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Enhanced operational reliability of irrigation canals through the application of modified concrete

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ABSTRACT

Introduction. In the conditions of Southern Kazakhstan, irrigation canals play a crucial role in supplying water for agricultural production. The operation of conventional concrete linings is complicated by their low resistance to cracking, frost heave, abrasive wear, and exposure to aggressive environments. These factors lead to increasing filtration losses, which in some cases exceed 20–25% of the water supplied volume-an especially critical issue for a region characterized by a sharp continental climate and limited water resources. To improve the durability and impermeability of hydraulic structures, a modified concrete (MC) mixture incorporating a combination of mineral and chemical additives has been developed. **Materials and Methods.** The composition of the MC includes Portland cement and slag-Portland cement, quartz sand, granite coarse aggregate, silica fume (7% of the cement mass), fly ash, an air-entraining agent (0.05%), and hydrophobizing components. The experimental investigations were conducted in accordance with relevant GOST standards: compressive and splitting tensile strength (GOST 10180), frost resistance (GOST 10060), water impermeability (GOST 12730.5), abrasive resistance (GOST 13087), and sulfate resistance (GOST 31384). The micro- and nanostructure of the material was analyzed using SEM, EDS, and XRD methods. **Results and Discussion.** Compared with the control concrete (CC), the modified concrete demonstrated significant performance improvements: an increase in compressive strength up to 55 MPa (+14.6%) and in splitting tensile strength up to 4.6 MPa (+27.8%); an increase in frost resistance from 220 to 320 cycles (+45%); an improvement in water impermeability from W6 to W9 (+50%); enhanced abrasion resistance by 26.9%; and an increase in the sulfate resistance coefficient by 11.5%. Microstructural analysis revealed densification of the cement matrix, a reduction in macroporosity, and an increase in the content of low-basic C–S–H phases, which confirms the material's enhanced durability. **Conclusion.** The developed modified concrete exhibits a comprehensive improvement in operational performance, ensuring a 30–40% extension of the service life of canal linings and a reduction in filtration losses by up to 20%. Its implementation in the construction and rehabilitation of irrigation canals in Southern Kazakhstan will enhance water-use efficiency and improve the resilience of hydraulic structures under aggressive environmental impacts and persistent water scarcity.

KEYWORDS: micro- and nanostructure, modified concrete, canal lining, water impermeability, frost resistance, abrasion resistance, sulfate resistance

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Повышение эксплуатационной надежности оросительных каналов за счет применения модифицированного бетона

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АННОТАЦИЯ

Введение. В условиях Южного Казахстана оросительные каналы играют ключевую роль в обеспечении сельского хозяйства водой. Эксплуатация традиционных бетонных облицовок осложняется их низкой стойкостью к растрескиванию, морозному пучению, абразивному износу и воздействию агрессивных сред. Эти факторы ведут к росту фильтрационных потерь, которые в отдельных случаях превышают 20–25 % поданного объема воды, что критично для региона с резкоконтинентальным климатом и дефицитом водных ресурсов. Для повышения долговечности и водонепроницаемости гидротехнических сооружений разработан модифицированный бетон (МБ) с комплексом минеральных и химических добавок. **Методы и материалы.** Состав МБ включает портландцемент и шлакопортландцемент, кварцевый песок, гранитный щебень, микрокремнезем (7% от массы цемента), золу-унос, воздухововлекающую добавку (0,05%) и гидрофобизирующие компоненты. Исследования проводились по методикам ГОСТ: прочность на сжатие и при расколе (ГОСТ 10180), морозостойкость (ГОСТ 10060), водонепроницаемость (ГОСТ 12730.5), абразивная стойкость (ГОСТ 13087), сульфатостойкость (ГОСТ 31384). Микро- и наноструктура анализировалась методами SEM, EDS и XRD. **Результаты и обсуждение.** По сравнению с контрольным бетоном (КБ) МБ показал: увеличение прочности на сжатие до 55 МПа (+14,6%) и при расколе до 4,6 МПа (+27,8%); повышение морозостойкости с 220 до 320 циклов (+45%); рост водонепроницаемости с W6 до W9 (+50%); улучшение абразивной стойкости на 26,9%; повышение коэффициента сульфатостойкости на 11,5%. Микроструктурный анализ выявил уплотнение цементного камня, снижение макропористости и увеличение содержания низкоосновных C–S–H фаз, что подтверждает долговечность материала. **Заключение.** Разработанный модифицированный бетон демонстрирует комплексное улучшение эксплуатационных характеристик, обеспечивая повышение межремонтного интервала облицовок на 30–40% и сокращение фильтрационных потерь до 20%. Его внедрение в строительство и реконструкцию оросительных каналов Южного Казахстана позволит повысить эффективность водопользования и устойчивость гидротехнических сооружений в условиях агрессивного воздействия среды и дефицита водных ресурсов.

КЛЮЧЕВЫЕ СЛОВА: микро- и наноструктура, модифицированный бетон, облицовка каналов, водонепроницаемость, морозостойкость, абразивная стойкость, сульфатостойкость

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INTRODUCTION

The degradation of traditional irrigation canal linings in Southern Kazakhstan is particularly critical in the context of the growing shortage of water resources for agriculture. This region is a major producer of cotton, vegetable, and fruit-and-berry crops, with 80–85% of total water consumption accounted for by irrigation. In dry years, the available volume of water resources decreases by 20–40% compared with long-term averages, while the overall deficit during the vegetation period reaches 1.0–1.5 billion m³ [1].

Given the region's high dependence on stable water supply for agricultural production, improving the durability and water impermeability of canal linings becomes a strategic priority.

In the southern regions of Kazakhstan-Turkestan, Zhambyl, and Almaty oblasts-over 12,000 km of irrigation canals lined with cement-concrete slabs are in operation. Most canals were constructed in the 1960s–1980s and have reached or exceeded their design service life. Field surveys and operational monitoring indicate that within 8–12 years after commissioning, most linings lose their design waterproofing and mechanical properties, which leads to a 20–35% increase in filtration losses and a reduction in the efficiency coefficient of irrigation systems to 0.55–0.65 [1, 4].

Damage to conventional linings is complex in nature and is caused by a combination of climatic, hydraulic, and chemical-mineralogical factors [1, 4, 10]. The main degradation mechanisms are summarized below:

1. Cracking concrete slabs. Cracks develop due to temperature-moisture deformations, shrinkage of the cement matrix, and uneven settlement of the foundation. In summer, daily temperature fluctuations of the lining reach 45–50 °C, causing alternating compression and tension in the concrete. Crack widths typically range from 1 to 5 mm, and their depth often exceeds the thickness of the protective layer. Through such defects, filtration losses may reach 0.5–1.0 L/s·m^2, which is critical under water scarcity conditions [4, 11].

2. Leaching of the cement matrix (hydro-abrasive erosion). In sections with curved canals and elevated flow velocities (1.5–2.0 m/s), intensive degradation of the cement matrix occurs due to the impact of abrasive particles (sand, silt) with concentrations up to 2–3 kg/m^3. Within only five years of operation, compressive strength in the flow-contact zone decreases by 15–25% relative to the initial value [5, 12].

3. Exposure to aggressive environments. Chemical analyses of canal water in the region show elevated sulfate concentrations (SO_4^{2-} up to 250–350 mg/L) and chloride concentrations (Cl^- up to 150-200 mg/L), leading to sulfate and chloride corrosion of the cement matrix. This process is accompanied by expansion of reaction products, the formation of microcracks, and a progressive decrease in concrete water impermeability from W6 to W2–W4 within 7–10 years of operation [2, 13].

4. Frost heave. In winter, air temperatures can drop to –25 °C, while the concrete lining is saturated with moisture. Repeated freeze-thaw cycles increase internal pore pressure due to ice crystallization, reducing frost resistance from F200 to F50–F100 after just 5–7 winter seasons [1, 4, 13–18].

5. Cavitation damage. In local hydraulic drops and junctions where flow velocity exceeds 3.0–3.5 m/s, cavitation occurs, forming pits 5–20 mm deep in a single vegetation season. These defects act as stress concentrators and accelerate overall deterioration of the lining [5, 19–23].

In Southern Kazakhstan, these processes occur with increased intensity due to high evaporation rates (1000–1200 mm/year), large temperature amplitudes, and chronic water shortages for irrigation, making the reduction of losses and extension of lining service life critically important. Loss of lining integrity not only increases filtration but also leads to erosion of the canal foundation, deformation of the cross-section, and ultimately a reduction in hydraulic capacity [1, 4, 33–34].

Filtration through defective sections of canal linings is one of the most significant causes of inefficient water use in the irrigation systems of Southern Kazakhstan. According to operational organizations, once the concrete lining is damaged and the soil foundation becomes exposed, water losses increase exponentially. Over long canal segments, this is equivalent to tens of thousands of cubic meters of water lost in a single vegetation season [33, 34].

In addition to water losses, filtration processes gradually erode the soil foundation, causing void development and cross-sectional deformation. This reduces the hydraulic capacity of the structure, necessitates frequent repairs, and increases operational costs. Collectively, leakage and deformation reduce the service life of canals by 25–40% relative to the design period [33, 34].

Against the backdrop of intensifying water scarcity, climate variability, and rising construction material costs, hydraulic structures face increasingly stringent requirements for durability, energy efficiency, and environmental sustainability [1, 4, 24–32]. The modern concept of irrigation system operation includes the following priorities [10-22]:

- minimizing operational water losses using materials with high water impermeability and crack resistance;
- reducing energy consumption for water pumping by lowering filtration losses and decreasing hydraulic resistance of the lining;
- increasing inter-repair intervals from 10–12 years to 25–30 years using modified concretes with durability compliant with modern standards.

