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Determination of Abrasion Characteristics of Ancient Stone Architectural Elements by Field-based Measurements and Laboratory Testing

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Abstract

This study examines the applicability of non-destructive test methods for the indirect estimation of Böhme abrasion values of archaeological materials from Ephesus and Kerkenes, Türkiye. Direct determination of abrasion resistance by laboratory testing is not always feasible for valuable heritage stones. Therefore, ultrasonic pulse velocity (UPV) and Schmidt hammer measurements were considered as practical non-destructive alternatives to estimate abrasion resistance. Within the scope of this study, marble samples from Ephesus region and granodiorite samples from Kerkenes region were tested under laboratory conditions by means of UPV, Schmidt hammer, and Böhme abrasion experiments. Moreover, in-situ UPV and Schmidt hammer measurements were conducted on archaeological threshold and paving stones at both sites.

To evaluate the predictive capability of the non-destructive parameters, the laboratory results were compared with empirical correlations relating Böhme abrasion values to UPV and Schmidt rebound values available in related literature. The newly obtained data were subsequently integrated into the published datasets, and updated relationships were derived. The analysis showed that the marble dataset was better represented by the updated UPV-Böhme abrasion relationship, while granodiorite dataset showed better agreement with the updated Schmidt hardness-Böhme abrasion relationship. Overall, the findings demonstrate that non-destructive methods can provide a practical basis for the future in-situ estimation of abrasion behaviour of archaeological stones, especially where sample collection and testing cannot be performed on archaeological sites.

Keywords

Böhme abrasion, Ultrasonic Pulse Velocity, Schmidt Hardness, Archaeology, Ancient Traffic.

1 Introduction

Architectural elements, such as threshold stones or paving stones in archaeological and historical structures are subjected to surface abrasion induced by long-term pedestrian and vehicular traffic during residency and afterwards, tourism activities. Moreover, the resulting material loss is governed not only by the intensity and duration of use, but also by the intrinsic physico-mechanical properties of the rock, including mineralogical composition, texture, fabric, hardness, and abrasion resistance. In this respect, the characterization of resistance to abrasion constitutes a relevant rock mechanics problem, particularly where the material behaviour must be assessed without causing further damage to culturally valuable elements. Within the broader project framework, abrasion resistance is treated as one of the key material parameters for interpreting the wear behaviour of threshold and paving stones, and the analytical workflow includes petrographic characterization, abrasion resistance testing, and ultrasonic measurements. The mentioned research, titled "Testimony of Stones: A New Method in Ancient Traffic Analysis," aims to bridge by combining experimental archaeology, rock mechanics, tribology, and computational modelling (ABM-Agent Based Modelling) to quantify and predict pedestrian-vehicular traffic in the ancient period. The method, their influence extends to cultural heritage management, can guide preventive conservation strategies, such as visitor diversion or surface reinforcement, based on measurable risk assessment.

One of the most critical stages of this methodological essay is the obligation of determining abrasion loss in stone material using a non-destructive method. Because when working on an archaeological find, you cannot make any intervention that would damage its physical integrity. For this very reason, from a rock mechanics perspective, the main question is whether non-destructive index tests can provide sufficiently reliable indirect estimates of abrasion resistance for the natural stone types considered in this study. This issue is particularly relevant for archaeological and heritage applications, where direct abrasion testing on in situ elements is either undesirable or impossible. If consistent empirical relationships can be established between Böhme abrasion values and non-destructive test parameters such as UPV and Schmidt rebound values, the abrasion performance of threshold and paving stones may be estimated without material damage, thereby enabling a more practical evaluation of worn stone materials in the field.

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Previous studies have shown that the abrasion behaviour of natural stones is strongly influenced by their mineralogical and textural characteristics, as well as by testing and loading conditions (Karaca et al., 2012a; Karaca et al., 2012b). Among the available laboratory methods, the Böhme abrasion test provides a direct measure of abrasion resistance under standardized conditions and is therefore suitable for quantifying the wear susceptibility of natural stones (EN 14157; ASTM C241/C241M-21; Mucha, 2023). However, as a destructive or semi-destructive procedure, its direct application to archaeological materials is inherently limited. For this reason, the use of non-destructive index tests becomes especially important in the assessment of stone-made archaeological materials.

