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COMPREHENSIVE ANALYSIS OF THE ELEMENTAL COMPOSITION AND THERMAL STABILITY OF REINFORCED CONCRETE BASED ON RECYCLED MATERIALS

This paper presents a comprehensive comparative study focused on the elemental composition, physicochemical properties, and thermal stability of traditional reinforced concrete (TRC) versus alternative reinforced concrete (ARC) developed using recycled raw materials. The research aligns with the fundamental principles of circular economy and green chemistry, aiming to address the urgent need for sustainable infrastructure reconstruction in Ukraine. The investigation primary focuses on the synergy between the chemical nature of binders and their macro-scale performance under extreme conditions. Elemental analysis, conducted via X-ray fluorescence (XRF) spectroscopy using the ElvaX Pro spectrometer, revealed a fundamental divergence in the chemical profiles of the studied systems. It was established that ARC, based on alkali-activated slag cements and recycled concrete aggregates, forms a high-calcium matrix (with calcium content reaching 91.494 %). This composition significantly differs from the multi-component silicate structure of traditional Portland cement-based systems.

Experimental heating tests, simulating fire conditions with temperatures reaching up to 700 °C, allowed for the identification of a specific thermal damper effect in the alternative compositions. From a thermochemical perspective, the high concentration of calcium-bearing phases, such as calcium silicate hydrates (C-S-H) and carbonates, facilitates enhanced energy absorption through endothermic dehydration and decarbonisation processes. This mechanism results in a 15–20 % reduction in the rate of internal temperature rise compared to traditional concrete. To verify the structural integrity of the materials after thermal exposure, non-destructive ultrasonic testing was employed using an AU2000 flaw detector. The results demonstrated that despite surface-level degradation, the internal layers of the ARC maintain superior stability and acoustic consistency. The study concludes by justifying the environmental and technical feasibility of integrating recycled aggregates into construction practices as a tool for decarbonisation. Furthermore, the practical potential for implementing these findings into the educational process for chemical technology and civil engineering students is discussed, emphasizing the importance of quality control and innovative material certification in modern industry.

Keywords: *alternative reinforced concrete (ARC), X-ray fluorescence analysis (XRF), high-calcium matrix, kinetics of temperature fields, thermal damper effect, ultrasonic testing, recycled raw materials, quality of chemical technology products.*

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КОМПЛЕКСНИЙ АНАЛІЗ ЕЛЕМЕНТНОГО СКЛАДУ ТА ТЕРМІЧНОЇ СТІЙКОСТІ ЗАЛІЗОБЕТОНУ НА ОСНОВІ ВТОРИННОЇ СИРОВИНИ

У роботі представлені результати порівняльного дослідження традиційного та альтернативного залізобетонів на основі шлакоцементів та рециклінгових бетонних заповнювачів. Метою дослідження було встановлення взаємозв'язку між елементним складом матеріалів та їхньою термічною стійкістю в контексті циркулярної економіки. Елементний аналіз методом рентгенофлуоресцентної спектроскопії виявив формування в зразках альтернативного залізобетону висококальцієвої матриці, що зумовлює відмінну від традиційних систем кінетику фазових перетворень. Експериментально підтверджено ефект термічного демпфера в альтернативних складах: енергія високотемпературного впливу витрачається на ендотермічні процеси дегідратації гідросилікатів кальцію та декарбонізації, що сповільнює прогрів внутрішніх шарів зразків бетону на 15–20 %. Методом ультразвукової дефектоскопії підтверджено збереження структурної цілісності альтернативних зразків бетону після термічного навантаження. Результати обґрунтовують хіміко-технологічну доцільність використання вторинної сировини для декарбонізації будівництва та відновлення інфраструктури України.