A review of operational practices in water-deficient regions demonstrates that the durability and water-saving performance of irrigation canals depend primarily on the choice of lining material, the presence of an anti-filtration barrier, and the quality of operational monitoring (Fig. 1).

In the United States (Western states, USBR networks), the standard solution remains monolithic or precast concrete linings combined with a regulated schedule of inspections and targeted repairs. To extend service life, wet-mix shotcrete reinforced with microfibers, latex- or polymer-modified leveling layers, crack injection, and waterproof joint keys are used. The key issues include thermal cracking, joint degradation, and localized cavitation at transitions. Practice shows that combined “concrete + barrier” systems (geomembrane beneath the slab) consistently reduce filtration and lower the frequency of major repairs [10–12].

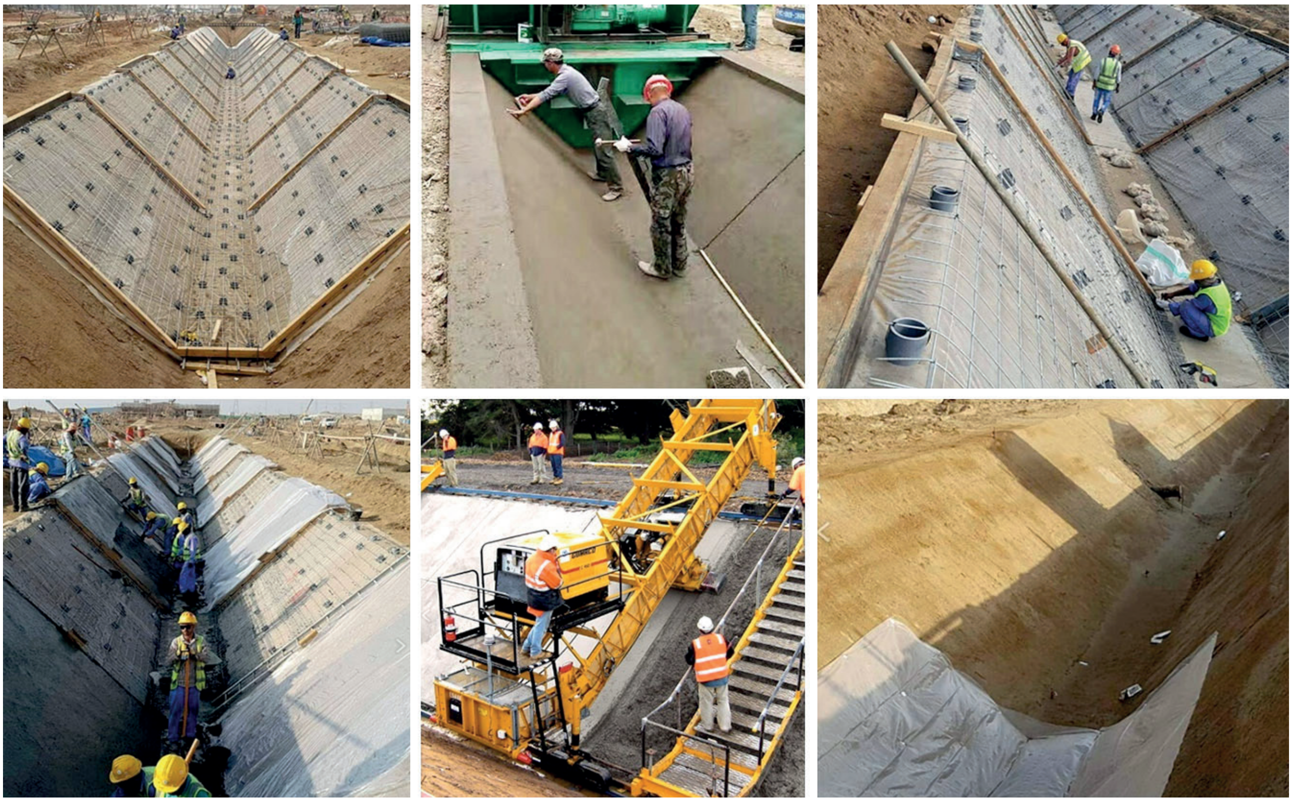

Fig. 1. Construction technologies and design practices for irrigation canals in different countries

In Egypt, within the national program for reconstructing distribution canals, fast-deployable technologies are widely applied: geosynthetic cementitious composite mats (GCCM) on sections with short shutdown windows and precast concrete panels installed over prepared bases with geotextiles or membranes. The benefits include a marked reduction in residual filtration and improved hydraulic efficiency; however, the quality of subgrade preparation and edge protection is critically important. Where anchoring or panel joints are violated, uplift pressures and undercutting are frequently observed [16, 19].

In Pakistan, comparisons between conventional concrete lining, polyethylene membrane systems, and their combinations demonstrate significant reductions in filtration in favor of membrane-based and hybrid schemes. In practice, the main risk is mechanical damage to membranes under debris-laden flow and abrasive runoff; therefore, membranes are protected by a concrete or soil cover and subjected to stricter quality control of welded seams. GCCM is additionally applied on problematic reaches with high flow velocities and unstable subgrades [25, 26].

In China (North China Plain, Xinjiang), HDPE geomembranes beneath concrete slabs are widely used, and roller-compacted concrete (RCC) is applied on critical structures. This combined configuration demonstrates minimal filtration losses, providing adequate protection against ultraviolet degradation and punctures. Typical challenges include membrane anchorage defects, poor subgrade preparation, and operational damage from construction equipment [10, 11, 13, 20, 21].

In India, design solutions rely on a standardized selection of lining materials based on local soil and hydrological conditions. Monolithic concrete, brick lining with cement mortar, and soil-cement is used for cost-effective structures; on aquiferous or collapsible soils, geomembranes beneath concrete are prescribed. Major risks include shrinkage cracking driven by water-cement ratio and temperature regime, as well as detachment of the lining caused by insufficient adhesion to the prepared base [25, 26].

In Spain (Ebro Basin), alongside converting portions of open canals into pressurized pipelines, thin polymer-modified protective coatings and shotcrete rehabilitation of existing linings are employed to reduce roughness and longitudinal losses. The positive effect is expressed in increased hydraulic capacity and reduced leakage; typical challenges include carbonate scaling and the need for regular cleaning to maintain hydraulic efficiency [30].

In Turkey (GAP project), precast panels and fiber-reinforced shotcrete are used on main canals to control crack formation under sharp daily temperature fluctuations. Thermal stress issues are addressed through a combination of fibers, optimized mixes with mineral additives, and rational placement of temperature and deformation joints [16, 19].

In Israel, a significant share of irrigation networks has been converted to pipelines; however, for the remaining open canals, polymer-modified coatings and strict monitoring protocols with targeted repairs are applied. Practice underscores the importance of institutional discipline in operation: even high-quality linings rapidly lose their water-saving performance without timely maintenance [12, 29].

In Mexico and several Latin American countries, pozzolanic modifications (fly ash, natural pozzolans) and silica fume are used to enhance chemical resistance and reduce permeability. These solutions improve the micro- and nanostructure of the cement matrix, reduce water absorption, and increase resistance to sulfate attacks. On reaches with unstable foundations, the key issue remains the interaction between the lining and the subgrade, as well as the performance of drainage systems [27–29].

A comparative analysis (Table 1) shows that the most reliable water-saving performance is achieved when three components are combined: modified concrete with high crack resistance and low permeability; an anti-filtration barrier (geomembrane or geocomposite) beneath the protective layer; and a regulated monitoring system with targeted repair. For the conditions of Southern Kazakhstan, the most relevant measures include controlling thermal-shrinkage deformations (through mix optimization, fiber reinforcement, and joint layout), proper protection and anchoring of the barrier, and institutionalizing regular inspections with repair prioritization based on actual water losses [10–17].

Figure 2 presents a dual bar chart comparing the reduction in filtration losses and the inter-repair interval for each country and lining technology.

Figure 3 presents an extended radar chart illustrating the performance profile of irrigation canal lining technologies. The chart is constructed using normalized values and includes six key parameters: reduction of filtration losses (efficiency), durability (inter-repair interval), relative implementation cost, water impermeability (W-class), frost resistance (F-class), and abrasion resistance. This visualization enables a clear comparative assessment of the comprehensive operational properties of technologies used in different countries and highlights their strengths and weaknesses.