The related literature was extended by investigating the relationship between mechanical properties of rocks and their abrasion resistance (Böhme abrasion value etc.) (MacGregor and Chiu 2000; Kahraman and Fener 2008; Ureel and Momaye 2017; Strzałkowski et al. 2020). Ultrasonic pulse velocity (UPV) testing, known as one of the most practical non-destructive techniques for rock characterization, enables samples to be analysed without any damage during measurements based on their integrity and elastic response being sensitive to discontinuities, microcracking, pore structure, and textural heterogeneity. In rock mechanics and construction materials research, UPV has long been used as an indirect indicator of mechanical and durability-related properties, and previous studies have reported numerical correlations between ultrasonic data and Böhme abrasion value (Sadezadeh and Kettle 1986; Yağız 2011; Kılıç and Teymen2008; Çobanoğlu and Çelik 2017; Bozdağ 2020). This makes UPV a potentially useful predictive parameter for estimating abrasion-related behaviour without the need for direct destructive testing.

In addition to UPV, Schmidt hammer testing may also provide a practical non-destructive means for assessing the surface-related mechanical characteristics of natural stones. The Schmidt hammer offers a rapid and cost-effective assessment of surface hardness, widely utilized for evaluating the mechanical properties of rock materials (Aydin and Basu 2005). Since Schmidt rebound values are associated with surface hardness and near-surface competence, they may offer supplementary information for the indirect estimation of abrasion resistance. Various researchers derived numerical correlations between the Schmidt hammer rebounding value and Böhme abrasion value in previous studies (Aloğluand Yavuz 2023; Strzałkowski and Köken 2020). In this respect, the present study also considers Schmidt hammer measurements as an additional non-destructive parameter and evaluates their compatibility with abrasion-related trends provided in related literature.

Accordingly, this study focuses specifically on the rock mechanics component of the broader archaeological project and does not address the subsequent Agent-based modelling stages for foot traffic density in detail. The principal aim is to compare experimentally obtained Böhme abrasion test results with non-destructive measurements and to evaluate whether the observed relationships are compatible with empirical correlations previously proposed in the literature. In this sense, the study primarily seeks to verify the applicability of non-destructive predictive approaches for abrasion resistance assessment, rather than to directly reconstruct traffic intensity or movement patterns.

The technical contribution of the study lies in assessing the extent to which UPV and Schmidt hammer measurements can be used as surrogate parameters for abrasion resistance in natural stone materials relevant to archaeological architectural elements. Demonstrating agreement between measured Böhme values and literature-based non-destructive correlations would provide a practical methodological basis for estimating abrasion resistance with minimal intervention. Such an approach will support subsequent archaeological, conservation, and modelling analyses that require abrasion-related input parameters. The broader project context (mentioned above) links abrasion resistance data to later interpretive and modelling stages, including archaeological assessment and Agent Based Modelling workflows.

2 Study Materials and Testing

This study focuses on rock materials associated with two archaeological sites in Türkiye which are Kerkenes (Yozgat) and Ephesus (İzmir). Kerkenes is an Iron Age settlement on the Central Anatolian plateau and is particularly important due to its relatively short and archaeologically well-defined occupation history. On the other hand, Ephesus represents a major urban center of the Hellenistic and Roman periods and provides a different archaeological and material context. This contrast is reflected not only in their chronological frameworks but also in patterns of urban organization, production, and material circulation (Summers 1997; Ladstätter 2010). It is also evident in the primary construction materials employed at each site: while Kerkenes was constructed predominantly using locally available granodioritic bedrock—forming both the geological substrate of the city and the principal building material—thus reflecting a direct adaptation to its immediate lithological environment (Summers 1997), Ephesus is characterized by the extensive use of high-quality marbles from major quarrying centers such as Aphrodisias and Proconnesus, alongside other worked stones. While Kerkenes exhibits a largely self-contained, regionally oriented material culture with limited long-distance exchange, this reliance on imported marble at Ephesus underscores the role of complex trade networks, standardized production, and specialized quarrying systems in shaping its architectural fabric (Foss 1979; Fant 1989; Ladstätter 2010). Consequently, the scale of socio-economic complexity and the degree of integration into supra-regional systems differ markedly between the two sites.

In the scope of this study, both in-situ and laboratory tests have been conducted to determine abrasion characteristics of archaeological architectural elements. Field measurements were carried out directly on threshold and paving stones which are significant parts of the settlements, such as entrances, circulation routes, and public spaces. These measurements were based on non-destructive techniques, which are ultrasonic pulse velocity and Schmidt hammer testing, in order to characterize the existing material condition without causing damage to the archaeological fabric. UPV and Schmidt hammer tests are carried out in accordance with the recommended methods by the International Society for Rock Mechanics (ISRM) (ISRM 1981; ISRM 2007; Aydin 2009; Aydin 2014). The locations of measurements in ancient cities are presented in Fig. 1.

