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THE USE OF LIMESTONE IN HISTORIC ROAD SURFACES – A CASE STUDY

Abstract: The article presents the problem of selecting the correct type of limestone for producing paving stones used to renovate the surface of Mariacki Square in Krakow. Due to using up local limestone deposits, imported limestones began to be used. The first one was a Turkish limestone with the trade name Lotus Beige. Despite substantial physical and mechanical parameters (compressive strength 134 MPa, water absorption 0.26%), after several years of use, the paving stone cracked and, as a result, fell apart into smaller fragments. Hauteville limestone from France has been selected for the following reconstruction of the surface. This limestone in the air-dry state was characterised by even higher parameters, i.e. compressive strength of 157 MPa, flexural strength at 16.9 MPa, Bohme Abrasion test at 15275 mm^3, and water absorption at 0.23%. The tests also showed absolute frost resistance and high resistance to thermal shock. Unfortunately, after several years of using the surface of Mariacki Square, cracks and flaking of the rock material have been observed in terms of some paving stones. These cracks appeared within the so-called stylolite seams, which are a natural feature of limestone. Despite a very strict selection of materials, unfortunately, problems with the surface's durability could not be avoided.

Keywords: paving stones; historic road surface; limestone

1. Introduction

To preserve the historical character of cities, it is crucial to protect their historic buildings. If such protection cannot be carried out, it is possible to recreate old buildings along with their historic character. Unfortunately, it happens very often that the raw materials from which a given building was originally made have already been exhausted or do not meet the modern requirements concerning the functioning of a given building. The aim of the work was a presentation of the problem of selecting the correct stone material for producing the paving stones necessary for

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paving the surface of Mariacki Square in Krakow. The article presents the history of pavement renovation and a description of the properties of limestone used in the last few decades. Based on the author's research on physical and mechanical properties, the material was assessed in terms of resistance to destructive factors and suitability for the production of paving stones. The main reasons for the rapid destruction of stone elements made of carbonate rocks were also identified, and the legitimacy of using limestone for reconstructing a road surface has been questioned.

2. A short history of reconstructing the pavement of Mariacki Square in Krakow

The Mariacki Square in Krakow is located in the Old Town, in the vicinity of the Main Market Square (Fig. 1). St Mary's Church is located in the middle of the square, and it was created at the beginning of the 19th century on the site of a liquidated parish cemetery. To mark the boundaries of the former cemetery, the location was paved with white limestone.

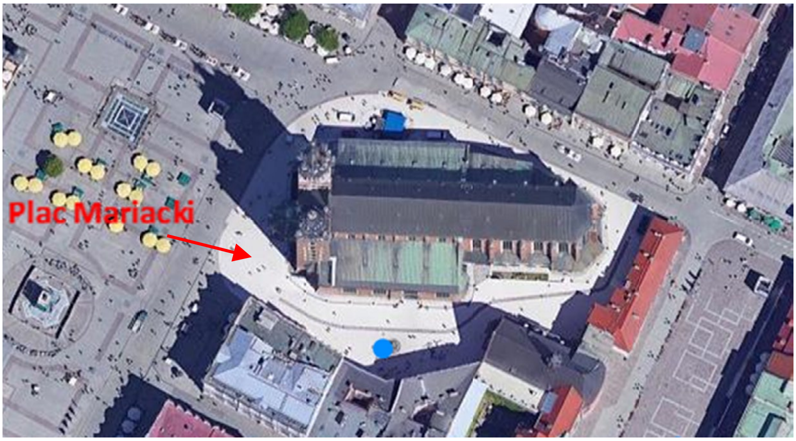


Fig. 1. Mariacki Square in Krakow [1]

The first stone road surfaces of Krakow were built in the 13th and 14th centuries and were made of selected stones obtained mainly from broken limestone or ceramics. The paving stones were shaped into wedges and driven into the sand bed. As a result of use, especially under the impact of vehicle traffic, the paving stones got deformed, and their edges crumbled. Surfaces made in this way were called „cobblestones" [2,3]. Over the centuries, most of the street and square surfaces in Krakow were rebuilt using stone materials that were more durable and resistant to the increasing traffic of vehicles, such as granite, basalt, etc. Nevertheless, limestone surfaces have remained in several historic locations in Krakow. Such surfaces are found, for example, at Mariacki Square, around the Church of St. Wojciech on the Main Square, at the end of ul. Gołębia, around the Florian Gate, or in the courtyard of the Wawel Royal Castle. In many places, to present the historical „cobblestones", fragments of surfaces were reconstructed with the use of irregular cubes recovered during disassembly (Fig. 2).

