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Optimisation of the composition and properties of decorative columns and arches using travertine (shell limestone)

Abstract. The need to enhance the durability and aesthetic stability of decorative architectural elements under the climatic conditions of the Kyrgyz Republic underscores the relevance of researching the properties of natural building materials such as travertine. The aim of this study was to analyse the physical and mechanical characteristics of travertine and optimise its properties for effective use in the design of decorative columns and arches. The research involved comprehensive laboratory methods, including tests for compressive strength, water absorption, abrasion resistance, frost resistance, and ultraviolet (UV) radiation resistance. The experiments examined the behaviour of travertine under variable humidity and temperature fluctuations. It was established that the material has a compressive strength of 45-55 MPa but shows water absorption of up to 10-15%, indicating its porous structure and the need for additional

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protection. The abrasion coefficient ranged from 0.8 to 1.2 mm, while compressive strength decreased by 15-20% after 50 freeze-thaw cycles. The study of hydrophobic and polymeric impregnations revealed a twofold reduction in water absorption and an increase in frost resistance. The paper also summarises data on the deterioration of travertine's decorative qualities under UV exposure and proposes technological solutions to preserve them. The practical value of this research lies in the development of recommendations for travertine treatment to improve its performance characteristics. These findings can be applied by architects, designers, restorers, and construction professionals when designing buildings and structures in the sharply continental climate of Kyrgyzstan

Keywords: decorative architectural elements; physical and mechanical properties; material durability improvement; construction materials and climate

INTRODUCTION

Improving the performance characteristics of decorative architectural elements is a key task in modern construction, especially in the harsh climate of the Kyrgyz Republic. Natural stone materials such as travertine, with their high aesthetic and physico-chemical properties, are widely used for facade cladding and the creation of columns, arches, and other architectural forms. However, travertine's porous structure, high water absorption, and susceptibility to abrasion limit the durability of such elements in conditions of cyclical temperature changes and high humidity. Therefore, optimising the composition and properties of travertine is of particular relevance.

The processing and use of natural stone in construction have been addressed in several studies. Zh. Usubaliev & K.T. Elikbaev (2024) analysed modern technologies for extracting and processing natural stone in Kyrgyzstan, emphasising the need to improve cutting, grinding, and polishing methods to enhance the quality and durability of building products. They noted that the introduction of modern processing lines contributes not only to increased strength but also to greater resistance to climatic influences. B.T. Assakunova *et al.* (2018) explored the use of travertine sawing waste to produce gypsum composites, demonstrating that secondary mineral raw materials can significantly improve mechanical strength, reduce water absorption, and optimise the cost of final products – an important factor for Kyrgyzstan's construction sector. A.N. Zhakanov (2023) showed the potential of using travertine waste in the production of lightweight concrete, stating that the addition of porous mineral fillers improves thermal insulation properties while maintaining sufficient strength, thus expanding travertine's application in small architectural forms and facade systems.

G.A. Issabayev (2022) focused on architectural solutions involving cantilever structures made of natural materials, highlighting the importance of stone's resistance to deformation and external loads. The author emphasised that using natural stone in load-bearing and decorative elements requires careful consideration of its strength characteristics and proper preparation at the design stage. S. Rescic *et al.* (2024) investigated the historical use of travertine in Tuscan architecture and confirmed that, when properly processed, the stone exhibits high resistance to weathering and retains its decorative properties for centuries. S.Y. Erdinç (2023) explored the potential of natural stone in contemporary architecture and identified key technological factors influencing product longevity, including pre-treatment hydrophobisation and minimisation of surface microcracks.

M. Casazza & F. Barone (2024) stressed the importance of vibration monitoring systems for the timely detection of internal defects in stone structures, particularly when using travertine in architectural elements exposed to dynamic loads and seasonal temperature changes. C. Conforti *et al.* (2021) analysed the practice of creating full-scale architectural models, highlighting the critical role of proper preparation and processing of building materials, including natural stone, in ensuring operational reliability and aesthetic stability in real-world conditions. M. Grawehr (2022) explored stylistic and structural aspects of travertine in Ancient Roman architecture, with special attention to its durability and cultural and engineering significance in monumental construction. J.L. Sánchez-Cortez *et al.* (2022) investigated methods for assessing the resistance of karst formations to external impacts, directly relevant to evaluating the longevity of porous natural materials like travertine in aggressive climates.

Despite the wealth of research, issues related to improving the moisture resistance, wear resistance, and frost resistance of travertine in the context of the Kyrgyz Republic remain insufficiently explored, necessitating further comprehensive studies. The aim of this research was to comprehensively study the physical and mechanical properties of travertine and to identify ways to optimise its use in the design of decorative architectural elements – particularly columns and arches – taking into account the climatic conditions of Kyrgyzstan.