These findings form a practical foundation for defining the performance targets of modified concrete mixtures intended for lining irrigation canals in Southern Kazakhstan: materials are required that exhibit reduced permeability and enhanced crack resistance, are compatible with barrier layers, and remain stable under sharply

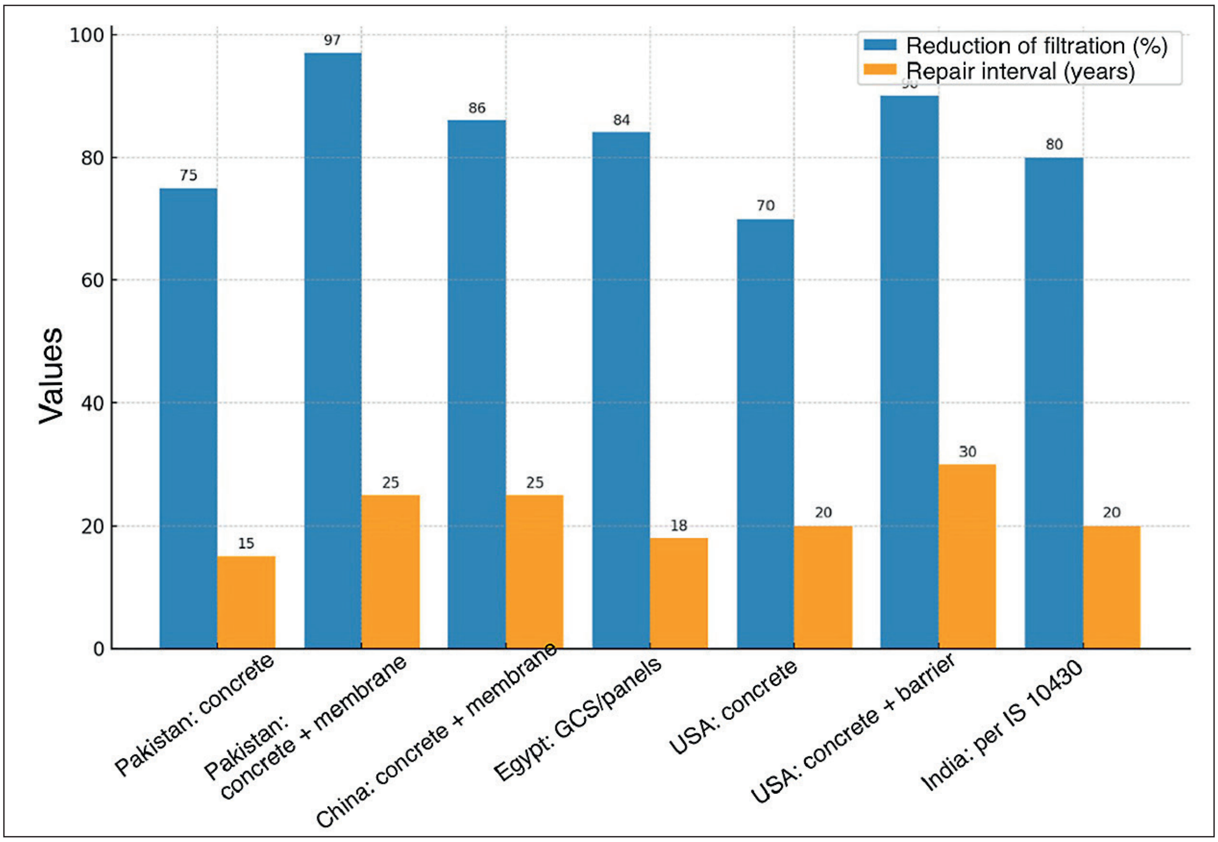

Fig. 2. Global practices compared: efficiency and durability of canal lining systems

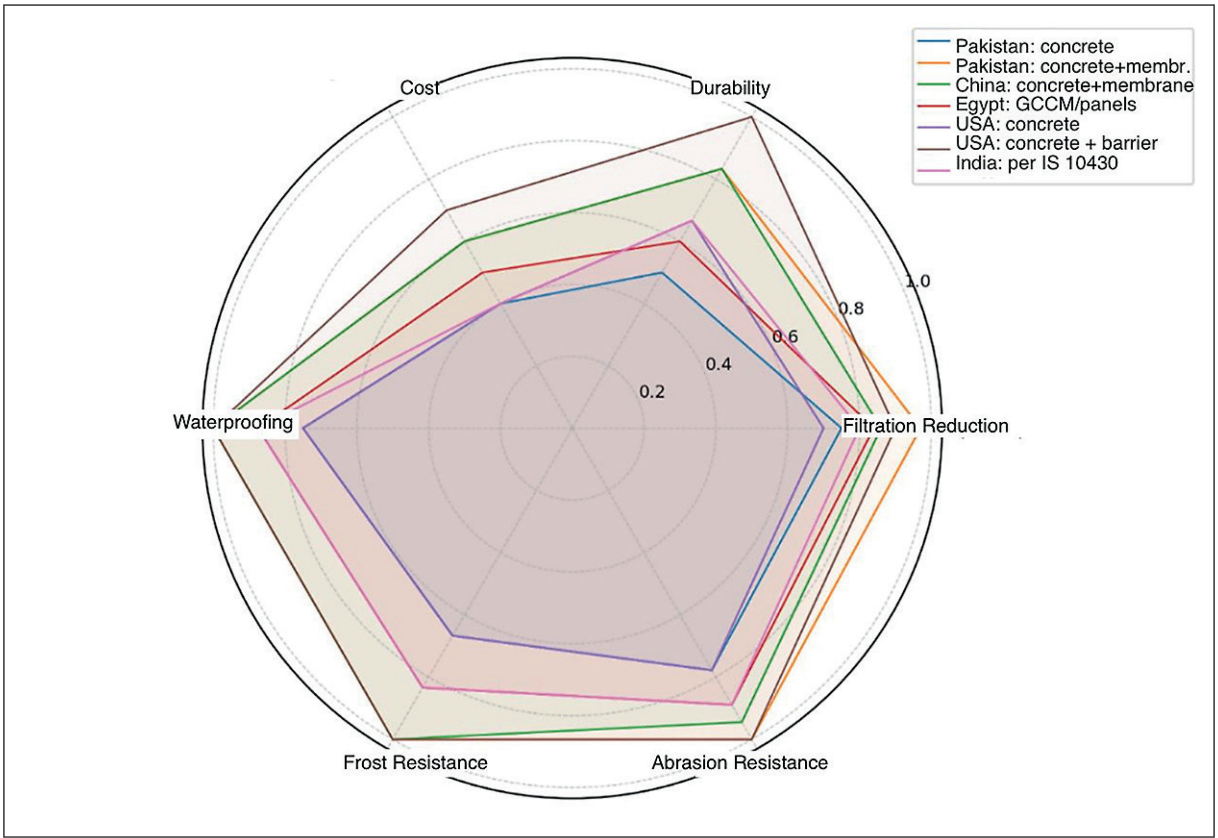

Fig. 3. Extended performance profile of canal lining systems

Table 1. Comparative analysis of irrigation canal lining practices in different countries

Country / Region	Type of Solution	Effect on Filtration / Hydraulics	Durability / Operational Features
Pakistan	Concrete; concrete + geomembrane	–75% (concrete), up to –97% (geomembrane)	Rapid water-saving effect; protection of joints and membrane seams is critical
China	Concrete, geomembrane, combined lining systems	Concrete + geomembrane: –86% compared to unlined canals	Wide application of combined systems on main canals
Egypt	Large-scale canal rehabilitation program	Up to –84% loss reduction (case studies), stable savings after 3–9 years	Hydraulic efficiency confirmed after rehabilitation (HEC-RAS)
USA (USBR)	Concrete linings; prioritized maintenance	Defect and repair guidelines increase actual reliability	Emphasis on inspections, checklists, and condition-based targeted repairs
India	IS 10430 standards; lining selection based on soil permeability	Regulatory focus on minimizing seepage and improving canal stability	Standardized material/thickness selection; water-economy considerations required
Global (review)	Concrete and smooth linings	Reduced roughness → ↑capacity and ↓losses	Additional effect: reduced waterlogging and lower O&M costs

continental climatic conditions, while also ensuring high-quality preparatory and operational procedures.

Thus, traditional concrete linings no longer meet modern requirements for durability and water-saving performance. The solution lies in the development and implementation of modified concrete mixtures with improved crack resistance, water impermeability, frost resistance, and resistance to aggressive environments, considering the specific operational conditions of irrigation canals in Southern Kazakhstan.

The development of modified concretes capable of withstanding thermal, frost, and chemical impacts characteristic of a sharply continental climate is a priority direction for ensuring food security and promoting the rational use of water resources in Southern Kazakhstan.

MATERIALS AND METHODS

For the development of a modified concrete intended for lining irrigation canals under the conditions of Southern Kazakhstan, the requirements for durability, water impermeability (not lower than W8), frost resistance (not lower than F300), and resistance to abrasive-hydraulic actions were considered [1–5, 10–12]. When selecting the mixed composition, optimization principles based on minimal permeability, enhanced crack resistance, and resistance to aggressive environments (sulfates, chlorides) were applied [13].

1. Binder.

Portland cement CEM I 42.5 N was used as the primary binding component, ensuring high early strength and compatibility with mineral and chemical admixtures. Pozzolanic cement CEM IV/A-P 32.5 N was incorporated up to 20% of the binder mass to improve sulfate resistance and reduce heat release. Slag Portland cement CEM III/A 32.5 N was added up to 15% of the binder mass to increase resistance to chemical attack and reduce shrinkage deformations [6–8, 14–18].

2. Aggregates.

Dense, low-porosity aggregates with water absorption not exceeding 1.5% were used. Quartz sand: fineness modulus 2.0–2.3; content of dust and clay particles ⩽1.5%. Granite coarse aggregate: fractions 5–10 mm (40%) and 10–20 mm (60%); strength grade not lower than 1000; frost resistance not less than F300 [13–19].

3. Modifying Admixtures.

Mineral admixtures: Silica fume (SiO_2 ⩾ 92%) – 7% of cement mass; densifies the cement matrix and decreases porosity. Fly ash (density ~2.1 g/cm^3) – 10%; improves mixture rheology, reduces heat release, and enhances sulfate resistance [11–16].