Ключові слова: *альтернативний залізобетон, рентгенофлуоресцентний аналіз (РФА), висококальцієва матриця, кінетика температурних полів, ефект термічного демпфера, ультразвукова дефектоскопія, вторинна сировина, якість продукції хімічних технологій.*

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Problem Statement

Construction represents a pivotal segment of the global industry, ensuring the functionality of residential and industrial infrastructure. Reinforced concrete serves as the fundamental material in this field – a composite system that, through the synergy of concrete and steel reinforcement, provides high strength, durability, and fire resistance to structures. The uniqueness of reinforced concrete lies in the rational combination of its components' properties: the concrete matrix effectively withstands compressive loads and protects the reinforcement from corrosion and fire, while the steel bars absorb tensile stresses. However, traditional production technologies for reinforced concrete structures face significant challenges due to the scarcity of natural raw materials and the high energy intensity of manufacturing processes.

The central component of concrete production is cement clinker – a product of the high-temperature calcination of limestone and clay. Its synthesis involves not only substantial fuel consumption but also a complex crystallochemical structure of calcium silicates and aluminates, which determine the subsequent strength of the cement stone. Parallelly, the extraction of significant volumes of aggregates, such as crushed stone and sand, along with the production of reinforcing steel, necessitates the search for new resource optimization pathways. One such path, aligning with sustainable development strategies and industrial decarbonisation, is the development of alternative reinforced concrete (ARC).

ARC involves the utilisation of slag cements instead of traditional Portland cement and the replacement of natural gravel with recycled concrete aggregate (RCA). This allows not only for a reduction in construction costs but also for the effective management of construction waste, the volume of which has surged in Ukraine due to large-scale destruction caused by military aggression. However, the use of secondary raw materials introduces substantial changes to the physicochemical properties of the material. Slag-based binders and porous aggregates exhibit hardening kinetics and pore structures distinct from traditional analogues and, most critically, respond differently to thermal exposure.

The issues of fire resistance and structural integrity under conditions of fire or extreme heating are decisive for the operational safety of buildings. As temperature increases, complex phase transformations occur within the concrete: dehydration of hydrosilicates, thermal dissociation of components, and the emergence of internal stresses due to the differential thermal expansion coefficients of the matrix and the aggregate. While these processes are well-documented for traditional reinforced concrete (TRC), experimental data for alternative compositions based on slag cements and recycled aggregates remain insufficient. Given the necessity of reconstructing Ukraine's infrastructure amidst heightened anthropogenic risks, monitoring the behaviour of new concrete types is a pressing task. A comprehensive comparative analysis of temperature fields within the structures of traditional and alternative reinforced concrete is required to verify the reliability of the latter. Such research is a vital step toward improving the regulatory framework, particularly the EN 1996 series standards, and developing recommendations for implementing environmentally safe yet technically resilient technologies in modern construction.

Analysis of recent research

The development and implementation of alternative concrete types using recycled raw materials are currently at the forefront of research for many scientific schools worldwide. Recent studies focus on finding a balance between environmental feasibility and the operational reliability of structures. The current state of the construction industry necessitates a transition to circular economy principles, leading to an active search for opportunities to reuse construction waste. Analysis of accumulated global experience demonstrates that the organisation of rational technological schemes for processing concrete and reinforced concrete ensures the competitiveness of recycled aggregate compared to natural stone [1]. One of the most promising avenues for industry decarbonisation is the introduction of alkali-activated cements, which demonstrate significant advantages over traditional Portland cement due to the formation of a stable hydrate phase without free $Ca(OH)_2$ [2].

Special attention in scientific literature is paid to the microstructure and mechanical properties of concretes based on recycled aggregates. Research indicates that the presence of old cement mortar on the surface of aggregates can impair the composite's characteristics, necessitating the application of surface treatment methods to improve adhesion [3]. In particular, accelerated carbonation of recycled aggregates is an effective method for strengthening the interfacial transition zone, allowing micropores to be filled with calcite and significantly increasing the compressive strength of the concrete [4]. Simultaneously, structuring processes in the "cement paste – aggregate" contact zone within alkaline systems can exhibit both destructive and constructive characteristics, which determine the material's durability [5].