MATERIALS AND METHODS

The study was conducted at the Building Materials Laboratory of the Kyrgyz State Technical University named after I. Razzakov from January to October 2024. The laboratory experiments were based on travertine samples extracted from the Kyzyl-Tuu and Sulyikta deposits in the Kyrgyz Republic. These sites were selected due to their industrial significance, stable physico-mechanical properties of raw material, and the need to develop effective technologies to enhance the durability of decorative architectural elements under the region's continental climate conditions. Sample selection was carried out directly at the Kyzyl-Tuu and Sulyikta quarries. To ensure representativeness, six samples were collected (three from each site). Inclusion criteria included structural homogeneity, absence of visible cracks, minimal weathering, and uniform pore distribution. Exclusion criteria were mechanical damage, prominent cracking, foreign mineral inclusions, and non-uniform texture. Selection was conducted visually and using a Schmidt hammer for preliminary field strength assessment. Samples measuring 150×150×150 mm were delivered to the laboratory for testing. Physical and mechanical properties were determined in accordance with international standards. Density was measured using the hydrostatic weighing method as per ASTM C97/C97M-18 (2025) (USA). Water absorption was calculated using the full water saturation method. Porosity was determined by the ratio of pore volume to the total sample volume, using formula (1):

$$P = \frac{Vpore}{Vtotal} \cdot 100\%, \tag{1}$$

where P – porosity in percent; V_{pore} – pore volume; V_{total} – total volume of the sample.

Compressive strength was determined using a Controls Group MCC8 hydraulic press (Italy) according to ASTM C170/C170M-17 (2023) (USA) and EN 1926:2006 (2008). Flexural strength was measured in accordance with EN 12372:2022 (2022). Abrasion resistance was evaluated using an abrasive disc simulating the impact of sand particles on the surface. To simulate operational conditions, samples were subjected to temperature fluctuations from -20°C to +50°C and relative humidity from 30% to 90%. Frost resistance tests followed EN 12371:2010 (2010), including 50 freeze-thaw cycles in a water medium. UV resistance was assessed using an Atlas Suntest CPS+ climate chamber (USA) with 500 hours of irradiation. A comparative analysis of the physical properties of travertine with granite and marble was also conducted, using benchmark data from G. Sarıışık *et al.* (2016), which detailed construction stone properties, including density, porosity, compressive strength, and abrasion resistance. Travertine samples from Kyzyl-Tuu and Sulyikta (10 samples of 100×100×50 mm) were used, conforming to EN 1926:2006 (2008). Inclusion criteria included natural origin, relevance to decorative architecture in Central Asia, and availability of reliable lab data. Benchmark granite and marble properties were drawn from published results, as those materials were not tested in this study. Samples were irradiated for 500 hours under simulated outdoor Kyrgyz conditions. Brightness and colour saturation changes were recorded every 100 hours via colorimetric analysis. Statistical data were processed using Statistica 13.5 (Dell, USA), with the Student's t-test used to assess differences between independent samples. A paired correlation analysis between travertine characteristics and strength indicators was performed first. In the second stage, regression models were constructed using the least squares method. Model quality was evaluated with multiple determination coefficient (MCD), root mean square error (RMSE), and mean absolute error (MAE). To avoid multicollinearity, a correlation matrix was used.

RESULTS

Experimental data analysis revealed the physical and mechanical characteristics of travertine from the Kyzyl-Tuu and Sulyikta deposits and the effects of surface treatment on material performance. In the first research stage, initial physical properties such as density, porosity, and water absorption were determined. Sample density ranged from 1,850 to 2,450 kg/m³. Higher density corresponded to lower porosity and, consequently, better mechanical properties. Porosity was calculated using formula (1). Results showed a range of 12% to 22%. Higher porosity increased moisture absorption capacity, confirmed by test data: water absorption was 10% to 15% by sample mass. Density, porosity, and water absorption results are summarised in Table 1.