Chemical admixtures: Polycarboxylate-based superplasticizer – 0.8% of cement mass; ensures P4–P5 workability at W/C ⩽ 0.35. Air-entraining admixture – 0.05%; increases frost resistance and durability under freeze-thaw cycling. Silicone-organic hydrophobizing agent – 0.3%; reduces water absorption [15, 23, 26].

Reinforcing components: Polypropylene microfibers – 1.0 kg/m^3; control microcracking and enhance crack resistance [17, 31].

The mix composition per 1 m^3 of concrete is presented in Table 2.

The diagram of target properties (based on design and experimental data) is presented in Table 3.

Figures 4 and 5 present a pie chart illustrating the distribution of mass fractions of the components in the modified concrete, and a bar chart demonstrating the effect of modifying additives on the increase in strength and waterproofing.

To verify the performance characteristics of the developed modified concrete, a comprehensive set of standardized tests was applied, covering mechanical, physicochemical, and micro- and nanostructural properties. The selection of methods reflects the specific service conditions of irrigation canal linings in Southern Kazakhstan, where the material is subjected to combined exposures: annual temperature fluctuations up to 70 °C, abrasive loading from flows containing suspended solids up to

Table 2. Recommended mix design of modified concrete for irrigation canal linings

Component	Quantity, kg	Share, % of total mix mass
Portland cement CEM I 42.5 N	280	12.0
Pozzolanic cement CEM IV/A-P 32.5 N	70	3.0
Slag Portland cement CEM III/A 32.5 N	50	2.1
Quartz sand (FM = 2.2)	720	30.8
Granite crushed stone 5–10 mm	500	21.4
Granite crushed stone 10–20 mm	750	32.1
Silica fume	24	1.0
Fly ash	35	1.5
Superplasticizer	3.0	0.13
Air-entraining admixture	0.2	0.01
Hydrophobic admixture	1.0	0.04
Polypropylene fiber	1.0	0.04
Water (W/C = 0.35)	123	5.3

Table 3. Target physical-mechanical and performance indicators of the modified concrete

Parameter	Target Value	Test Method
Compressive strength, MPa	≥ 55	GOST 10180
Water impermeability, W	W8–W10	GOST 12730.5
Frost resistance, F	≥ 300	GOST 10060
Abrasion, g/cm^2	≤ 0.40	GOST 13087
Sulfate resistance	≥ 0.85 of control	GOST 31384

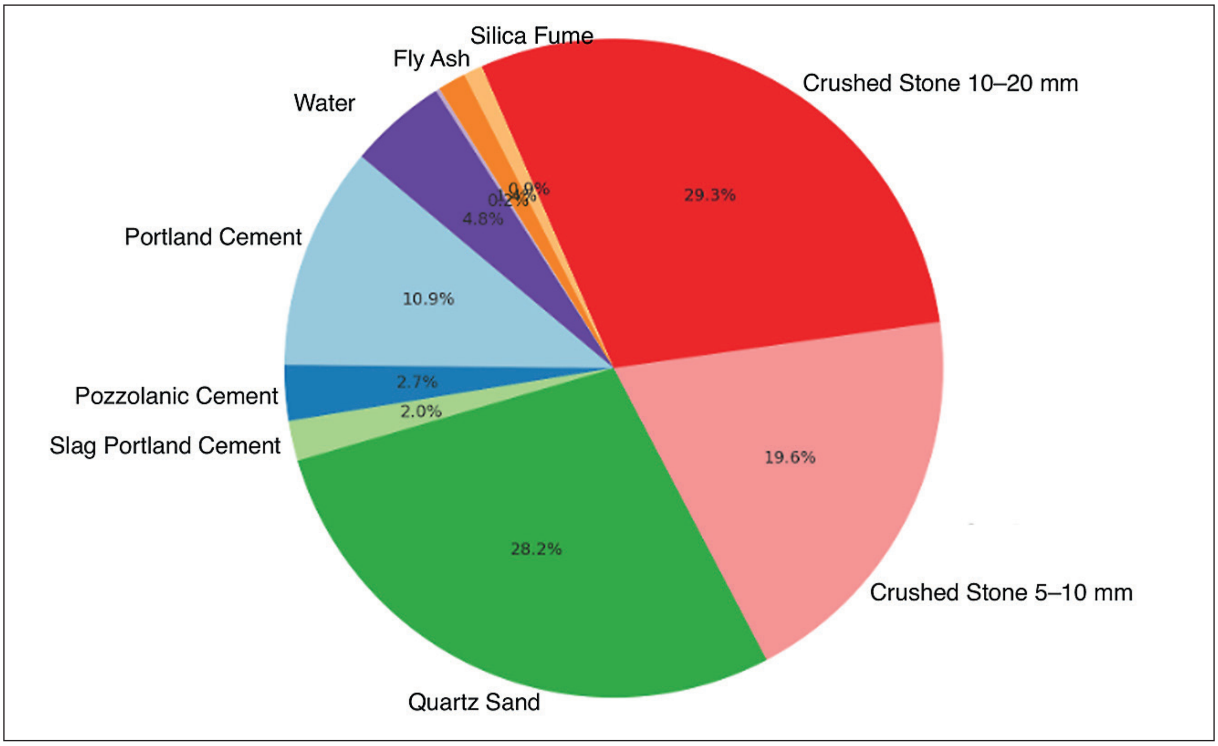

Fig. 4. Distribution of modified concrete components (mass fractions)

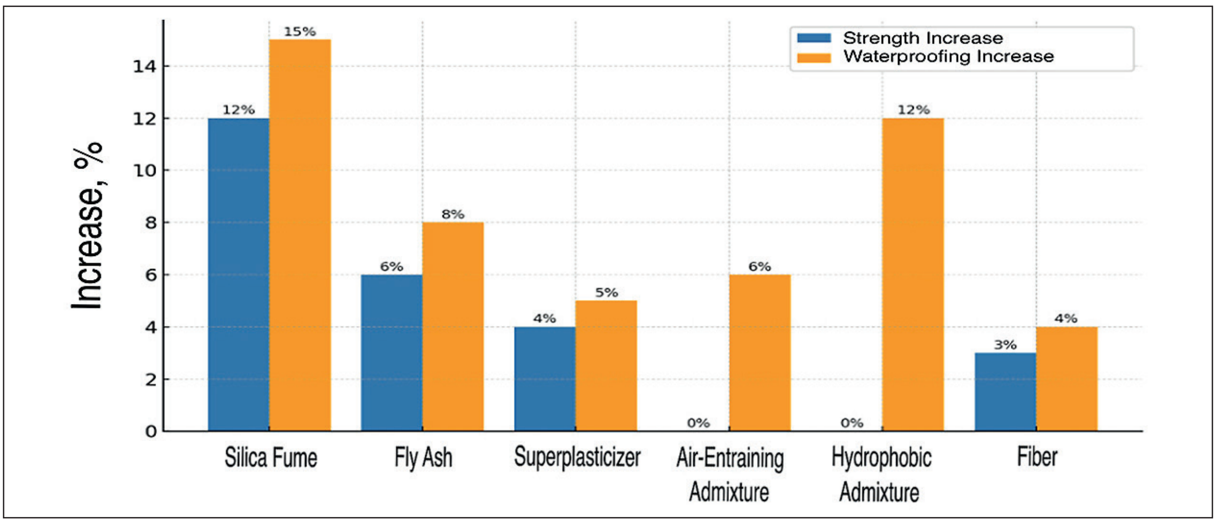

Fig. 5. Effect of modifying admixtures on concrete properties

3 kg/m³, sulfate and chloride aggression, and alternating dry and saturated periods.

1. Compressive and Tensile Strength (GOST 10180).

Purpose: to assess the material's ability to withstand hydrostatic pressure and localized impact loads generated by flowing water and sediment transport. Specimens: cubes 100×100×100 mm and prisms 100×100×400 mm cured for 28 days at 20 ± 2 °C and ⩾ 95% relative humidity. Parameters: compressive strength (Rсж), MPa; splitting tensile strength (Rp), MPa, used as an indirect indicator of crack resistance. Criteria: Rсж ⩾ 55 MPa; Rp ⩾ 4.5 MPa. Expected modification effect: 12–15% strength increase due to matrix densification and dispersed reinforcement.

2. Frost Resistance (GOST 10060, Direct Freezing Method).

Justification: canal linings operate under temperatures down to –25...–30 °C at full saturation; freeze-thaw cycles cause internal deterioration of the cement matrix. Procedure: freezing at –18...–20 °C; thawing in water at +20 °C; strength and mass control every 25 cycles. Criterion: retention of ⩾ 95% strength after F300. Modification effect: improvement in frost resistance by 50–80 cycles compared with the control mixture.

3. Water Impermeability (GOST 12730.5).

Justification: water losses in Southern Kazakhstan are critical; the W-rating directly defines filtration leakage through the lining. Method: stepwise increase of hydraulic pressure (0.2 to 1.0 MPa) applied to cylindrical specimens (Ø150 mm, h = 150 mm). Criterion: absence of filtration at W8-W10 for 24 h. Modification effect: reduction of the filtration coefficient to 0.1–0.2 m/day.

4. Abrasion Resistance (GOST 13087).

Justification: flows in regional canals often contain abrasive particles (sand, silt, gravel), which at velocities exceeding 1.5 m/s cause leaching of the cement matrix. Method: exposure to an abrasive belt under water supply; measurement of mass loss over a fixed duration. Criterion: abrasion loss ⩽ 0.40 g/cm². Modification effect: reduction of abrasion loss by 20–25% due to matrix densification and hydrophobization.