Fig. 2. Section of a reconstructed pavement made of cobblestone

In the Middle Ages, the raw material for producing paving stones consisted of white Upper Jurassic limestone from quarries located within the city of Krakow, including from Wzgórze Wawelskie, Skałka, Krzemionki Podgórskie, and Zakrzówek [4], and during later centuries also from the Silesian-Krakow monocline. White Jurassic limestone was an Oxford variety of Upper Jurassic stones and created several different facies: rocky, coarse-grained with flints, and chalk and plate limestones [5,6]. The colour of this limestone resulted from the weathering of the surface, while fresh breaks had a slightly yellowish or pinkish colour. Rocky limestone and limestone with flints were mainly used for paving [2,7-9]. The average compressive strength of limestone samples taken from Wzgórze Wawelskie (Table 1) was about 100 MPa, while the bulk density was about 2650 kg/m^3 [10].

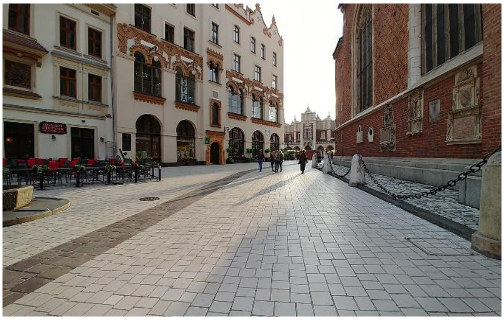
TABLE 1

Physical and mechanical properties of limestones from Wzgórze Wawelskie [10]

No.	Property	Mean value	Min.	Max.
1	Natural water content, %	2,0	1,16	3,35
2	Apparent density, kg/m^3	2650	2600	2742
3	Compressive strength, MPa – in natural water content – after the samples are saturated with water	 100,0 90,0	 20,0 13,0	 182,6 180,7

Due to the exhaustion of local Jurassic limestone deposits in the 1960s, there was not enough material for ongoing repairs and replacing damaged stones. Due to this, various types of imported limestones have been used for the renovation of Krakow's pavements and other architectural structures [11] (Fig. 3a and 3b). A thorough renovation of the surface of Mariacki Square was carried out at the beginning of the 21st century. Limestone from Turkey, under the trade name Lotus Beige, was used for the reconstruction. The tests carried out at that time at the Laboratory of Rocks & Stone Products of the AGH University of Science and Technology [12] showed an average compressive strength of this stone in the air-dry state at 134 MPa (spread from 114-155 MPa), while its water absorption was at the level of about 0.26%. For reconstructing

a)



b)

Fig. 3. Fragment of the current paving surface made of limestone a) courtyard of the Wawel Castle, Lotus Beige limestone paving, b) renovated Mariacki Square, Hauteville limestone paving

the surface of Mariacki Square, mechanically cut paving stones with the following dimensions: 150×150 mm, 200×200 mm, 200×150 mm, 300×150 mm, and thickness of 100 mm were used.

Even though the used elements were much larger than the historical „cobblestones", they formed significant cracks and broke into smaller fragments after several years of use (Fig. 4). To determine the causes of such a rapid and intensive destruction of the used material, Rembiś and Smoleńska [13] as well as Mazurek [14] carried out tests of samples taken from the paving stones from Mariacki Square used at that time. Mazurek [14] showed primarily a very high variability of mechanical properties. The compressive strength values ranged from 93 to 180 MPa (average 140 MPa), while the flexural strength was from 0.45 to 13.3 MPa (average 7.6 MPa). During a frost resistance test, some samples were completely destroyed, while for the remaining samples, after 56 cycles of freezing and thawing, only a few percent decrease in strength parameters was noted. The cause for the damage, as well as significant discrepancies in the results, consisted

Fig. 4. Numerous cracks and damages of Turkish limestone paving stones [15]

of cracks that developed extremely quickly within the discontinuity zones, i.e. stylolite seams and calcite veins. It was confirmed by observations of these cracks carried out by Rembiś and Smoleńska [13] with the use of an SEM scanning microscope. They showed that the main cause of the damage consisted of the crystallisation of salts from deicing agents.