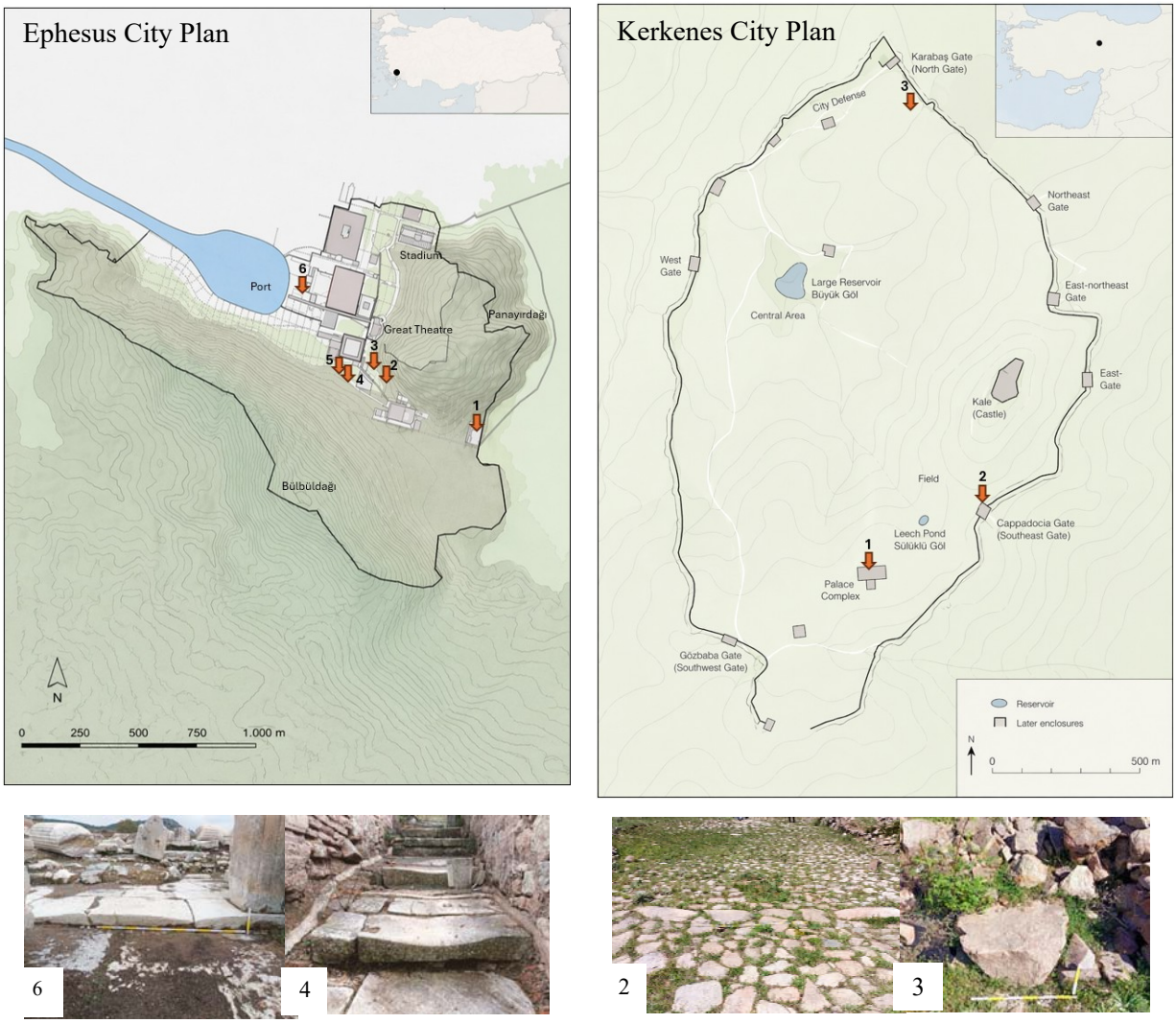


Fig. 1 The locations of the on-site measurements in ancient cities.In Ephesus: 1. Coresian Gate, 2. Odeon3. Varius Bath 4. Terrace House stairs5. Terrace Houses - inside 6. Middle Harbore Gate. In Kerkenes: 1. The Palace, 2. Cappadocia Gate, 3. UB8 space.