The operational reliability of such composites is closely linked to their behaviour under thermal loads. It has been established that high temperatures cause significant changes in the thermophysical properties of concrete, namely thermal conductivity and specific heat capacity, which are critical factors for high-strength compositions [6]. Since concrete performs both a static and a protective function for reinforcement during a fire, analysing the behaviour of cement composites under extreme temperatures is a priority research area to ensure the safety of building structures [7]. In Ukraine, the methodology for calculating fire resistance and assessing the condition of structures after thermal exposure is regulated by state standards harmonised with European norms [8].

The **aim of this work** is to conduct a comparative analysis of the physicochemical properties and thermal stability of traditional reinforced concrete (TRC) and alternative reinforced concrete (ARC) using recycled raw materials. This study explores the feasibility of implementing ARC for the reconstruction of Ukraine's infrastructure in accordance with the principles of green chemistry and the circular economy. To achieve this aim, the following objectives were defined:

- to investigate the elemental composition and specific chemical characteristics of the binder systems in TRC and ARC using X-ray fluorescence (XRF) analysis to identify high-calcium phases within the recycled raw materials;
- to experimentally establish the patterns of temperature field dynamics within the concrete structure under

high-temperature exposure and to investigate the nature of the thermal damper effect in alternative compositions;

- to perform non-destructive testing of structural integrity and evaluate the degree of material degradation following thermal loading using ultrasonic flaw detection;
- to assess the environmental and energy efficiency of using recycled aggregates in the context of construction decarbonisation and to develop recommendations for integrating the research findings into the educational process for training specialists in chemical technology.

Main body of research

In this study, TRC was investigated – iron-reinforced concrete [9] of class B15 and grade M200, which consists of Portland cement (80–94 % clinker), natural sand, and gravel (diameter 8–16 mm, density 0.680 kg/dm³), and steel reinforcement. The ARC composition consists of slag cement, natural sand, recycled concrete aggregate used instead of gravel, and steel reinforcement made from secondary raw materials. Samples of both TRC and ARC were obtained from a specialised construction materials enterprise.

To establish the relationship between the macroscopic properties of the concretes – specifically their thermal stability and heating dynamics – and their chemical nature, an investigation of the elemental composition of the TRC and ARC samples was conducted using XRF analysis. The application of this method within the scope of the study was necessitated by the need to: identify the chemical profile of the binder systems to confirm the differences between traditional Portland cement and alternative slag cement; assess the purity and origin of the secondary raw materials; and evaluate the potential susceptibility of the materials to dehydration and decarbonisation under extreme heating. Since the chemical composition determines the temperature of phase transformations within the cement stone, XRF spectroscopy serves as a tool for the preliminary assessment of the fire resistance of composites.

XRF analysis of the concrete samples was performed using an ElvaX Pro spectrometer. Representative aliquots, uniform in composition, were selected and subsequently ground in a crusher to a homogeneous powder to ensure optimal contact with the X-ray radiation. The powdered samples were placed into a specialised cuvette and installed in the chamber of the ElvaX Pro spectrometer. To acquire spectra for both heavy and light elements, configurations for standard and light-element tasks were applied. To facilitate the detection of light elements, the working chamber was purged with helium [10, 11]. Data processing and analysis were carried out using the proprietary ElvaX Pro software. The results of the X-ray fluorescence spectroscopy (XRS) study for the TRC and ARC samples are presented in Tables 1–2 and Figures 1–2, respectively.