Table 1. Density and porosity of studied travertine samples

Sample No.	Place of birth	Density (kg/m³)	Porosity (%)	Water absorption (%)
1	Kyzyl-Tuu	1,850	22	15
2	Kyzyl-Tuu	2,100	18	12
3	Kyzyl-Tuu	2,450	12	10
4	Suliukta	1,880	21	14
5	Suliukta	2,150	17	11
6	Suliukta	2,400	13	10

Source: compiled by the authors

Analysis of the data presented in Table 1 showed that the density of travertine ranged from 1,850 to 2,450 kg/m³, while porosity varied between 12% and 22%. The water absorption rate of the samples ranged from 10% to 15%, indicating the material's relatively high capacity for moisture retention. Samples from the Kyzyl-Tuu deposit demonstrated slightly higher density and lower porosity compared to those from Sulyikta, suggesting potentially greater resistance to mechanical loads and better suitability for use in structural elements. Nevertheless, all samples exhibited high water absorption rates, highlighting the need for measures to reduce the material's permeability. These results confirm the necessity of applying additional protective treatments – such as hydrophobisation and surface densification – to improve the durability of travertine under conditions of frequent humidity and temperature fluctuations. The analysis of compressive strength test results before and after 50 freeze-thaw cycles made it possible to assess the frost resistance of travertine from the Kyzyl-Tuu and Sulyikta deposits. The tests were conducted in accordance with EN 12371:2010 (2010), simulating the climatic conditions of the Kyrgyz Republic, where frequent temperature changes and high humidity can significantly affect the durability of construction materials. The changes in compressive strength are summarised in Table 2. Strength values were recorded before the freeze-thaw cycles and again after 50 full cycles.

Table 2. Changes in compressive strength of travertine after freeze-thaw cycles

Sample No.	Place of birth	Strength before cycles (MPa)	Strength after cycles (MPa)	Strength reduction (%)
1	Kyzyl-Tuu	45	36	20
2	Kyzyl-Tuu	50	42	16
3	Kyzyl-Tuu	55	46	16
4	Suliukta	46	37	19
5	Suliukta	51	43	16
6	Suliukta	54	45	17

Source: compiled by the authors

As shown in Table 2, the compressive strength of the travertine samples before the frost tests ranged from 45 to 55 MPa. After 50 freeze-thaw cycles, a consistent decrease in strength by 16-20% was observed, depending on the specific sample and its original properties. The most significant strength loss occurred in samples with higher porosity, confirming the critical role of material structure in frost resistance. On average, travertine from Kyzyl-Tuu showed slightly greater strength reduction compared to samples from Sulyikta, likely due to differences in texture and density. The overall trend indicates high sensitivity of travertine to repeated temperature fluctuations, necessitating protective treatments for use in environments with frequent freeze-thaw cycles.

The analysis confirmed that the highest strength loss occurred in samples with higher initial porosity, indicating a direct correlation between material porosity and frost resistance. The destruction mechanism can be explained by water expansion during freezing within the pores, leading to microcrack formation and a decrease in the load-bearing capacity of the material. Figure 1 illustrates the correlation between the number of freeze-thaw cycles and the decline in strength, visually representing the progressive degradation of the stone structure due to repeated temperature changes.

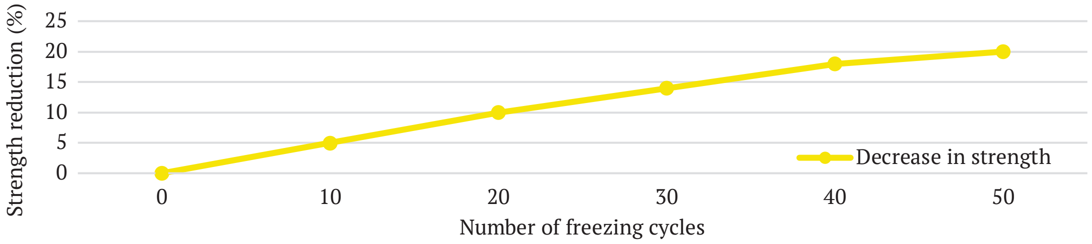

Figure 1. Correlation between number of freeze-thaw cycles and compressive strength reduction
Source: compiled by the authors

As shown in Figure 1, the decrease in travertine strength after freeze-thaw cycling was distinctly progressive. Samples with higher initial porosity showed a significantly greater percentage loss in mechanical strength compared to less porous counterparts. A clear trend is observed: as the number of freeze-thaw cycles increases, the deterioration of mechanical properties becomes more pronounced (Ermolaev *et al.*, 2017). This confirms that travertine's internal structure is prone to damage due to water expansion when freezing, leading to the accumulation of microcracks and a loss of structural integrity. These dependencies underscore the importance of assessing the physical structure of travertine in advance before using it in constructions exposed to temperature variations, as well as the need to apply protective measures to improve the stone's frost resistance.

The analysis of experimental data also allowed for the assessment of travertine's water absorption capacity and its impact on material durability in comparison with other natural stones – namely granite and marble. The goal of this research stage was to determine the relationship between porosity, moisture absorption capacity, and resistance to environmental influences characteristic of the Kyrgyz Republic's climate. Water absorption data are summarised in Table 3, which presents average values for travertine, granite, and marble.