Since destructive or semi-destructive laboratory tests could not be applied directly to archaeological stone elements, laboratory investigations were performed on reference materials obtained from nearby locations for similar geological and geomechanical material properties to represent the original stone provenance. In this context, a literature review was conducted. Numerous studies investigating the source of the marble raw material used in the construction of Ephesus mostly indicate that the quarries of Aphrodisias, Prokonnessos (Marmara Island), Dokimeion, and locally Göktepe-Ephesus were used for this purpose(Prochaska&Attanasio2024, Prochaska et al. 2024, Attanasio et al., 2008, Anevlavi et al., 2021). Samples from the aforementioned sources were obtained and used in mechanical tests to represent the raw material used in the construction of Ephesus.In the construction of Kerkenes, it is observed that granodiorite, a local rock type, was widely used. This rock type is also the bedrock upon which the city was built. For controlled laboratory tests, samples of granodiorite bedrock exposed in and around Kerkenes were taken to represent the raw material used in the construction of Kerkenes (Branting, 2011). The rock samples collected from the sites were selected by considering the weathering condition by site investigation, especially for Kerkenes the outcrop of grandiorite was observed to have representative features. Although it is not technically possible to pinpoint the exact location of the marble used in the construction of Ephesus, as mentioned above, analyses have been carried out on samples showing different weathering characteristics taken from quarries indicated in the relevant literature. Undoubtedly, in the field of archaeometry, it is impossible to accurately represent an artifact if you cannot obtain a sample from it. Therefore, samples that best represent the artifacts have been collected, considering the measurable and observable characteristics of the artifacts using non-destructive methods.

This approach enabled direct measurement of abrasion resistance through the Böhme test, together with laboratory Schmidt hammer and UPV measurements, and provided the basis for comparing

destructive and non-destructive test results within the same material groups. Fig. 2 presents marble and granodiorite samples collected for Böhme abrasion, UPV, and Schmidt hammer laboratory experiments.



Fig. 2 Rock samples collected for laboratory experiments.

3 Results and Discussion

In the scope of this study, in situ UPV and Schmidt hammer tests, laboratory scale UPV, Schmidt hammer and Böhme testswere conducted for samples representing each region (Ephesus and Kerkenes). Test results categorized according to the test type and region are summarized in Table 1.

Table 1. Summary of Test Results.

Ultrasonic Pulse Velocity Test Results							
Site	**Material**	**Test**	**n**	**V_pMean(km/s)**	**Std.Dev.**	**Min**	**Max**
Ephesus	Marble	UPV-Lab	24	4.150	0.853	2.115	5.469
Ephesus	Marble	UPV-Field	144	4.119	1.044	1.901	6.602
Kerkenes	Granodiorite	UPV-Lab	36	2.925	0.824	1.215	4.488
Kerkenes	Granodiorite	UPV-Field	212	3.003	0.894	1.048	5.071
Schmidt Hammer Test Results							
Site	**Material**	**Test**	**n**	**Rebound Value Mean**	**Std.Dev.**	**Min**	**Max**
Ephesus	Marble	Schmidt-Lab	46	65.02	3.095	56	70
Ephesus	Marble	Schmidt-Field	114	71.10	3.701	60	78
Kerkenes	Granodiorite	Schmidt-Lab	92	55.51	9.997	23	72
Kerkenes	Granodiorite	Schmidt-Field	581	67.57	12.004	15	84
Böhme Abrasion Test Results							
Site	**Material**	**Test**	**n**	**BAV Mean(cm^3/50cm^2)**	**Std.Dev.**	**Min**	**Max**
Ephesus	Marble	Böhme	8	24.35	4.599	17	29.6
Kerkenes	Granodiorite	Böhme	6	8.52	2.733	4.9	13.1

Table 1 summarizes the results of the laboratory and in-situ non-destructive tests together with the laboratory Böhme abrasion test results for the investigated rock types from Ephesus and Kerkenes. Both UPV and Schmidt hammer measurements were carried out in the laboratory on samples, and in the field on the archaeological stone elements themselves. This approach made it possible to compare controlled laboratory measurements with in-situ values obtained from directly from the heritage stones. In addition, field measurements were also required in view of the broader objective of the project, namely, to enable future estimation of the Böhme abrasion values of archaeological stones in situ by using non-destructive test data together with the empirical correlations in the literature.