Table 1

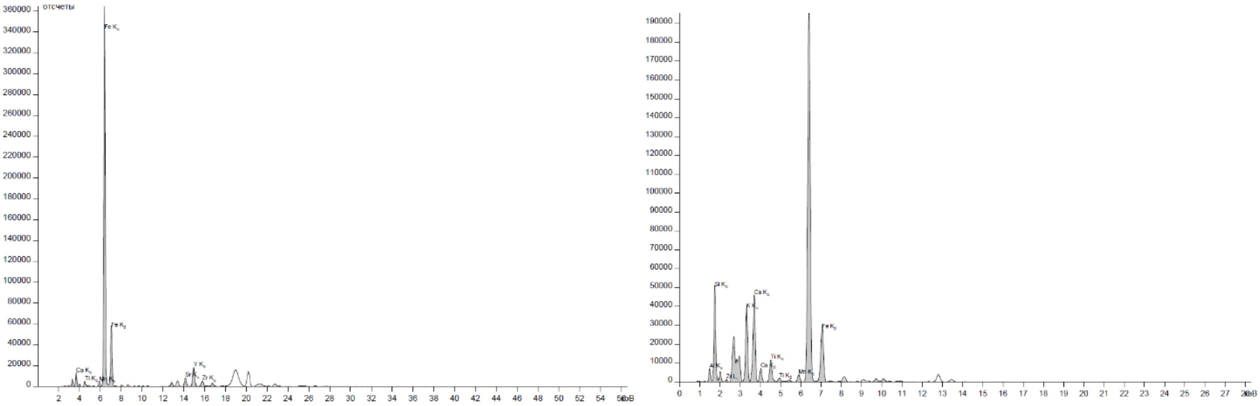
Elemental composition analysis protocol for TRC

Atomic number	Element	Series	Intensity	Concentration
26	Fe	K	1425089	37.147 ± 0.068%
20	Ca	K	262488	23.861 ± 0.108%
19	K	K	222881	20.125 ± 0.096%
14	Si	K	234477	9.990 ± 0.042%
13	Al	K	29312	3.830 ± 0.058%
22	Ti	K	17644	2.519 ± 0.066%
15	P	K	23634	1.132 ± 0.023%
25	Mn	K	17498	0.698 ± 0.018%
39	Y	K	103059	0.429 ± 0.005%
38	Sr	K	44004	0.173 ± 0.004%
40	Zr	K	24130	0.094 ± 0.005%

Table 2

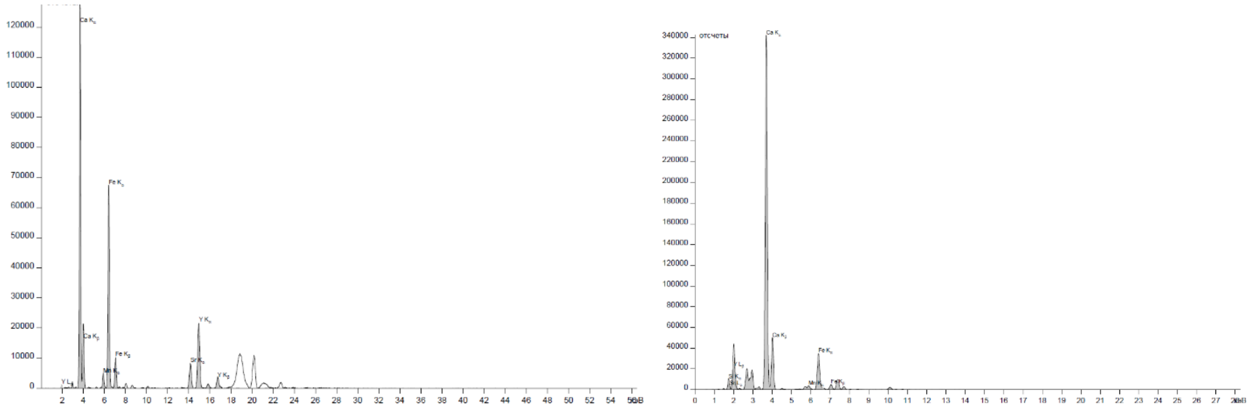
Elemental composition analysis protocol for ARC

Atomic number	Element	Series	Intensity	Concentration
20	Ca	K	1944056	91.494 ± 0.056%
26	Fe	K	258031	6.343 ± 0.027%
14	Si	K	42611	1.044 ± 0.014%
25	Mn	K	18997	0.740 ± 0.016%
39	Y	K	123221	0.279 ± 0.003%
38	Sr	K	45050	0.097 ± 0.002%
40	Zr	K	1346	0.003 ± 0.002%