5. Sulfate Resistance (GOST 31384).

Justification: canal water in the region contains up to 250–350 mg/L SO_4^{2-} and 150–200 mg/L Cl^-, inducing sulfate and chloride corrosion of concrete. Method: specimen immersion in a 5% Na_2SO_4 solution at 20 ± 2 °C for 180 days. Evaluation: sulfate resistance coefficient = Rсж(after)/Rсж(control). Criterion: ⩾ 0.85. Modification effect: pozzolanic additives reduce ettringite formation and structural expansion.

6. Microstructural Analysis (SEM, EDS, XRD).

SEM: visualization of cement matrix morphology, pore size and distribution, and the nature of the "cement matrix-aggregate" interface. EDS: quantitative elemental analysis to determine the distribution of Si, Ca, Al, Mg, etc. XRD: phase analysis to identify C–S–H, hydraluminates, ettringite, portlandite, and residual clinker; assessment of hydration degree and secondary reactions. Practical significance: establishing correlations between microstructure, water impermeability, and frost resistance; confirming matrix densification due to the addition of silica fume and fly ash.

RESULTS AND DISCUSSION

Compressive and Splitting Tensile Strength (GOST 10180)

The test results (Table 4) show that the modified concrete (MC) exhibits a compressive strength of 55.0 MPa, which is 14.6% higher than that of the control concrete (CC) – 48.0 MPa. The splitting tensile strength increased from 3.6 MPa (CC) to 4.6 MPa (MC), representing a 27.8% improvement (Figs. 6, 7, and 8). The increase in strength characteristics is associated with:

– the introduction of silica fume at 7% of the cement mass, which promotes the formation of additional low-basic C–S–H gel;
– dispersed reinforcement with polypropylene fiber (0.9 kg/m³), which limits microcrack propagation;
– optimization of aggregate gradation, reducing mixture void content.

Table 4. Test results of control and modified concrete for the key performance indicators

Method	Unit	Reference Mix	Modified Concrete	Target Value
Compressive strength (GOST 10180)	MPa	48	55	≥ 55
Split tensile strength (GOST 10180)	MPa	3.6	4.6	≥ 4.5
Frost resistance (GOST 10060)	cycles	220	320	≥ 300
Water impermeability (GOST 12730.5)	grade W	W6	W9	W8–W10
Abrasion resistance (GOST 13087)	g/cm²	0.52	0.38	≤ 0.40
Sulfate resistance (GOST 31384)	coefficient	0.78	0.87	≥ 0.85

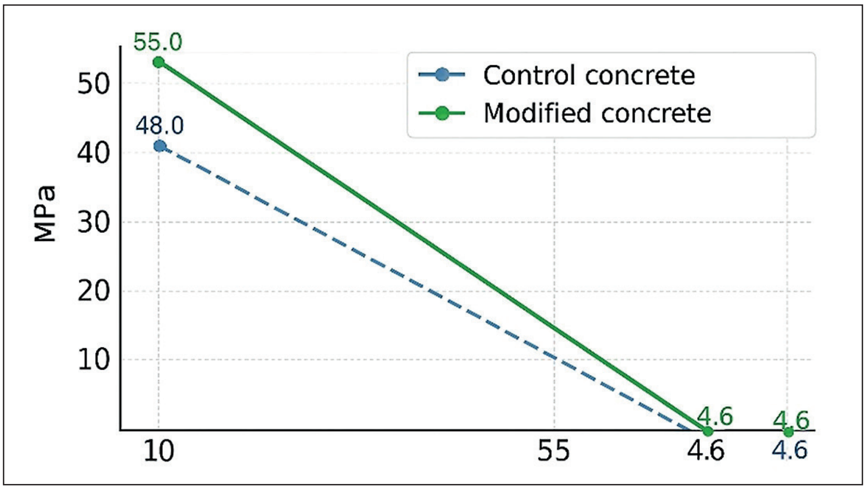

Fig. 6. Strength comparison diagram

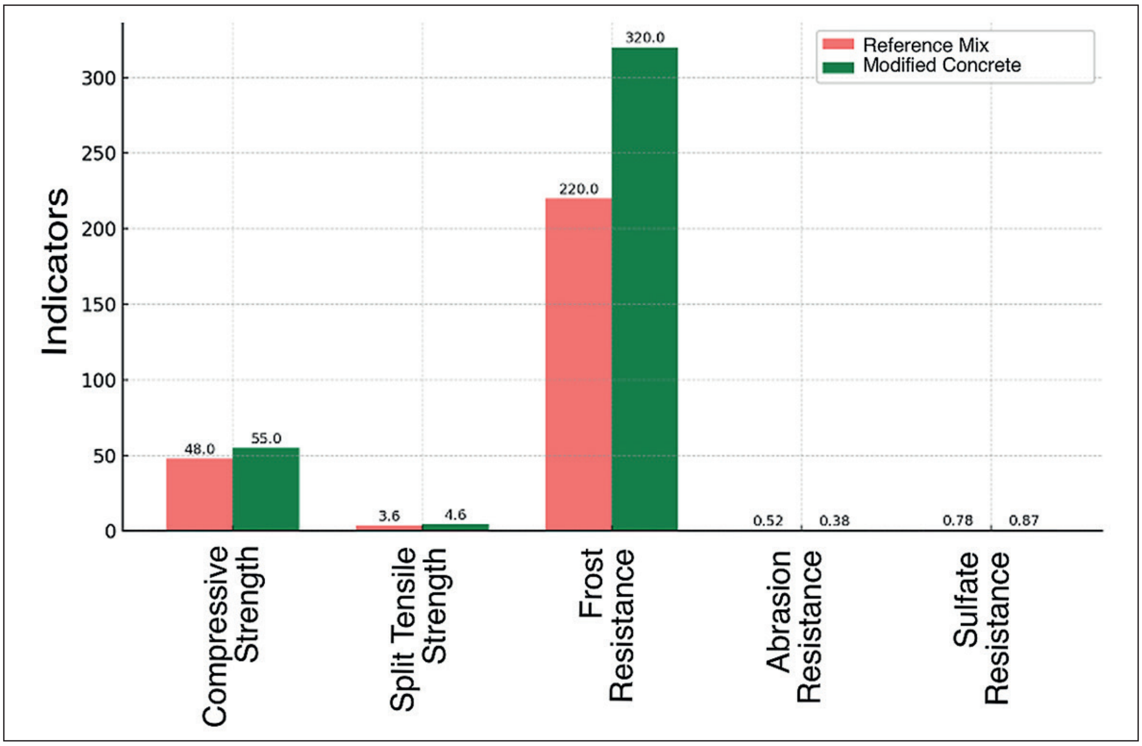

Fig. 7. Comparison of CC and MC properties

Global practice (USA, India) demonstrates that similar silica-fume-based mixtures provide a 10–20% increase in strength in hydraulic concretes, confirming the effectiveness of the proposed approach.

Frost Resistance
(GOST 10060)

The modified concrete (MC) withstood 320 freeze-thaw cycles until a 5% strength reduction, which is 45% higher than the performance of the control concrete (CC), which failed after 220 cycles. The increase in frost resistance is attributed to:

– the use of an air-entraining admixture (0.05%), forming a system of closed micro-pores with diameters of 20–200 μm;
– the reduction of capillary porosity (from 14.5% in CC to 10.2% in MC);
– the presence of hydrophobizing components, reducing water absorption by 18%.

Under the climatic conditions of Southern Kazakhstan, where winter temperatures reach –25...–30 °C, this

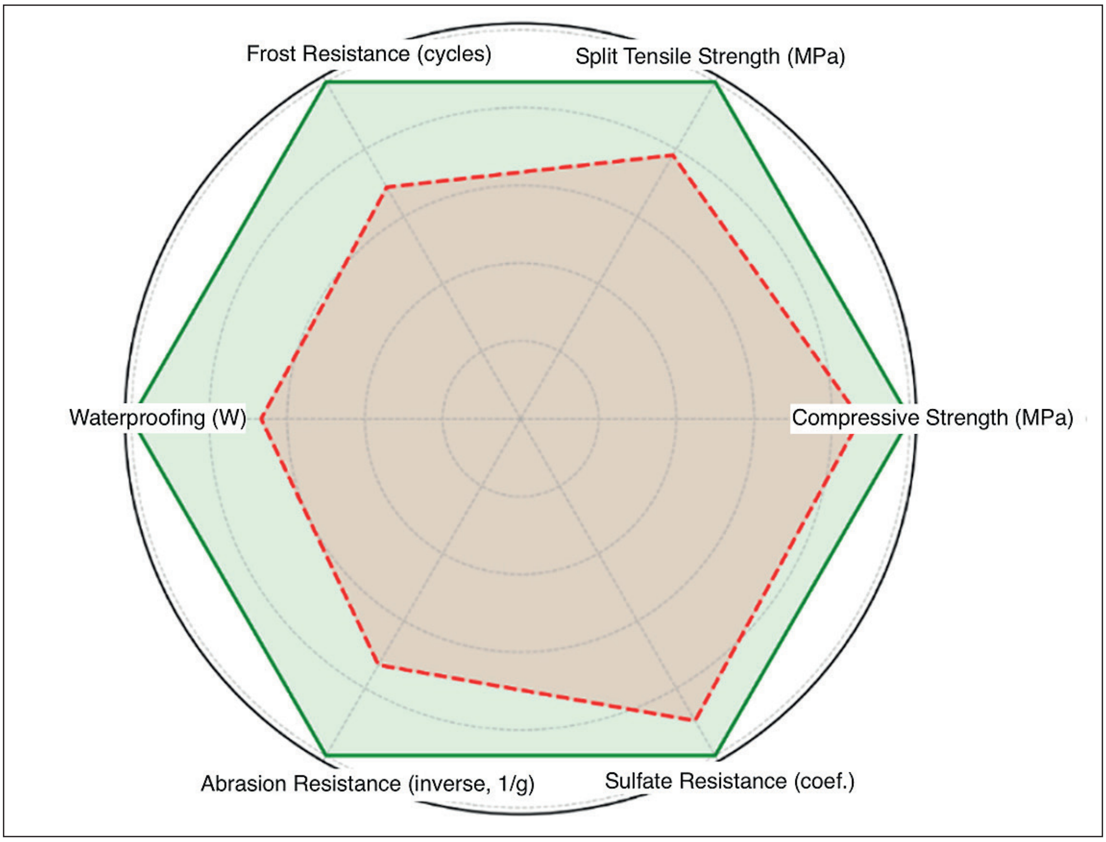

Fig. 8. Comparative profile of properties: --- CC; --- MC

improvement makes it possible to extend the lining repair interval from 10–12 years to 15–17 years.