In 2015, a decision was made to carry out a thorough renovation of Mariacki Square and dismantle the damaged Lotus Beige limestone surface. According to the conservation requirements, after detailed research, the Hauteville limestone from the Lompnes mine (Rhone Alpes region) in France [16] was selected. The renovation of Mariacki Square's surface was carried out in 2016-2017.

3. Reasons for the destruction of stone road surfaces

Poland is located in a temperate, warm transitional climate with a considerable range of temperature variations. Days with the temperature transition at 0°C occur from September to June, with the annual average being circa 54 days [17]. Air temperature has a direct impact on the temperature of road surfaces. Research [18] shows that annually temperatures of road surfaces below 0°C last from a dozen to even 700 hours, depending on the location. Therefore, temperature changes may reduce the performance of paving stones. Temperatures below 0°C are particularly dangerous. In the case of porous and water-saturated stone materials, the stone structure may burst as a result of the increased pressure of freezing water (Table 2) [19].

TABLE 2

Impact of temperature on pressure exerted by ice [19]

Temperature, °C	0	–5	–10	–15	–20	–22
Pressure, MPa	0,6	61,0	111,3	159,0	197,0	211,5

Usually, stone materials with very low water absorption are considered to be frost resistant. However, it sometimes happens that despite the negligible open porosity, the material was damaged from the impacts of changing temperatures. This applies to both negative temperatures as well as temperatures reaching several dozen degrees Celsius. High temperatures in stone material result mainly due to the surface being heated by the sun's rays. Then the cause of destruction may consist of various temperature expansions concerning the minerals that form the rock structure. In the case of limestones, these may also be structural discontinuities, or the so-called stylolite seams, as well as the inclusion of other minerals [20-25]. For example, in a work [26] concerning the freezing and thermal shock resistance of selected limestone variations from Turkey, a decrease in compressive strength for both tests was shown at the level of 0 to 35%.

Water constitutes a very serious factor when it comes to destroying limestone. This applies to any rock material exposed to external weather conditions, especially rainfall and melting snow. As a stone becomes saturated with water, its technical parameters deteriorate. The degree of these changes depends on the sorption properties of the material, its structure, and its chemical composition. In a paper [27] concerning an assessment of the properties of Sanliurfa limestone, it was shown that the water absorption level of 6.5-12%, resulted in a decrease in compressive strength from 11% to 26%. Whereas, changes in compressive strength after a frost resistance test were only at 4% to 8%.

The direct impact of water results in the dissolution processes of rock-forming minerals and the swelling of clay minerals. On the other hand, any chemical contamination causes deterioration of the stone material as a result of salt migration and crystallisation. Chemical water pollution is caused by rinsing air pollutants (sulphur and nitrogen compounds) by rain and by dissolving de-icing agents (mainly sodium chloride). Wilczyńska-Michalik and Michalik carried out extensive research concerning the historic limestone buildings in Krakow [28]. The main reason for intensifying the processes of carbonate rocks destruction has been shown to consist of reactions between the unstable components of carbonate rocks and sulphur compounds, causing the formation of gypsum and the crystallisation of minerals from, for example, polluted rainwater. Similar phenomena have been described in other works [29-31]. For limestones from historical buildings in Budapest and Lesno Brdo, the main reason for the deterioration consisted of the crystallisation of gypsum.

The rate of rock destruction in a polluted atmosphere is much higher than in the case of the natural weathering process. This is confirmed by an assessment of changes in the strength parameters of carbonate rocks carried out by Pinińska and Bobrowska [24,32]. Two types of carbonate rocks were tested in terms of resistance to deterioration. The assessment of susceptibility to deterioration has been determined based on microscopic observation of changes in the structure, as well as tests of compressive strength of samples seasoned in various environmental conditions. The research material subjected to the cyclic impact of sodium sulphate solution to determine the resistance to salt crystallisation showed a decrease in strength, strictly dependent on porosity, at the level of 16% and 29%. As a result of seasoning in a tightly closed container with a sulphur dioxide solution, pitting appeared on the surfaces of the tested samples due to dissolving $CaCO_3$ as well as crystallised gypsum phases in many places. The decrease in strength for both types of material amounted to about 32-36%.