Heavy elements Light elements

Fig. 1 – XRF spectrum of the TRC sample



Heavy elements Light elements

Fig. 2 – XRF spectrum of the ARC sample

For TRC, high concentrations of iron (37.147 %) and potassium (20.125 %) were recorded. Such an iron level represents an integral result of the reinforced concrete system analysis, where significant contributions are made by the steel reinforcement and the diffusion of steel oxidation products into the adjacent concrete layers. The high content of potassium and silicon (9.990 %) confirms the use of traditional Portland cement and natural silicate aggregates. In the ARC samples, a fundamental shift in the elemental profile is observed: the calcium fraction rises to 91.494 %, accompanied by a substantial decrease in silicon content to 1.044 % and iron to 6.343 %. This indicates the formation of a high-calcium matrix, characteristic of slag-cement systems utilizing recycled concrete aggregate.

Based on the XRF results, the behaviour of the samples during high-temperature testing can be predicted. The high calcium content in ARC typically correlates with a greater quantity of calcium silicate hydrates (C-S-H) and carbonates. Upon heating above 500 °C, this should lead to intensive decarbonisation and dehydration. The presence of iron in TRC may facilitate the formation of vitreous phases at high temperatures, which slightly alters the material's thermal conductivity compared to the high-calcium ARC. XRF analysis also enables the determination of the degree of substitution of natural components; specifically, the absence or low content of specific impurities (such as potassium or titanium) in ARC confirms the successful replacement of natural sand/gravel with recycled waste.

Thus, the elemental composition analysis via XRF revealed a significant divergence in the chemical nature or chemism of the studied systems. The predominance of the calcium phase in ARC (91.494 %) compared to the multi-component TRC confirms the formation of a different crystallochemical structure, which directly influences the heat transfer kinetics under extreme thermal loads.

To verify or refute the assumptions derived from the XRF results, thermal endurance tests of the concrete samples were also conducted. The experiments were performed by heating in a specialised furnace according to the standard [12] using a gas burner applied to a small area of the sample. The temperature was measured with a shielded thermocouple (1 mm in diameter) at various locations within the samples throughout the experimental duration of 1.5–2 hours. Temperatures were recorded both within the furnace itself and inside the concrete samples. Upon completion of the tests, the concrete samples were removed from the furnace and allowed to cool to ambient temperature.

The dependence of the furnace temperature on the duration of the experiment is shown in Table 3 and Fig. 3a. The heating kinetic curves for the concrete samples at depths of 10, 25, and 50 mm for both TRC and ARC are shown in Table 4, Fig. 3b and Table 5, Fig. 3c, respectively.

Table 3

Furnace temperature dynamics during the experiment

Time, min	**0**	**0,2**	**0,5**	**1**	**2**	**3**	**5**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
Temperature, °C	15	70	140	210	287	350	420	490	546	595	623	644	662	679	693	700

Table 4

Heating kinetics of Traditional Reinforced Concrete (TRC)

Time, min	**Temperature at 10 mm Series 1, °C**	**Temperature at 25 mm Series 2, °C**	**Temperature at 50 mm Series 3, °C**
0	15	15	15
9	110	40	20
27	320	130	85
45	445	225	140
63	520	300	190
81	575	355	240
90	590	380	265

Table 5

Heating kinetics of Alternative Reinforced Concrete (ARC)

Time, min	Temperature at 10 mm Series 1, °C	Temperature at 25 mm Series 2, °C	Temperature at 50 mm Series 3, °C
0	15	15	15
13	25	20	15
39	100	65	40
65	250	145	105
90	575	400	270