Table 3. Water absorption of travertine compared to granite and marble

Material	Water absorption (%)	Compressive strength (MPa)
Travertine	10-15	45-55
Granite	0.05-0.4	120-250
Marble	0.1-0.5	70-150

Source: compiled by the authors based on G. Sarıışık *et al*. (2016)

As shown in Table 3, travertine significantly exceeds granite and marble in water absorption but falls considerably short in terms of strength. Travertine's porous structure accounts for its high moisture retention, leading to strength reduction, crack formation from water freezing within the pores, and a heightened risk of chemical degradation due to salt crystallisation (Adjamskiy *et al*., 2022). It was demonstrated that granite has a compressive strength of 120-250 MPa with water absorption of 0.05-0.4%, and marble – 70-150 MPa with water absorption of 0.1-0.5%. By comparison, travertine demonstrated a compressive strength of 45-55 MPa and water absorption of 10-15%. These findings confirm the need for additional processing of travertine to reduce its water absorption and improve resistance to environmental exposure. Statistical analysis confirmed a high degree of positive correlation between porosity and water absorption of travertine (correlation coefficient $r = 0.91$). This indicates that the higher the porosity, the greater the material's moisture retention capacity, which negatively affects its durability. Figure 2 illustrates the relationship between water absorption level and expected material durability.

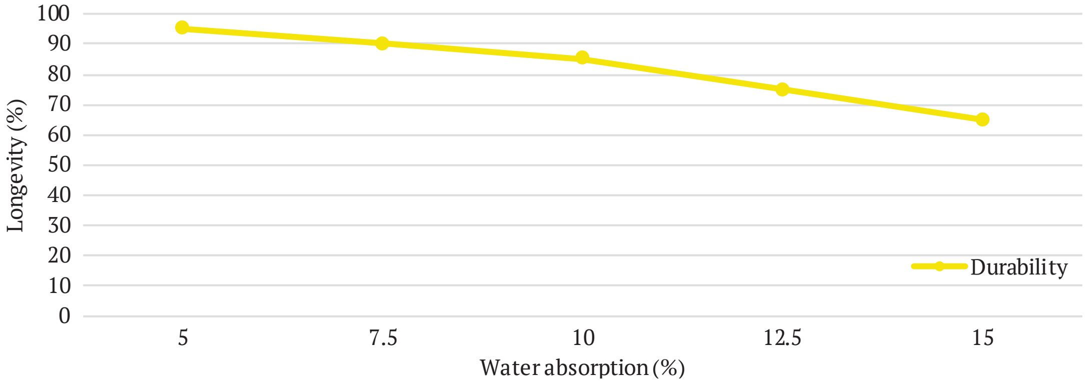

Figure 2. Influence of water absorption level on durability

Source: compiled by the authors

Figure 2 clearly illustrates that as the level of water absorption increases, there is a distinct trend toward a reduction in the durability of travertine. Based on the experimental data, it is evident that samples with water absorption above 12% exhibit accelerated loss of strength and decreased resistance to external climatic influences. This confirms the necessity of pre-treating the travertine surface with hydrophobic agents or by polishing, which significantly reduces moisture penetration into the material's structure, lowers the risk of microcrack formation, and increases the overall service life of the stone when used for façade cladding, interior finishing, and other architectural applications under variable temperature and humidity conditions. Abrasion tests revealed that untreated travertine samples had higher wear coefficients, ranging on average from 1.0 to 1.2 mm, while treated surfaces (polished and ground) showed significantly better results, with abrasion coefficients within the range of 0.5-0.7 mm. These findings confirm that surface pre-treatment can significantly improve the material's resistance to abrasive stresses. The study established that the difference between average abrasion coefficients was statistically significant at the $p < 0.05$ level, confirming the effectiveness of surface treatment of travertine. The results are summarised in Table 4.

Table 4. Abrasion coefficients of the tested samples

Sample No.	Place of birth	Surface treatment	Abrasion coefficient (mm)
1	Kyzyl-Tuu	Untreated	1.2
2	Kyzyl-Tuu	Polished	0.7
3	Kyzyl-Tuu	Ground	0.6
4	Suliukta	Untreated	1
5	Suliukta	Polished	0.5
6	Suliukta	Ground	0.6

Source: compiled by the authors

As shown in Table 4, untreated travertine samples from both Kyzyl-Tuu and Suliukta exhibited the highest abrasion coefficients – 1.2 mm and 1.0 mm, respectively. In contrast, the samples that underwent polishing and grinding showed much better performance, with abrasion coefficients reduced to 0.5-0.7 mm. This indicates that surface treatment significantly increases the wear resistance of travertine by reducing the rate of material degradation under abrasive stress. The differences between treated and untreated samples were statistically significant, confirming the advisability of polishing or grinding to improve the operational durability of architectural elements made from travertine. Figure 3 presents the dynamics of mass loss during abrasive testing, visually confirming the benefits of surface pre-treatment.