The last group of stone-destroying factors consists of mechanical influences. They may lead to cracking or abrasion of the material. Referring this directly to road surfaces, especially those used by numerous vehicles. It can be seen that the scale of the influence intensity is incomparably greater than in the case of building facades. In addition, the low abrasion resistance of the paving stone surface causes its excessive machining. A worn and slippery surface becomes too dangerous to be used correctly.

4. Samples and test methods

Two series of samples were prepared for the tests. Series I (Table 3) included a set of tests typical for assessing the properties of natural stone for paving works in accordance with the requirements of PN-EN 1342 [33] and PN-EN 12058 [34]. Whereas, series II (Table 4) was used additionally to assess the degree of degradation resulting from thermal shock and the effect of sulphur dioxide in the presence of moisture. A frost resistance test was also carried out, in which a 1% NaCl solution was used for defrosting. This procedure was aimed at assessing the effect of de-icing agents on the degradation of rock material and was dictated by the results of research carried out by Rembiś and Smoleńska (2012). Tables 3 and 4 provide the number of tested samples and the test methods [35-43].

The frost resistance test consisted in performing 56 cycles of freezing to a temperature of about –12°C and thawing in water at a temperature of about +20°C. The impact of the freezing

TABLE 3

Test methods and the number of samples, Series I

No.	Property	Number of samples	Sample sizes [mm]	Test method
1	Apparent density and open porosity	42	50×50×50	PN-EN 1936:2006
2	Water absorption	42	50×50×50	PN-EN 13755:2008
3	Freeze-thaw durability	39	50×50×50	PN-EN 12371:2010
4	Compressive strength – air-dry – saturated with water – after 56 freeze-thaw cycles in water – after 56 freeze-thaw cycles in NaCl	 48 49 39 10	50×50×50	PN-EN 1926:2007
5	Flexural strength – air-dry – saturated with water – after 56 freeze-thaw cycles	 10 10 10	50×50×300	PN-EN 12372:2010
6	Abrasive resistance – air-dry – saturated with water – after 56 freeze-thaw cycles	 30 6 6	71×71×71	PN-EN 14157:2005
7	Slip resistance	30	50×30×150	PN-EN 14231:2003
8	Petrographic research	3	Thin section	PN-EN 12407:2007

TABLE 4

Test methods and the number of samples, Series II [44]

No.	Property	Number of samples	Sample sizes [mm]	Test method
1	Apparent density and open porosity	10	50×50×50	PN-EN 1936:2006
2	Water absorption	10	50×50×50	PN-EN 13755:2008
4	Thermal shock resistance	10	50×50×50	PN-EN 14066:2004
5	Resistant to SO_2 in the presence of moisture	20	50×50×50	PN-EN 13919:2004
4	Uniaxial compressive strength – air-dry – after 20 thermal shock cycles – after seasoning in SO_2 in the presence of moisture (solution A) – after seasoning in SO_2 in the presence of moisture (solution B)	 10 10 10 10	50×50×50	PN-EN 1926:2007

and thawing cycles on the tested rock material has been assessed based on changes in the samples' volume as well as changes in the compressive and flexural strength of the samples subjected to freezing in relation to the original samples. In both cases, the strength test was performed on samples saturated to a constant weight. According to PN-EN 1342 and PN-EN 12058, a material regarded as frost resistant is considered to be one whose volume changes do not exceed 1% and/or the decrease in the value of both compressive and flexural strength does not exceed 20%.

To assess the impact of the sorption properties of limestones on their durability, the percentage change in compressive strength, flexural strength, and abrasion resistance with the Boehme disk after saturation to the identical air-dry condition was calculated. A very important test for paving stones is the abrasion resistance test. It was carried out with the use of a Boehme disc. The test aimed at determining the wear of a sample with dimensions of 71×71×71 mm resulting from abrasion on a rotating disc with an abrasive agent (corundum powder). Assessing the skid resistance value (SRV) was performed with the use of a pendulum friction tester. This instrument is equipped with a rubber skid, by means of which the friction between the skid and the tested surface is measured. The skid resistance values (SRV) have been calculated as the product of the average friction value of the pendulum device and a correction factor of 1.2. The test was performed on a wet surface.