Experimental heating of the samples in a specialised furnace using a gas burner and shielded thermocouples allowed for the monitoring of the concrete's behaviour under conditions closely simulating a real fire. The furnace heating process is characterised by a rapid temperature rise to 500 °C within the first 15–20 minutes, subsequently reaching a plateau of approximately 700 °C by the 90th minute. This dynamics creates a temperature gradient that triggers a series of physicochemical transformations within the concrete structure. The correlation between elemental composition and thermal behaviour is evident through the phase composition of the binder. Specifically, in TRC, the high iron content and the presence of potassium lead to the formation of a structure where ferrite phases C_4AF and alkali silicates play a significant role. It was established that the ratio of basic oxides in the studied samples deviates significantly from the classical silicate modules of pure cements. In particular, the low silicon content in ARC determines the specific kinetics of thermal transformations. The high concentration of calcium-bearing phases (hydrosilicates and carbonates) in the ARC structure acts as an energy buffer: during thermal exposure, a significant portion of the thermal energy is consumed by the endothermic processes of dehydration and decarbonisation. This is confirmed by the thermal test results (Table 3, Fig. 3), where ARC demonstrates a thermal damper effect, slowing the heating of the structure's internal layers compared to TRC. On the TRC heating graph (Table 3b, Fig. 3b), an almost linear relationship between temperature and time is observed at shallow depths, indicating the relatively uniform thermal conductivity of the Portland cement matrix. In ARC, the dominant calcium content indicates the prevalence of a carbonated matrix from the old mortar and slag hydrates. The ARC graph (Fig. 3c) reveals a so-called induction period – a delay in active heating during the first 40 minutes of the experiment, even at a depth of 10 mm. The divergence between the curves in Fig. 3b and 3c is explained by endothermic effects, which are significantly more pronounced in ARC [6, 7]. The large quantity of Ca-bearing phases (C-S-H hydrosilicates and calcite $CaCO_3$) absorbs a substantial amount of energy for dehydration and the initial stages of decarbonisation upon heating [13]. This thermodynamic feature ensures the stability of the internal layers of ARC, as supported by experimental data: at a depth of 50 mm, the temperature barely exceeds 250 °C by the end of the test, whereas in TRC, it approaches 300 °C.

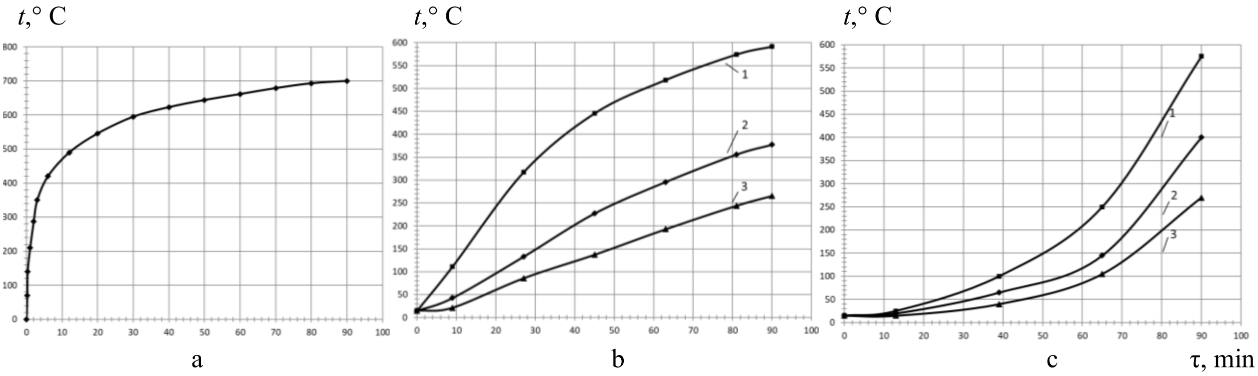


Fig. 3 – Heating kinetics of the samples: a – in the furnace during the experiment. Temperature within the sample depth at: 1 – 10 mm, 2 – 25 mm, 3 – 50 mm: b – TRC; c – ARC

To compare the endurance of the concrete samples after thermal testing, they were investigated using ultrasonic flaw detection. The measurement of the ultrasonic pulse travel time and the calculation of velocity were conducted in accordance with the standard [14] using an AU2000 flaw detector. To eliminate air gaps and ensure stable acoustic contact (coupling) between the transducer and the concrete surface, a specialised contact gel was employed. The results of the ultrasonic investigations for the TRC and ARC samples are presented in Table 6, as well as in Fig. 4a and Fig. 4b, respectively.

