating a cement composite with the addition of a grinding intensifier, shows that the $Ca(OH)_2$ diffraction peaks in the 18°, 28° and 34° are weaker than the $Ca(OH)_2$ diffraction peaks in the 18°, 34° and 47° regions in the conventional cement sample (Figure 6a). As a result of the hydration of alite C_3S in cement, $Ca(OH)_2$ crystals are formed, but the weak diffraction peaks are due to the fact that active SiO_2 combines with the Ca^{2+} ion during the hydration process, forming C-

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S-H. Over time, an increase in the amount of C-S-H and calcium sulfoaluminate hydration products in the cement matrix increases the strength of the cement. $Ca(OH)_2$ crystals that remain unhydrated have a negative effect on the strength of the cement.

4 CONCLUSIONS

1. Based on a review of the literature, it was shown that polyamide polyelectrolytes were obtained by polymer-chemical transformations of selected raw materials – diethanolamine and HYPAN – during the synthesis of a grinding intensifier based on IR spectroscopy analysis.
2. When testing the compressive strength of cement samples produced with the addition of 0.1% grinding accelerator, it was found that after 2 days it was 41.4% higher, after 7 days it was 45.4% higher, and after 28 days it was 31.2% higher. The flexural strength of these samples was 20% higher after 2 days, 4.3% higher after 7 days, and 23.8% higher after 28 days. Thus, it was demonstrated that a 0.1% dosage of the grinding accelerator is optimal.
3. When comparing the physical and mechanical properties of modified and unmodified cement, it was found that the water consumption for producing cement paste in the modified cement was reduced by 11% compared to the control sample. This is explained by an improved hydration process due to the additional effect of increasing the fineness of the cement particles.
4. Research using differential thermal analysis showed that the content of free water in the modified cement stone sample decreased several times, and the reduction in endoeffects indicates a significantly more efficient formation of the structure in the cement stone.
5. It has been established that, over time, the amount of C-S-H hydration products and calcium sulfoaluminate in the cement matrix of modified cement stone increases, which leads to an increase in the strength of the cement.
6. The research was carried out within the grant funding of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Project AP26102705 «Development and Production of Cement Grinding Intensifiers Based on Local Raw Materials»).

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

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During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

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