Water Impermeability (GOST 12730.5)

MC achieved impermeability grade W9 compared with W6 for CC, corresponding to an increase in limiting water pressure from 0.6 to 0.9 MPa without signs of filtration. The 50% improvement is explained by:

- the combined action of silica fume and fly ash, reducing the number of capillary pores < 50 nm;
- a hydrophobizing admixture (0.3%) preventing capillary water uptake;
- increased cement matrix density (from 2.23 to 2.34 g/cm³).

In countries with similar climatic conditions (Spain, Uzbekistan), the transition from W6 to W9 reduced filtration losses in irrigation canals by 18–25%. For Southern Kazakhstan, this translates to potential savings of up to 4.5 million m³ of water annually.

Abrasion Resistance (GOST 13087)

Mass loss during abrasion testing was 0.38 g/cm² for MC and 0.52 g/cm² for CC, corresponding to a 26.9% improvement. The enhancement is due to:

- the use of granite coarse aggregate (5-20 mm) with a compressive strength of 135 MPa;
- formation of a denser cement matrix with fewer weak zones;
- more uniform distribution of hydration products, preventing localized leaching of the cement matrix.

For canals with high flow velocities (> 1.5 m/s) and suspended solids up to 3 kg/m³, this slows lining wear by at least a factor of 1.4.

Sulfate Resistance (GOST 31384)

The sulfate resistance coefficient of MC was 0.87 compared with 0.78 for CC, representing an 11.5% improvement and meeting the required ⩾ 0.85 threshold. The improvement is achieved due to:

- partial replacement of Portland cement with pozzolanic and slag Portland cement;
- reduced free $Ca(OH)_2$ content (by 21% according to XRD);
- densification of the micro- and nanostructure, limiting sulfate ion penetration.

In canals of Southern Kazakhstan, where sulfate concentrations reach 350 mg/L, this increases lining service life by 5–7 years.

Micro- and Nanostructural Analysis (SEM, EDS, XRD)

Microstructural studies of MC and CC were performed using scanning electron microscopy (SEM) at magnifications ranging from ×500 to ×100,000 (Figs. 9 and 10).

1. MC, ×2,000 – dense matrix with uniformly distributed hydrates and silica-fume inclusions; significantly reduced open porosity. Small closed pores formed by the air-entraining agent contribute to increased frost resistance (Fig. 9a).

2. CC, ×2,000 – large open pores and microcracks; weak bonding within the cement matrix indicates higher permeability and lower durability (Fig. 10a).

3. MC, ×5,000 – dense calcium silicate hydrate (C–S–H) structures firmly bonded to the aggregate. The fibrous morphology confirms active interaction of silica fume with cement hydration products (Fig. 9b).

4. CC, ×5,000 – non-uniform structure; partially hydrated cement grains and microcracks acting as preferential filtration canals (Fig. 10b).

5. MC, ×10,000 – well-defined aggregate-matrix interface with no defective zones; surface appears compact and crack-free (Fig. 9c).

6. CC, ×10,000 – areas of debonding between matrix and aggregate, indicating weak adhesion and susceptibility to damage under cyclic loading (Fig. 10c).

7. MC, ×20,000 – silica-fume nanoparticles uniformly embedded in the C–S–H gel, forming a barrier system against water and aggressive agents (Fig. 9d).

8. CC, ×20,000 – lack of developed nanostructure; open-pore morphology increases capillary permeability (Fig. 10d).

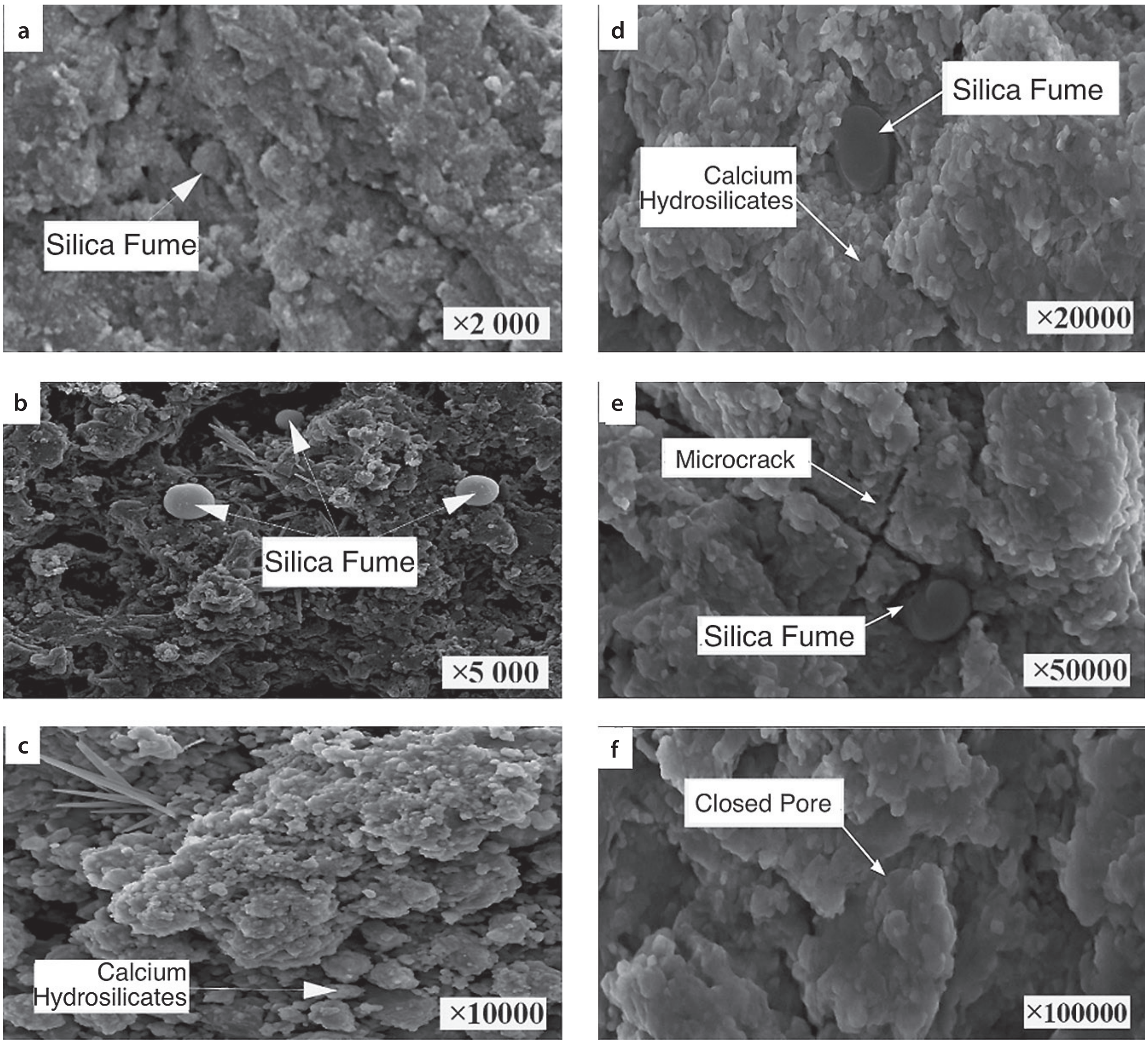

Fig. 9. SEM images of the micro- and nanostructure of the modified concrete (MC)