The analysis of the obtained experimental data (Table 6, Fig. 4) allows for a quantitative assessment of the destructive changes in the concrete structure following thermal exposure. For the heavy TRC, the pulse travel time at the minimum base (20 mm) is approximately 17 µs. For ARC, this indicator is similar; however, the character of the curve is more stable, indicating the consistency of the concrete matrix produced using recycled raw materials [4]. After heating (curve 1), a sharp increase in the ultrasonic travel time is observed, signifying a significant reduction in pulse velocity. The most pronounced effect was recorded at short distances (d = 20–40 mm), where the τ values for both concrete types increased from 17 µs to nearly 28–29 µs. This corresponds to a drop in ultrasonic velocity of approximately 40 %, which is a direct consequence of micro-cracking and the dehydration of Ca-bearing phases [6, 13].

Table 6

Comparative analysis of ultrasonic pulse travel time τ, µs for TRC and ARC samples

Distance (*d*), mm	TRC (after heating)	TRC (Control)	ARC (after heating)	ARC (Control)
22	29.0	16.7	28.0	17.0
30	24.5	15.8	24.5	16.6
40	21.5	15.8	23.0	16.6
50	20.5	15.4	20.5	16.7
60	19.3	15.6	20.0	15.3
70	19.0	15.6	20.0	16.7
80	19.3	16.0	20.0	15.5
100	18.0	17.5	20.0	15.3
140	18.0	17.5	19.0	17.5
180	18.0	18.5	19.5	18.0

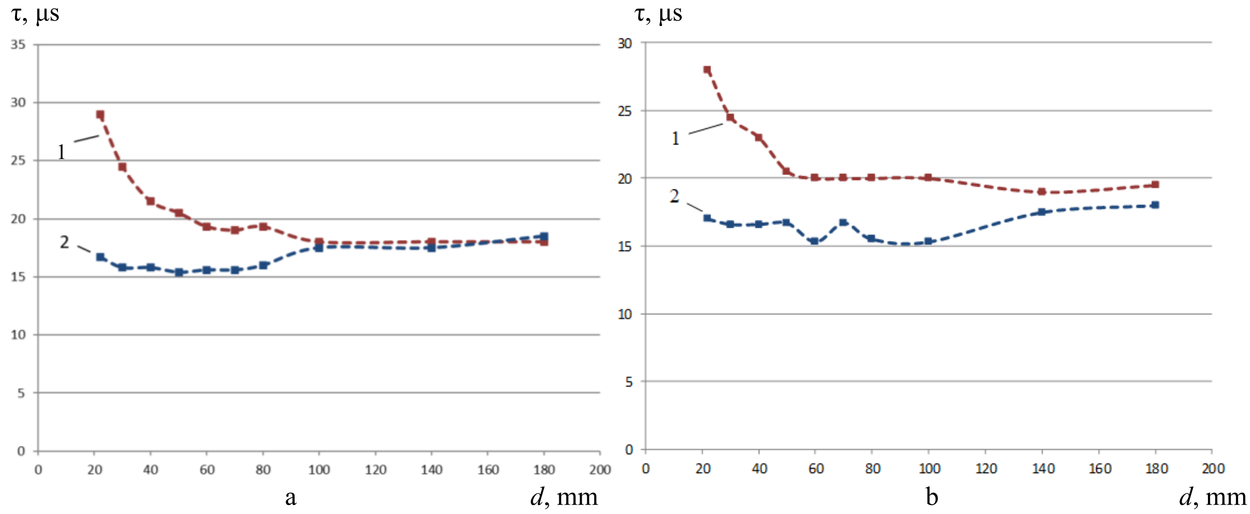


Fig. 4 – Dependence of the ultrasonic pulse travel time on the distance for the samples: a – TRC; b – ARC. 1 – samples after thermal exposure; 2 – control samples.

As the measurement base increases to 100 mm and beyond, curves 1 and 2 begin to converge. In the range of *d* = 100 mm, the travel time values stabilise within 18–20 µs. This confirms the thermal damper effect: despite surface-level structural degradation, the internal layers of the material maintain a certain degree of structural integrity, and local defects are mitigated (levelled out) as the wave propagates through a larger volume of the sample [7]. The use of contact gel eliminated errors associated with surface micro-relief, ensuring clear signal registration even for heat-damaged samples in accordance with [14].