Macroscopic observations were carried out with the use of an MSt 130 stereoscopic microscope at magnifications up to 50×. These observations were used for the initial characterisation of the sample and for selecting the microscopic preparation site (thin section). Thin sections were prepared after the sample was impregnated with an epoxy resin. Transmitted light microscopy was performed on an AMPLIVAL field petrographic microscope at a magnification of 80-625×. The observations were carried out in polarised light with one polariser and two crossed polarisers. The microphotographic documentation has been prepared with the use of an OLYMPUS SX51 microscope.

Thermal shock resistance tests consisted in subjecting the samples to cyclic heating to a temperature of 110°C and cooling in water at a temperature of 20°C. 20 cycles were performed.

A study of resistance to the effect of sulphur dioxide in the presence of moisture consisted in observing changes that occurred in individual samples after 21 days of seasoning in a sealed container with sulphuric acid solutions. Solution A was prepared by diluting 500 ml of sulphuric acid (IV) (H_2SO_3) in 150 ml of H_2O, while solution B was prepared with 150 ml of sulphuric acid (IV) (H_2SO_3) in 500 ml of H_2O. Apart from weight changes, the changes in compressive strength were also verified.

5. Petrographic examination of Hauteville limestone samples

In terms of a macroscopic assessment, the Hauteville limestone was cream-coloured and characterised by high durability and hardness. Microscopic examination revealed a microcrystalline structure composed of micrite (crystal sizes 3-4 μm) and calcite microsparite (5-20 μm), as well as a massive and dense texture with few empty pore spaces. Carbonate components constituted 97% of the rock volume, mainly in the form of recrystallised calcite forming the rock background. Clay minerals and iron sulphides in the form of pyrite have been identified (Fig. 5) apart from calcite. Although non-carbonate phases occurred in small amounts (they did not exceed 3% of the rock volume), due to the possibility of further changes, mainly under the influence of atmospheric factors and anthropogenic processes, they constituted a very important component of the studied rock. Additionally, compaction discontinuities were observed referred to as stylolite seams. In Figure 6, red arrows mark a stylolite seam partially filled with iron compounds and calcite. In most cases, they were characterised by a complicated, so-called grid waveform. Their formation was directly related to the processes of calcite dissolution under the conditions of high pressure and contributed to the development of porosity in their immediate vicinity.