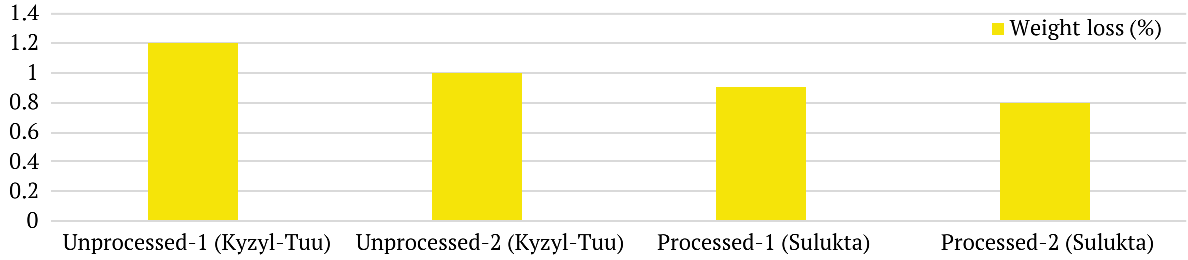

Figure 3. Dynamics of mass loss in travertine

Source: compiled by the authors

As can be seen from Figure 3, untreated travertine samples lost an average of 1.2 mm of mass during abrasion testing, whereas samples treated with hydrophobic agents showed a reduced abrasion loss of 0.8 mm. This means that the treatment reduced the mass loss by 33%. Thus, surface pre-treatment significantly enhances the wear resistance of travertine, slowing mechanical degradation and extending the material’s service life under intensive use. Tests also assessed changes in the colour characteristics of travertine under ultraviolet (UV) radiation in the Atlas Suntest CPS+ (USA) climatic chamber. The data processing showed that the average decrease in colour brightness was 8.3%, with a variance between samples not exceeding 1.2%, indicating a high level of repeatability. The greatest colour change was observed in untreated samples, while those treated with hydrophobic and protective coatings showed a much lower degree of fading. The results of UV exposure tests are summarised in Table 5.

Table 5. Colour change of samples after ultraviolet (UV) radiation tests

Sample No.	Place of birth	Treatment type	Colour change (%)
1	Kyzyl-Tuu	Untreated	12
2	Kyzyl-Tuu	Hydrophobised	8
3	Kyzyl-Tuu	Polished	5
4	Suliukta	Untreated	11
5	Suliukta	Hydrophobised	7
6	Suliukta	Polished	5

Source: compiled by the authors

As shown in Table 5, the most significant decrease in colour brightness was observed in untreated samples from the Kyzyl-Tuu and Suliukta deposits, with losses of 12% and 11%, respectively. These findings highlight the high sensitivity of exposed travertine surfaces to photochemical processes caused by UV radiation. In contrast, the hydrophobised samples showed much lower colour change – 8% for Kyzyl-Tuu and 7% for Sulyikta – confirming the effectiveness of hydrophobic agents as protective barriers that reduce UV penetration and slow the degradation of the stone’s mineral structure. The best results were observed in polished samples, where colour brightness decreased by only 5% for both deposits. This is explained by the lower surface roughness of polished travertine, which results in fewer active sites for UV absorption. Thus, polishing not only enhances the aesthetic qualities of the material but also significantly increases its resistance to photodegradation (Tagybayev *et al.*, 2023). The obtained results demonstrate that applying additional surface treatment methods can substantially delay the degradation of travertine’s decorative properties when exposed to intense solar radiation – an essential factor for construction and finishing work in high-insolation regions. Figure 4 shows that the decrease in travertine colour brightness is proportional to the duration of UV exposure.

As shown in Figure 4, travertine colour brightness gradually decreased with increased UV exposure time. The most pronounced fading was observed in untreated samples, clearly confirming their high vulnerability to solar radiation. Samples that were polished or treated with hydrophobic agents showed significantly lower brightness loss: the colour degradation curves were noticeably flatter compared to those of untreated samples. These data confirm the effectiveness of protective treatments in enhancing travertine's resistance to photodegradation. Thus, applying hydrophobic treatments and polishing can substantially extend the lifespan of the material's decorative properties under solar exposure. The effectiveness of protective treatments was evaluated based on laboratory experiments that analysed changes in water absorption and surface roughness after various technologies were applied. Calculations confirmed that hydrophobic impregnation and grinding-polishing significantly improve the material's operational performance. Table 6 presents comparative water absorption data for untreated, hydrophobised, and polished samples.