Despite the positive results obtained regarding the thermal stability of ARC, several open questions remain that necessitate further investigation. The analysis conducted has identified certain gaps that define the vector for future research in the field of green chemistry of building composites. Although the high calcium content ensures the necessary alkalinity of the environment for steel passivation, the use of slag binders and recycled aggregates may alter the diffusion permeability of the matrix to chlorides and carbon dioxide. Future studies should focus on assessing the carbonation rate of the internal layers of ARC and the resistance of steel reinforcement to pitting corrosion in aggressive environments.

The issue of adhesion at the micro-level requires further detail, alongside the search for chemical modifiers (plasticisers or nano-additives) that could mitigate the porosity of recycled raw materials and enhance the overall hydrophobicity of the system.

While this work has identified a thermal damper effect in ARC, the mechanism of decarbonisation of the high-calcium phase at temperatures exceeding 800 °C requires clarification using differential thermal analysis (DTA). This will allow for a more accurate prediction of the point at which the structural load-bearing capacity is lost.

A distinct aspect requiring careful consideration is the heterogeneity of the recycled raw materials' composition. Unlike traditional concrete, the properties of ARC significantly depend on the origin and purity of the recycled aggregate, as well as the chemical modulus of the slag binder. Such variability in chemism directly affects the material's operational limits, dictating the need for a differentiated approach to its application. Specifically, compositions with a high content of reactive calcium and minimal foreign impurities in the recycled aggregate can be recommended for structures with stringent fire resistance requirements. In cases of significant elemental variability or the presence of inclusions that reduce matrix adhesion, it is advisable to use ARC for auxiliary objects – road curbs, retaining walls, or blocks for temporary structures – where fatigue strength requirements are less rigorous. Therefore, developing a classification for alternative concretes based on their chemical nature and physicochemical indicators is a essential step toward their certification and safe implementation in mass construction.

The use of slag cements enables domestic enterprises to reduce their carbon footprint and align with European environmental standards. Utilizing recycled concrete products resulting from destruction addresses the issue of waste management, transforming debris into a resource for rapid construction. At the same time, the implementation of such technologies requires thorough economic evaluations [15].

The research results are being integrated into the educational process at Khmelnytskyi National University. Specifically, the XRF and ultrasonic testing data are utilised as practical case studies in courses such as "Analytical Chemistry" and "Quality of Raw Materials and Chemical Technology Products".

Conclusions

This work provides a comparative analysis of the physicochemical properties and thermal stability of TRC and ARC. It was established that the use of recycled raw materials and slag-cement binders not only meets the criteria of the circular economy but also provides specific technical advantages for composites under extreme loads. Specifically:

- XRF analysis revealed a fundamental difference in the chemism of the studied systems: ARC based on slag cement and recycled aggregate forms a high-calcium matrix (calcium content up to 91.494 %), which leads to the formation of a different crystallochemical structure and phase transformation kinetics compared to TRC;
- the advantage of ARC under high-temperature exposure was experimentally established: a thermal damper effect was recorded, slowing the internal heating of the structure by 15–20 %. This confirms the material's energy efficiency and its ability to maintain operational reliability due to energy absorption during endothermic dehydration reactions of Ca-bearing phases;
- ultrasonic flaw detection confirmed the preservation of the structural integrity of the internal layers of ARC after thermal exposure. Despite surface degradation, the nature of signal propagation in the alternative concrete remains more stable, proving the reliability of using recycled aggregates;
- the environmental feasibility of implementing ARC as a tool for construction decarbonisation was justified, allowing for the minimisation of environmental impact through the rational recycling of construction debris from destructions;
- the potential for integrating the research results into the educational process for training chemical engineers was identified, specifically in the teaching of fundamental disciplines such as General and Inorganic Chemistry, Analytical Chemistry, Physical and Colloid Chemistry, as well as "Quality of Raw Materials and Chemical Technology Products".

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