For the Ephesus marble, mean UPV values were 4.150 km/s in the laboratory and 4.119 km/s in the field, whereas the corresponding values for the Kerkenes granodiorite were 2.925 km/s and 3.003 km/s, respectively. Schmidt hammer results were also obtained from under both laboratory and field conditions. For the Ephesus marble, mean rebound values were 65.02 in the laboratory and 71.10 in the field, while for the Kerkenes granodiorite mean rebound values were 55.51 and 67.57, respectively. Compared with the Ephesus marble, the Kerkenes granodiorite exhibits a wider rebound value range, particularly in the field dataset. Laboratory Böhme abrasion tests yielded a mean value of 24.35 cm^3/50 cm^2 for the Ephesus marble and 8.52 cm^3/50 cm^2 for the Kerkenes granodiorite, indicating substantially higher abrasion loss for the marble samples.

Kılıç and Teymen (2008) proposed empirical correlations between P-wave velocity and Böhme abrasion value, and between Schmidt hardness and Böhme abrasion value, based on a multi-lithology dataset which includes marble and granodiorite. Within the scope of this study, the laboratory results obtained from the investigated materials were initially analyzed together with the data points available in published correlations to assess their compatibility with the general trends reported in the literature. Subsequently, the new experimental data were integrated into the original datasets and updated correlation equations were obtained. In cases where the revised equations produced higher coefficient of determination than the original correlations, they were considered more suitable for representing the present material set and will be therefore used for the indirect estimation of Böhme abrasion values for the in-situ archaeological stones. It was found that Ephesus marble test results yielded a higher coefficient of determination for the UPV-Böhme abrasion relationship, while Kerkenes granodiorite test results yielded a higher coefficient of determination in Schmidt hardness-Böhme abrasion relationship. The updated relationships based on the correlations proposed by Kılıç and Teymen (2008) are presented in Fig. 3 and Fig. 4.

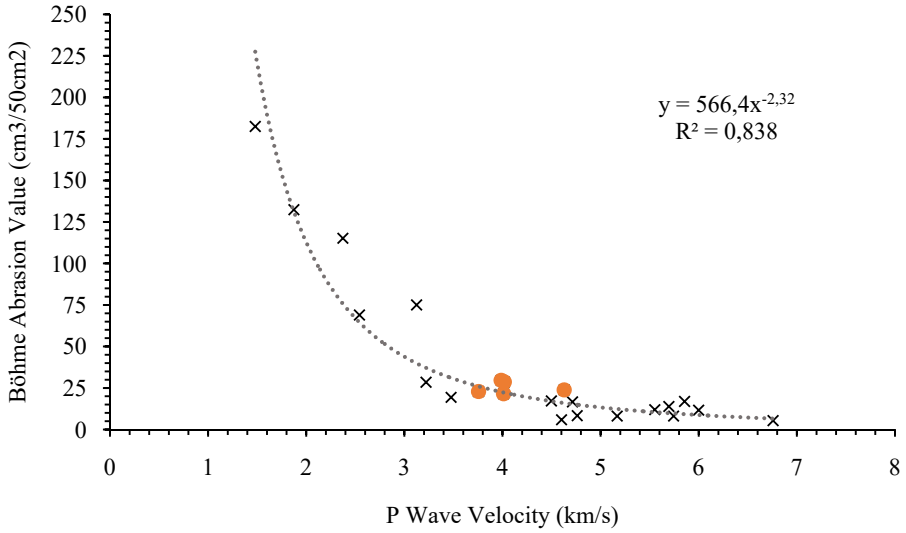


Fig. 3 Updated relationship between UPV-BAV for Ephesus marble (revised from Kılıç &Teymen, 2008).