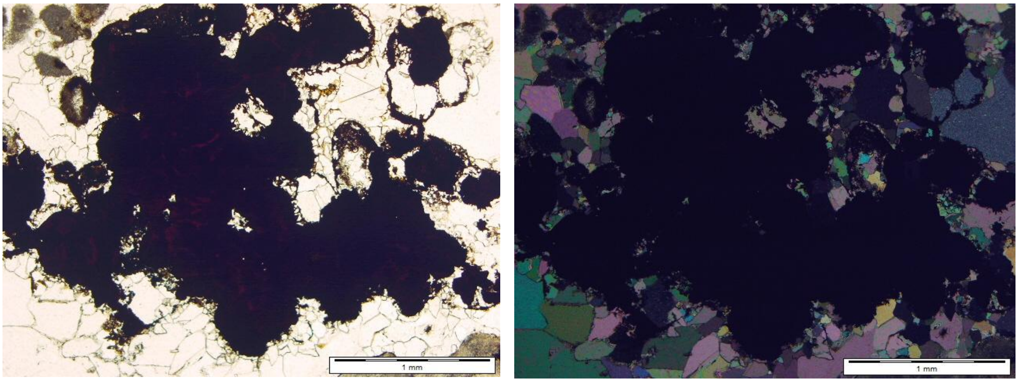


Fig. 5. Rock pores filled with pyrite. Petrographic microscope photo

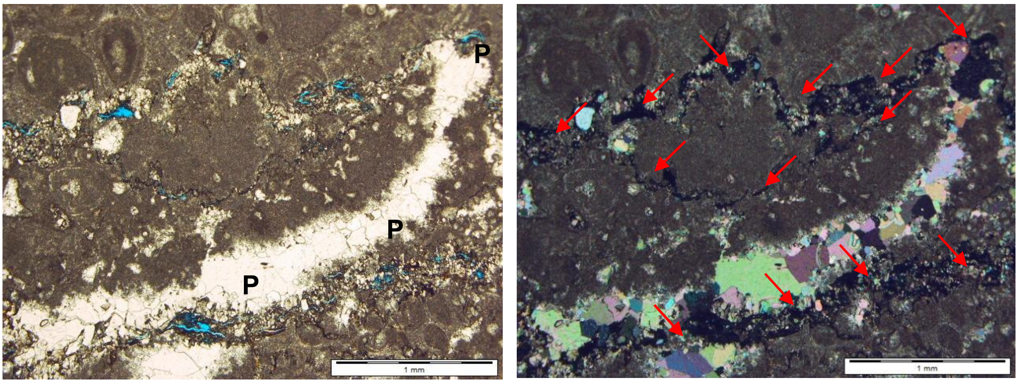


Fig. 6. Visible stylolite seam (arrows) filled with iron compounds as well as calcite and rock pores (P) covered with calcite cement, formed as a result of dissolution processes. Visible gaps (blue) within the stylolite seams. Petrographic microscope photo

6. Results of physical-mechanical test and their analysis

The results of the Hauteville limestone tests are included in Tables 5 and 6. Apart from the mean values, the tables contain the minimum and maximum values along the standard deviation and variation coefficients. The variation coefficients characterise the relative differentiation of an examined feature concerning the mean value.

Table 5 includes the results of tests necessary to assess the quality and suitability of rock raw material for producing paving stones and paving slabs concerning the requirements of PN-EN 1342 and PN-EN 12058. Based on these values, it is determined that in terms of mechanical resistance, Hauteville limestone is comparable to igneous rocks, e.g. the Strzegom or Strzelin granites, which are very popular in Poland [45], and meets the requirements for stone material for producing paving stones and paving slabs.

TABLE 5

Physical and mechanical properties of Hauteville limestones Series I

No.	Property	Mean value	Min.	Max.	Standard deviation	Coeff. of variation
1.	Apparent density, kg/m^3	2684	2675	2689	4	0.002
2	Open porosity, %	0.61	0.39	0.81	0.10	0.17
3	Water absorption, %	0.23	0.14	0.30	0.04	0.17
4	Uniaxial compressive strength, MPa – air-dry – saturated – after 56 freeze-thaw cycles in water – after 56 freeze-thaw cycles in NaCl	 157.2 141.3 139.0 129.3	 107.10 87.2 68.8 84.2	 214.1 194.4 204.8 145.3	 25.2 27.6 30.4 24.6	 0.16 0.20 0.22 0.19
5	Flexural strength, MPa – air-dry – saturated – after 56 freeze-thaw cycles	 16.9 15.9 15.8	 10.7 9.5 8.7	 23.9 22.3 22.0	 5.0 3.7 4.1	 0.30 0.24 0.26
6	Abrasive resistance, mm^3 – air-dry – saturated – after 56 freeze-thaw cycles	 15275 39020 39380	 12234 37003 35522	 17310 42289 43358	 1556 1817 2728	 0.10 0.05 0.07
7	Slip resistance (SRV)	68.9	45.6	96.0	13.7	0.20

Based on visual observations and changes in mechanical properties, absolute frost resistance has also been determined. No significant differences were observed between the parameters in the saturated state and after 56 cycles of freezing and thawing in water (reduction of the average value for compressive strength at 1.6%, for flexural strength at 0.6%, for abrasion an increase in the volume of the rubbed material at 0.9%). However, there were significant differences between the values of mechanical parameters in air-dry conditions and when fully saturated with water. Even though the absorbability of the material was negligible (0.23%), a 10.1% decrease was noted in the case of compressive strength, 5.9% for flexural strength, while in the case of abrasion, the volume of the old material increased by more than 2.5 times. In the case of the frost resistance test according to the modified method, with thawing rock samples in 1% NaCl solution, a greater reduction in compressive strength was noted, at 8.5%.

For materials intended for the production of paving stones, it is assumed that the minimum value of the SRV index, tested on wet samples, must be at least 35. However, with such a high abrasion index, there is a high risk of rapid wear, thus polishing the surface of the paving stone. This may reduce the grip of shoes or wheels when moving on such a road surface.