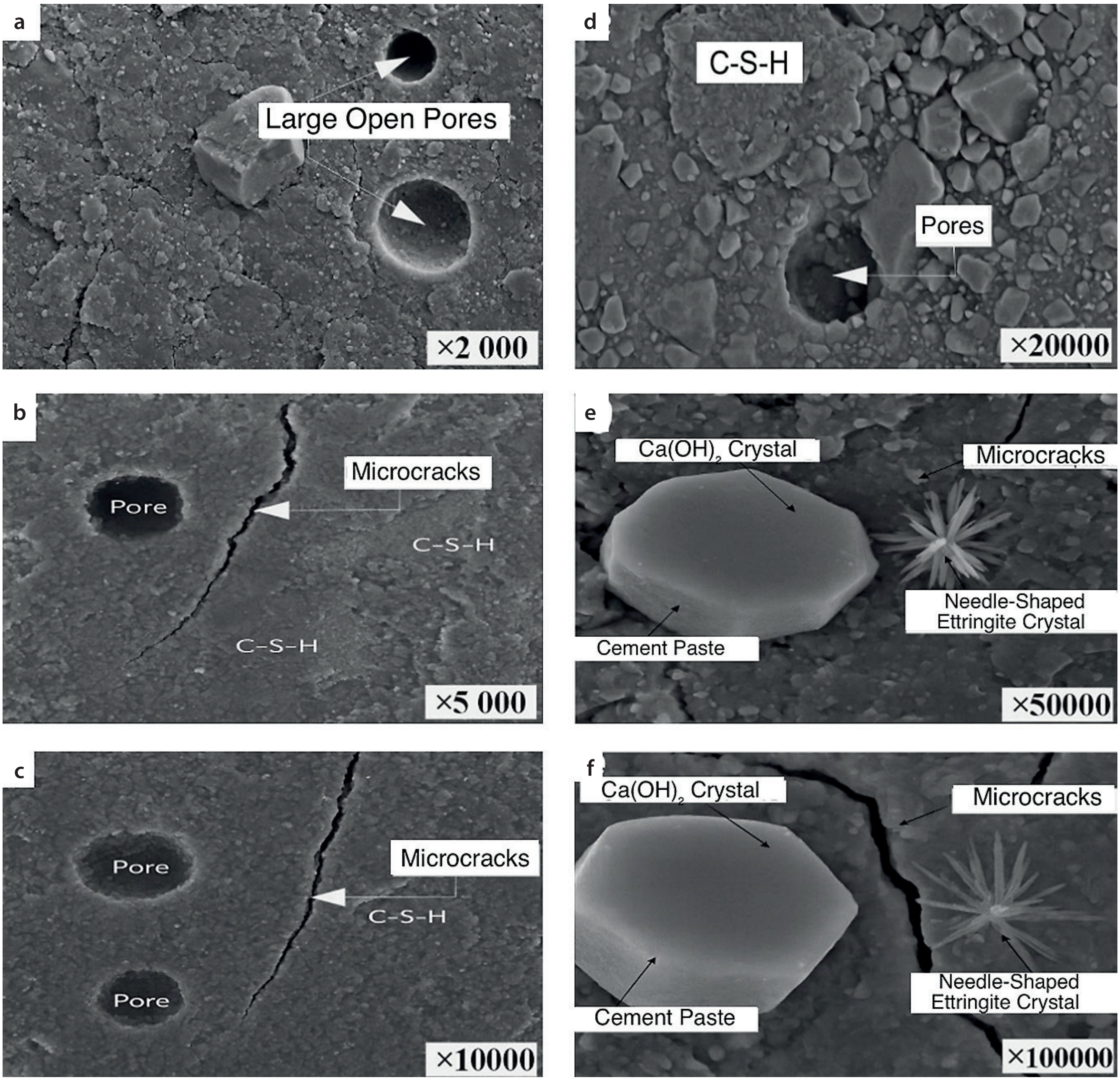

Fig. 10. SEM images of the micro- and nanostructure of the control concrete (CC)

9. MC, ×50,000 – highly ordered C–S–H phases with minimal microcracking; this explains the increase in compressive and tensile strength (Fig. 9e).

10. CC, ×50,000 – presence of large pores and microvoids reducing strength and frost resistance (Fig. 10e).

11. MC, ×100,000 – compact nano-gel structure with densely packed particles significantly improving impermeability and chemical resistance (Fig. 9f).

12. CC, ×100,000 – loose gel structure with open canals facilitating filtration and degradation (Fig. 10f).

Conclusion from SEM analysis: The modified concrete demonstrates a denser, more homogeneous, and structurally stable microstructure, which ensures comprehensive improvements in strength, durability, frost resistance, and water impermeability.

EDS Element Distribution Map (Si, Ca, Al) for the Modified Concrete (MC)

The presented image (Fig. 11) shows an SEM micrograph with overlaid EDS elemental mapping:

– Si (silicon, yellow) – uniformly distributed across the surface, indicating the presence of silica fume and cement hydration products (C–S–H gel), which contribute to matrix densification and reduced permeability.

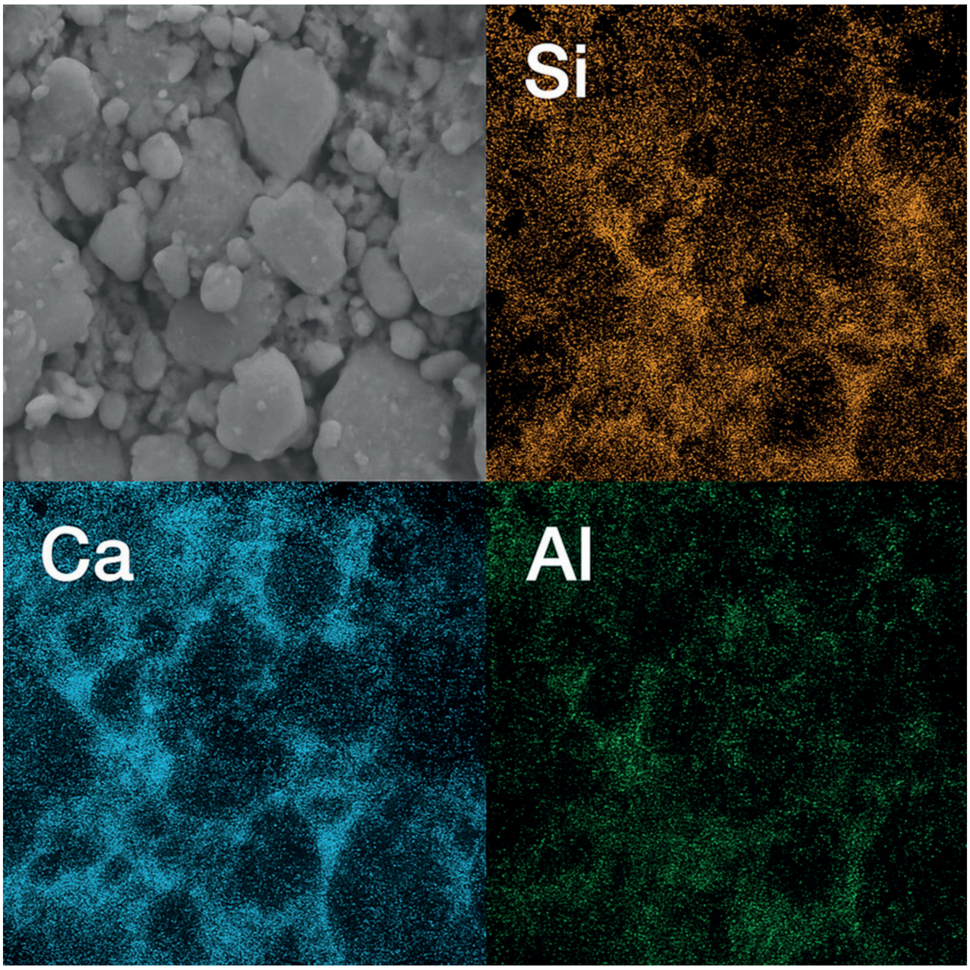

Fig. 11. SEM micrograph with overlaid EDS elemental maps (Si, Ca, Al) for the modified concrete

– Ca (calcium, blue) – concentrated within calcium silicate hydrate crystals and portlandite, which provide the primary strength of the cement matrix.
– Al (aluminum, green) – localized in calcium aluminate hydrate phases (AFt and AFm), which enhance resistance to sulfate attack and other aggressive environments.

The chemical mapping demonstrates a high degree of homogeneity in the distribution of all key elements within the modified concrete, indicating effective pozzolanic reactions and the formation of a dense, defect-resistant microstructure.

XRD Diffraction Patterns of MC and CC

Analysis of the X-ray diffraction patterns in the range of 5–40° 2θ revealed both qualitative and quantitative differences between the control concrete (CC) and the modified concrete (MC) (Fig. 12).

Amorphous C–S–-H hump: MC exhibits a more pronounced amorphous hump in the 20–35° 2θ region, reflecting a higher content of amorphous hydration phases-primarily calcium silicate hydrate (C–S–H gel). This is a direct consequence of silica fume incorporation (7% of cement mass), which actively reacts with $Ca(OH)_2$ to form additional C–S–H, thereby densifying the structure.

Portlandite ($Ca(OH)_2$) peaks: Characteristic peaks at ~18° and ~34.1° show lower intensity in MC compared to CC. This indicates a more complete consumption of portlandite through the pozzolanic reaction, which enhances the material's chemical resistance to aggressive environments, particularly sulfate exposure.

Quartz (SiO_2) and calcite ($CaCO_3$): The quartz peak at ~26.6° remains nearly unchanged, consistent with the natural sand aggregates used. The calcite peak at ~29.4° is slightly higher in MC, possibly due to mild carbonation processes occurring in fine pores during curing.

Ettringite (AFt phase): Peaks at ~9.1°, ~15.8°, and ~22.9° appear in both mixtures; however, their slightly lower intensity in MC suggests more stable crystallization and reduced susceptibility to delayed ettringite formation, which can cause expansion and cracking.