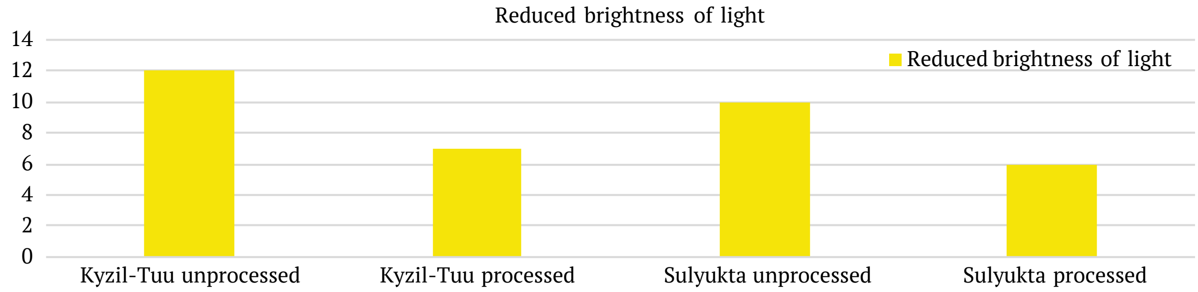

Figure 4. Correlation between colour brightness loss and UV exposure time

Source: compiled by the authors

Table 6. Comparison of water absorption after different treatments

Treatment type	Water absorption (%)	Reduction in water absorption (%)
Untreated	15.0	0
Hydrophobised	7.5	50
Polished	10.0	30

Source: compiled by the authors

As shown in Table 6, different surface treatment methods had a substantial effect on travertine's water absorption. The most effective method was the use of hydrophobic impregnations, which reduced water absorption from the initial 12-15% to an average of 6-7.5%. Polishing also had a positive effect, reducing water absorption to 8-10%, which confirms the effectiveness of this treatment in enhancing the material's performance. Hydrophobic treatment reduced travertine's water absorption by an average of 50%, while polishing reduced it by approximately 30% compared to the baseline. MAE and RMSE values confirmed the stability of the improvements achieved. The MCD for the constructed models was 0.92, indicating a high degree of explained variance and reliability of the conclusions drawn.

The study concluded that travertine demonstrates sufficient strength for use in architectural structures, including façade cladding, decorative elements, and interior finishes. However, despite its good strength characteristics, the material remains prone to mechanical wear, especially under intensive use, which necessitates the application of protective coatings to enhance its durability. The high porosity of travertine leads to significant water absorption, particularly under sharp changes in temperature and humidity, which reduces strength and causes cracking due to water freezing in the pores (Marchuk, 2021). Therefore, hydrophobic agents that create an effective protective layer are recommended to improve water repellency.

Frost resistance tests confirmed a reduction in material strength during repeated freeze-thaw cycles, making it necessary to apply special surface coatings to reduce moisture penetration. The moderate wear resistance of the material requires the use of protective lacquers or impregnations to significantly extend the service life of products subject to heavy mechanical stress, such as flooring and staircases (Lapshyn & Yaroshenko, 2023). UV radiation causes a loss of brightness and colour saturation in travertine; thus, for preserving the aesthetic appearance of exterior elements, UV-resistant coatings are recommended to prevent photochemical damage to the stone's structure (Bilousova, 2023). To improve the performance of travertine under the climatic conditions of the Kyrgyz Republic, a comprehensive approach is recommended, including polishing, grinding, hydrophobisation, and the use of UV-resistant protective compounds, as well as regular maintenance and renewal of protective layers to ensure the longevity and preservation of the material's decorative properties.

DISCUSSION

In the course of this study, a comprehensive analysis was carried out on the physical and mechanical properties of travertine from the Kyzyl-Tuu and Sulyikta deposits in order to assess its suitability for use in decorative architectural elements. The obtained results revealed that travertine possesses high porosity and water absorption capacity, which negatively affect its frost resistance, strength, and overall durability. The observed characteristics of travertine are in good agreement with the findings of M. Özkul *et* *al.* (2024), who emphasised the significant variability of travertine properties depending on the conditions of their formation. Similarly, M.Y. Çelik & M. Sert (2020) noted that natural stone materials such as marble and travertine require a comprehensive assessment of their physical and mechanical characteristics prior to architectural use. Following the data by G. Bozkaya *et al.* (2024), who highlighted the importance of the geochemical composition of carbonate rocks, it can be concluded that the mineralogical features of Kyrgyz travertine influence its porosity and water absorption. This fully aligns with the identified need in this study for additional treatment of travertine to enhance its resistance to external impacts.