Results of tests on samples from Series II (Table 6) showed that the tested material was characterised by better physical and mechanical parameters, especially the lower value of open porosity and water absorption. Furthermore, the average compressive strength in the air-dry state was about 9% higher than the average from Series I. Also, the weight loss of the samples after the thermal shock and SO_2 in the presence of moisture did not show significant changes. Only a decrease in compressive strength was noted after 20 cycles of thermal shock at about 4%. After seasoning in an atmosphere saturated with SO_2 vapours, strength drops of 10% for solution A and 21% for solution B were obtained.

TABLE 6

Physical and mechanical properties of Hauteville limestones Series II [44]

No.	Property	Mean value	Min.	Max.	Standard deviation	Coeff. of variation
1.	Apparent density, kg/m^3	2689	2679	2700	7	0,003
2	Open porosity, %	0,57	0,45	0,70	0,08	0,14
3	Water absorption, %	0,21	0,17	0,26	0,03	0,14
4	Thermal shock resistance, %	0,18	0,14	0,22	0,02	0,11
5	Resistant to SO_2 in the presence of moisture, %	0,11	0,08	0,15	0,03	0,27
4	Uniaxial compressive strength, MPa					
	– air-dry	172,8	138,5	201,6	19,0	0,11
	– after 20 thermal shock cycles	166,0	97,9	205,5	47,2	0,28
	– after seasoning in SO_2 in the presence of moisture (solution A)	156,2	147,5	164,9	8,9	0,06
	– after seasoning in SO_2 in the presence of moisture (solution B)	136,4	110,7	162,7	26,3	0,19

Comparing the results of tests included in Tables 5 and 6 with the results of tests carried out for materials used in the past as paving stones for the Mariacki Square (Jurassic from Wzgórze Wawelskie, Turkish Lotus Beige), it has been determined that the Hauteville limestone from the Lompnes mine (Rhone Alpes region) in France was characterised by better physical and mechanical parameters. The average compressive strength in the air-dry state compared to Jurassic limestone was higher at 57-72%, while in the state of complete saturation at approximately 57%. However, concerning the Lotus Beige limestone from Turkey, these values amounted to over a dozen percent. The differences concerning water absorption for limestone were similar: in relation to Jurassic limestone, it was almost 90%, and concerning Turkish limestone 11%.

Despite the high mean values of the examined mechanical parameters, the wide dispersion of results concerning mechanical properties, regardless of the state of the test, was disturbing. This was also confirmed by the high value of variation coefficients, which ranged from a dozen to even 30%, and the minimum values accounted for less than 50% of the mean values. In many cases, the dispersion of the results is due to the discontinuity of stylolite seams. Their impact on the manner of destruction was observed on more than ten samples subjected to the flexural resistance test (Fig.7). Both in terms of air-dry samples, as well as after saturation and frost resistance testing, breaking a sample with a load applied in the middle was asymmetric, and exactly along the stylolite seam.

Fig. 7. A sample with dimensions of 50×50×300 mm after the flexural strength test with visible cracks within the so-called stylolite seams

7. Summary

Renovating stone road surfaces in historic parts of many cities constitutes a challenge for both conservation and technical supervision services. A conservator of monuments requires a given object to be represented as faithfully as possible, whilst the technical services pay special attention to the mechanical parameters, as well as durability and resistance to external factors. In many cases, it is difficult to compromise, especially when raw material resources have been exhausted. Furthermore, the modern manner of using road surfaces requires completely different materials than 200 or 300 years ago.

The Mariacki Square example in Krakow constitutes an excellent example of these problems. Selecting the limestone for producing paving stones turned out to be a real challenge. Despite the fact that limestone with low water absorption, the highest mechanical parameters, and very high resistance to water, as well as cyclic freezing and thawing has been selected. It cannot be clearly stated that it was a stone that meets modern durability requirements. The most worrying was the wide dispersion of results, which was a direct consequence of the occurrence of compact discontinuities within some samples, i.e. stylolite seams. This confirmed the concerns, as cracks and slight peeling of the stones appeared within these seams (Fig. 8) after years of pavement use.

Fig. 8. Damages of Hauteville limestone paving stones in Mariacki Square in Krakow

In order to meet the requirements of preserving the historic character and the good condition of the historic pavement of Mariacki Square, the only solution seems to be using non-stylolitic limestone, which is more durable and homogeneous to outdoor conditions.

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