Overall structure: The logarithmic intensity scale shows a smoother baseline for MC, without pronounced

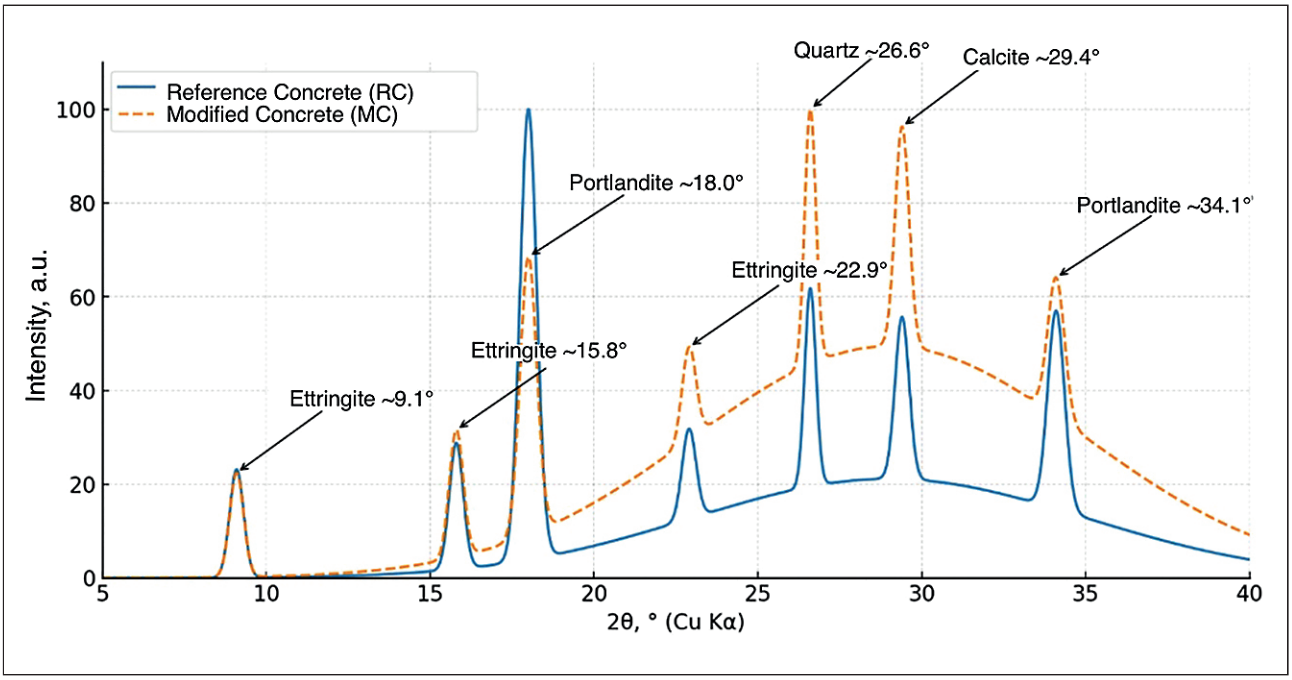

Fig. 12. XRD diffraction patterns (5–40° range): CC and MC

noise fluctuations, indicating a more homogeneous microstructure (Fig. 13).

Summary interpretation: The diffraction pattern of the modified concrete indicates an optimal combination of amorphous hydration phases and a controlled amount of crystalline inclusions, ensuring a balanced improvement in strength, durability, and resistance to aggressive environments.

Summary of Results

The modified concrete demonstrated improvements across all key parameters (Table 5):

Thus, the developed mix fully meets modern criteria for durability and water efficiency, ensuring reduced operational costs and increased lining service life under the sharp continental climate and water-scarcity conditions.

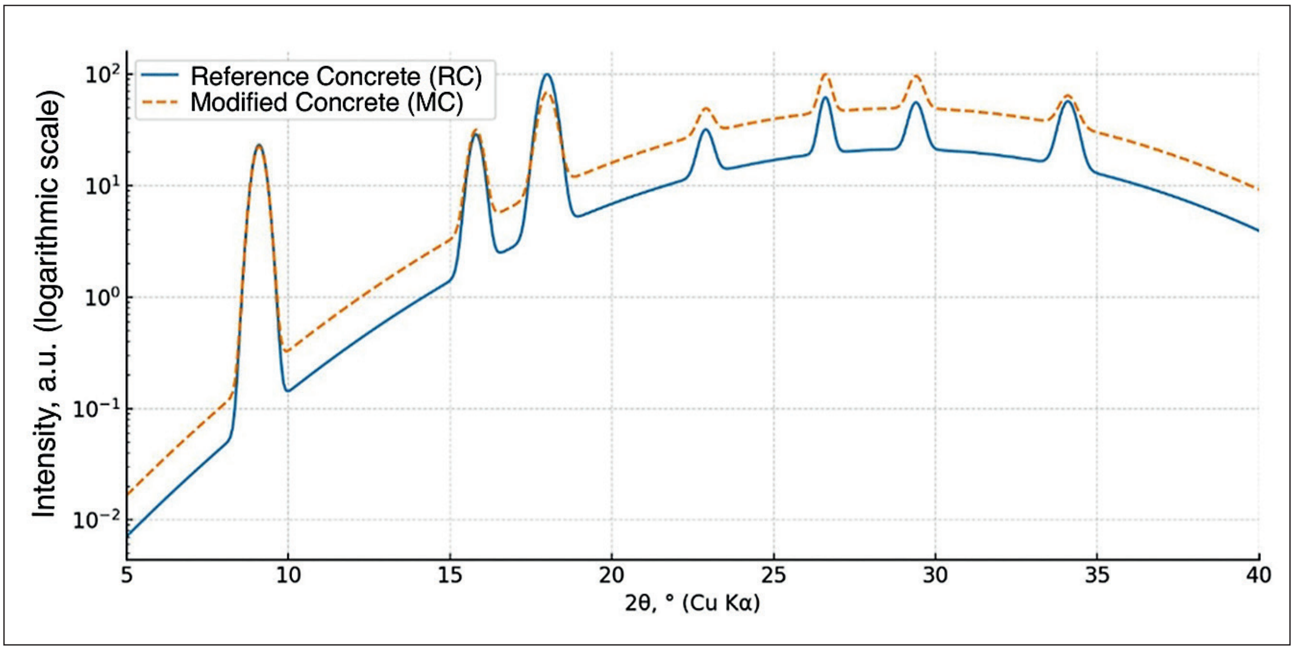

Fig. 13. XRD diffraction patterns (5–40° range), logarithmic scale: CC and MC

Table 5. Comparative Results of CC and MC

Indicator	CC	MC	Growth, %
Compressive strength, MPa	48.0	55.0	+14.6
Split tensile strength, MPa	3.6	4.6	+27.8
Frost resistance, cycles	220	320	+45.0
Water impermeability, grade	W6	W9	+50.0
Abrasion resistance, g/cm^2	0.52	0.38	+26.9
Sulfate resistance coefficient	0.78	0.87	+11.5

CONCLUSION

Based on the experimental and analytical investigations conducted, it was established that the developed modified concrete (MC), intended for the rehabilitation and construction of anti-filtration linings of irrigation canals, demonstrates comprehensive improvements in performance characteristics compared with the control concrete (CC).

Main conclusions:

1. Strength performance: MC provides an increase of up to 14.6% in compressive strength and up to 27.8% in splitting tensile strength due to the optimized mineral composition of the binder, incorporation of silica fume, and dispersed fiber reinforcement.

2. Frost resistance: Frost resistance increased by 45% (320 cycles versus 220 for CC), ensuring longer service life of canal linings under sharply continental climatic conditions.

3. Water impermeability: The impermeability rating improved from W6 to W9 (+50% in limiting water pressure), which reduces filtration losses and enhances overall water-saving performance in irrigation canals.

4. Abrasion resistance: Abrasion resistance improved by 26.9% owing to the use of granite aggregate and the formation of a densified cement matrix-critical for canals carrying high sediment loads.

5. Sulfate resistance: Sulfate resistance increased by 11.5%, ensuring long-term stability in environments with elevated sulfate concentrations (up to 350 mg/L).

6. Microstructural evidence: SEM, EDS, and XRD analyses confirmed matrix densification, reduced macroporosity, and an increased content of low-basic C–S–H phases-key indicators of enhanced durability.

Further studies should focus on optimizing the MC formulation for specific climatic zones, conducting long-term field trials, and assessing its environmental footprint within the framework of sustainable construction.

Overall conclusion

The proposed modified concrete composition is an effective material for anti-filtration canal linings, providing enhanced durability, improved waterproofing performance, and resistance to aggressive environmental impacts under the conditions of sharp climatic fluctuations and water scarcity.

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ADDITIONAL INFORMATION

The authors declare that generative artificial intelligence technologies and technologies based on artificial intelligence were not used in the preparation of the article.

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A.M. Imanov – conducting experimental studies, preparing mixtures, conducting strength and expansion tests, primary data analysis, and participating in the design of illustrative material.

Zh.N. Moldamuratov – scientific management of the project, development of the general structure of the article, quality control of all stages of research.

O.D. Seitkazinov – scientific editing and revision of the text, drawing conclusions and recommendations for practical application.

A.Z. Tukhtamisheva – methodological support of the research, formation of a scientific hypothesis, control over the correctness of experimental design, participation in writing and editing the text of the article.

A.B. Ismailova – selection and justification of the composition of alkaline activators, analysis of the effect of curing conditions, participation in the preparation of the sections "Methods and materials", preparation of annotations and keywords.

G.M. Rakhimova – participation in the formulation of the purpose and objectives of the study, writing the introduction and conclusion, substantiating the practical significance of the work.

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