The analysis of travertine performance under freeze-thaw conditions also support the conclusions of C. Aratman *et al.* (2020), who found that the textural features of travertine significantly affect its strength and durability under changing climatic conditions, especially in regions with extreme temperature fluctuations. Special attention in the current study was given to the influence of surface treatment on the material's wear resistance. The data on water absorption and strength degradation due to moisture exposure are consistent with the research by P. Santi *et al.* (2021), who highlighted the vulnerability of natural stone in high-humidity environments – typical for several regions – thus confirming the need for protective coatings to improve the material's longevity.

The results of abrasion and mechanical behaviour tests also correspond with the observations of A. Maričić *et al.* (2023), who pointed out the importance of preliminary treatment of natural stone for successful use in restoration projects and modern construction. Similarly, the present study confirmed that untreated travertine surfaces are more prone to mechanical damage, which necessitates the use of pre-treatment methods to extend the service life of the material. Furthermore, the influence of ultraviolet radiation on the decorative qualities of travertine is fully consistent with the findings of U.O. Usanmaz (2022), who studied the degradation of ancient Roman surfaces due to photochemical processes leading to mineral structure breakdown and loss of aesthetic properties. The necessity of using hydrophobic and UV-resistant coatings for travertine, as identified in this study, is also confirmed by the work of F. Fratini *et al.* (2022), which demonstrated the effectiveness of specialised protective measures in minimising the destructive effects of aggressive climatic factors on natural stone. In particular, the experiment showed that treated surfaces exhibited significantly less loss in colour brightness and strength compared to untreated samples. The study's recommendations for enhanced comprehensive protective treatment of travertine to improve its longevity are fully supported by the practical conclusions of S. Pescari *et al.* (2023), who emphasised the importance of selecting appropriate conservation technologies in restoring historical buildings and the necessity of considering material specifics to prevent accelerated deterioration in real-world conditions.

In addition, contemporary research underlines the necessity of adapting natural stones to meet new architectural requirements. G. Yıldırım & N. Erdoğan (2024) stressed the growing interest in using natural stone and marble in modern architectural projects, which confirms the relevance of the study's recommendations on using travertine in decorative elements, provided modern treatment methods are applied. Robotic technologies in construction, as shown by M. Alabbasi *et al.* (2023), offer promising opportunities for more precise processing of materials, including stone, thus improving quality and durability in architectural applications. The use of 3D printing technologies for creating architectural elements demonstrates the potential of integrating automated processing methods for travertine to enhance surface quality and optimise production processes, thereby significantly improving the material's performance characteristics (Tasán Cruz *et al.*, 2024; Xue & Bulhakova, 2024). Research by C. Zhang *et al.* (2024) in the field of generative design and structural optimisation shows that the advancement of digital technologies enables more efficient use of natural materials in complex architectural compositions. This aligns with the recommendation to precisely prepare travertine based on its physical and mechanical properties, enhancing its suitability for high-load and aesthetically demanding architectural solutions. The work by H. Wang *et al.* (2021) on generative design methods in construction systems further highlights the importance of new engineering approaches to designing and utilising natural stones in architecture, thereby reinforcing the significance of integrating processing technologies for travertine to improve its performance and resistance to external influences. Such innovative approaches open new possibilities for using travertine in construction and restoration projects, especially under variable climate conditions (Deshko *et al.*, 2024).

E. Yıldırım (2022) demonstrated that topological optimisation of architectural structures can maximise the efficient use of building materials, which is particularly relevant for travertine, given its physical and mechanical limitations. Research by W. Xiaojian & Y. Yuewen (2021) highlights the importance of modernising construction methods in the context of contemporary challenges, which corresponds to the need for enhancing the treatment and protection of travertine to extend its service life under variable climatic loads. The study by M. Attenni *et al.* (2022) on modelling historical structures using Heritage Building Information Modelling (HBIM) emphasises the importance of preserving the properties of natural materials in digital environments. This opens the prospect for digital documentation of travertine structures to enable ongoing condition monitoring. K.G.A.U. Samarakoon *et al.* (2023) provided a review of modern quarrying methods for cladding stone, noting the importance of environmentally sustainable technologies, which is directly related to the need for sustainable use of travertine resources in the Kyrgyz Republic. The study by R. Nadoomi *et al.* (2023) on regional building materials in hot and humid climates emphasises the importance of local adaptation of technologies, which supports the conclusion on the need for special travertine treatments for use in continental climates with wide temperature and humidity ranges. G. Duarte *et al.* (2021), in their study on 3D printing methods based on historical structures, underline that the use of traditional materials such as stone must be combined with modern design and construction technologies. This once again confirms that adapting travertine treatment methods is strategically important for expanding the scope of its application.