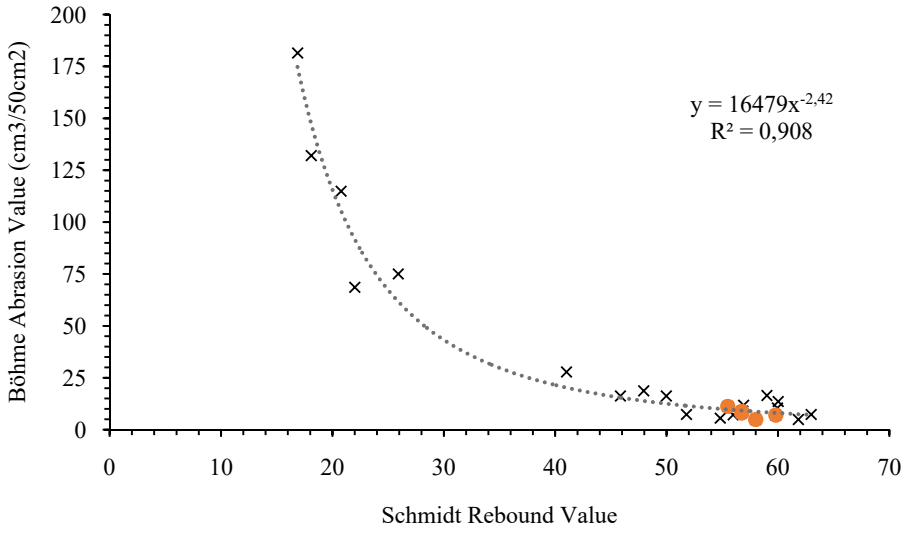


Fig. 4 Updated relationship between Schmidt hardness-BAV for Kerkenes granodiorite (revised from Kılıç &Teymen, 2008).

4 Conclusion

This study evaluated the applicability of non-destructive test methods for the indirect estimation of Böhme abrasion values of archaeological stones from Ephesus and Kerkenes. Laboratory and field UPV and Schmidt hammer measurements were assessed together with laboratory Böhme abrasion test

results obtained from marble and granodiorite samples. The laboratory data were compared with the empirical correlations proposed by other researchers and updated relationships were obtained by incorporating the new results into the published datasets. A comparison of the published and updated correlations is presented in Table 2.

Table 2 Comparison of published and updated correlations.

Definition	Derived Equation	R^2
UPV vs BAV for Marble (Kılıç and Teymen, 2008)	$BAV = 579.97V_p^{-2.4279}$	0.845
Updated UPV vs BAV for Marble	$BAV= 566.44V_p^{-2.329}$	0.903
Schmidt hardness vs BAV for granodiorite (Kılıç and Teymen, 2008)	$BAV = 136910SH^{-2.3621}$	0.914
Updated Schmidt hardness vs BAV for granodiorite	$BAV = 164793SH^{-2.424}$	0.974

As shown in Table 2, the updated correlations increased the coefficient of determination compared with the published empirical relationships. The highest R^2 value was obtained from the UPV–Böhme abrasion relationship for Ephesus marble and from the Schmidt hardness–Böhme abrasion relationship for Kerkenes granodiorite. This suggests that the most suitable non-destructive index may vary depending on the investigated rock type. The increase in R^2 values after introducing the present test results into the existing dataset available in the literature indicates that index test results for both sites conform to the proposed relationship. Therefore, these updated equations may provide a more reliable basis for preliminary estimation of Böhme abrasion values for the investigated rock types. Therefore, future research will focus on expanding the dataset by including samples of different types of rocks used as building materials, thus enabling a more robust assessment of the proposed relationships.

Overall, the study shows that non-destructive index tests can provide a practical basis for estimating on-site Böhme abrasion values of archaeological stone finds while reducing the need for destructive methods.

The rock samples collected and analyzed were selected to encompass the widest possible range of weathering conditions, reflecting the inherent variability of erosion processes across the study area. This approach was intended to capture the diversity of local environmental conditions. Nevertheless, the current dataset remains opportunistic in nature, and a more systematic sampling strategy is required to ensure a more representative characterization of regional variability. Likewise, many of the correlations reported in the existing literature are derived from relatively limited datasets. Consequently, the development of generalized relationships applicable across rock types remains theoretically challenging and should be approached with caution. Future research will therefore focus on expanding the dataset through the inclusion of additional archaeological sites characterized by different dominant construction materials, thereby enabling a more robust assessment of the proposed relationships and their broader applicability.

This research was conducted as part of a broader study (Testimony of Stones: A New Method in Ancient Traffic Analysis - MSCA.PF). Accordingly, the Böhme abrasion value obtained through non-destructive methods will be integrated into computational modelling (ABM - Agent-Based Modelling) using some fundamental laws of tribology and used in calculating and estimating pedestrian traffic that causes abrasion of stone architectural elements. Thus, for archaeological sites, it will be possible to both provide input for calculations aimed at estimating pedestrian traffic in ancient times and predict the medium and long-term effects of current tourism pressure (visitor traffic, etc.) in these areas.

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