Thus, the study's findings are fully aligned with current global scientific trends, demonstrating the necessity of a comprehensive approach to assessing, processing, and using travertine in contemporary architectural projects. The established relationship between the material's physical and mechanical properties and its operational performance highlights the importance of preliminary raw material diagnostics, optimisation of surface treatment methods, application of protective technologies such as hydrophobisation and polishing, and consideration of the climatic specifics of the region of application. In the context of rapid developments in digital design, additive technologies, and sustainable construction, the role of natural stone, particularly travertine, is increasing significantly. Therefore, integrating modern engineering solutions with traditional materials opens new prospects for improving the durability, aesthetic value, and environmental sustainability of architectural structures.

CONCLUSIONS

The comprehensive study of the physical and mechanical properties of travertine from the Kyzyl-Tuu and Sulyikta deposits in the Kyrgyz Republic has made it possible to establish important patterns in its behaviour under various operational conditions. The analysis of the material's baseline properties showed that the density of travertine ranges from 1,850 to 2,450 kg/m^3, and porosity from 12% to 22%, with water absorption levels between 10-15%. A clear correlation was identified between increased porosity and higher moisture retention, which directly impacts the reduction of strength characteristics. Frost resistance tests revealed that after 50 freeze-thaw cycles, the strength of travertine decreases by 16-20%, especially in samples with high initial porosity. This emphasises the need for preliminary protective measures to ensure the stone's effective use in conditions of temperature fluctuations. Statistical analysis confirmed a strong correlation between porosity and water absorption ($r = 0.91$), making water absorption a reliable indicator of the material's potential durability. Compared to granite and marble, travertine demonstrated a significantly greater tendency to absorb moisture, necessitating special processing approaches.

Abrasion tests showed that polishing and grinding reduced the abrasion coefficient by an average of 40-50%, significantly improving wear resistance. It was also found that under ultraviolet radiation, untreated travertine samples lost up to 12% of colour brightness, whereas polished and hydrophobised samples showed reduced colour loss (5-8%), confirming the effectiveness of protective treatments. Analysis of water absorption dynamics demonstrated that hydrophobic treatments reduced travertine's moisture absorption by an average of 50%, while polishing reduced it by 30%. High values of the multiple determination coefficient (MCD = 0.92) and low MAE and RMSE values confirm the reliability of the models developed and the stability of the improvements achieved.The data obtained in the study confirm that travertine is a promising material for use in decorative and structural elements such as columns and arches; however, its durability requires the application of additional protective measures. It is important to continue further research in the development of new hydrophobisation compounds and frost resistance enhancers, the optimisation of surface treatment technologies, the assessment of environmental safety in stone extraction and processing methods, and the study of how various climatic conditions affect travertine's durability. Advancing these directions will expand the applications of travertine in construction, increase its resistance to atmospheric influences, and ensure longer service life of architectural structures.

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Оптимізація складу та властивостей декоративних колон та арок з використанням травертину (черепашника)

Анотація. Необхідність підвищення довговічності та естетичної стійкості декоративних архітектурних елементів в умовах кліматичних особливостей Киргизької Республіки обумовлює високу актуальність дослідження властивостей природних будівельних матеріалів, таких як травертин. Метою даної роботи був аналіз фізичних та механічних характеристик травертину та оптимізація його властивостей для ефективного використання у створенні декоративних колон та арок. У процесі дослідження застосовувалися комплексні лабораторні методи, включаючи випробування на міцність при стисканні, водопоглинання, стирання, морозостійкість, а також стійкість до ультрафіолетового випромінювання. В результаті експериментів було досліджено поведінку травертину в умовах змінної вологості та температурних коливань; встановлено, що матеріал має міцність на стиск 45-55 МПа, але при цьому демонструє водопоглинання до 10-15 %, що свідчить про його пористу структуру та необхідність додаткового захисту. Було виявлено, що коефіцієнт стирання варіюється від 0,8 до 1,2 мм, а характеристики міцності знижуються на 15-20 % після 50 циклів заморожування і відтавання. Проведено аналіз впливу гідрофобних та полімерних просочень, який показав дворазове зниження водопоглинання та підвищення морозостійкості матеріалу. Також узагальнено дані про зниження декоративних якостей травертину під дією ультрафіолетового випромінювання та запропоновано технологічні рішення для їх збереження. Практична цінність роботи полягає у розробці рекомендацій щодо обробки травертину для підвищення його експлуатаційних характеристик, що може бути застосовано архітекторами, проектувальниками, реставраторами та спеціалістами будівельної галузі при проектуванні будівель та споруд в умовах різко континентального клімату Киргизстану

Ключові слова: декоративні архітектурні елементи; фізико-механічні властивості; підвищення довговічності матеріалів; будівельні матеріали і клімат