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# Comparative analysis of selected features of traditional and photocatalytical paving stones

**Key words:** technical properties, traditional and photocatalytical paving stones, cement TioCem®, smog

## Introduction

The matter of ecology of urbanised areas appeared in the 1970s, but recently the interest in the issue has considerably increased. Currently, the subject of scientific and social consideration is atmospheric air pollution associated with so-called low emissions. Concrete is a building material that predominantly shapes the urban landscape. Increasingly, it is also replacing asphalt used on road surfaces. Concrete paving stones are used on lower-ranking roads and pedestrian traffic routes. According to Łój (2007), cement is responsible for most of the properties of concrete. At the beginning of the 2000s, the cement developed by the HeidelbergCement Group called TioCem® was launched on the market. The product is characterized by photocatalytic properties owing to the use of nanometric titanium dioxide ($TiO_2$), which affects the removal of harmful compounds from the air and self-cleaning of concrete (Bolte, 2005; Sokołowski & Dziuk, 2008; Sokołowski, Kaczmarek & Szerszeń, 2010).

There are many examples of research on TioCem® cement itself (initial setting time, end of setting time, compressive strength after 2 and 28 days) and products based on it (Brylicki, 2004; Grupa Górażdże, n.d.; Sokołowski, 2008; Sokołowski & Dziuk, 2008; Sokołowski & Kaczmarek, 2009; Lucas, Ferreira & Barroso de Aguiar, 2013; Langier & Pietrzak, 2017). The research is focused on reducing pollution (Bolte, Dienemann & Smolik, 2008; Sokołowski & Dziuk, 2008; Giergiczny & Sokołowski, 2009). Unfortunately, there are not many tests carried out on materials that have been exploited. Most amount to foreign examples from Germany, the United Kingdom or Italy (Ente Italiano di Normazione [UNI], 2007; Sokołowski, 2008;

Sokołowski, 2010; Jackiewicz-Rek, 2019). There is a need to check not only reduction of pollution over time, but also technical properties of the paving blocks.

## The aim of the analysis

The aim of the research is to determine the main technical characteristics, i.e. absorbability, frost resistance, abrasion and splitting tensile strength concrete materials used for walking and driving routes in cities. The aim of the analysis is to compare the results obtained for traditional and photocatalytic paving stones. In addition, an attempt has been made to determine whether atmospheric conditions and air pollution affect the characteristics of these products.

The analysis was based on the provisions of the PN-EN 1338:2005 standard (Polski Komitet Normalizacyjny [PKN], 2005) and the requirements for concrete paving stones.

## Material and methods

It was assumed that test material would be prefabricated paving blocks. The choice of the material for analyses was primarily dictated by various air pollution reduction properties of selected products. They were finally selected for the research:

– rectangular concrete pavement block Mini Trio by Libet from the Monocolor line with nominal area dimensions of 9 × 18 cm and thickness of 6 cm in anthracite colour, made of unreinforced concrete using the vibro-press method, composed of an abrasive layer with minimum thickness of 5 mm and a construction layer, used according to the manufacturer, among others for: private properties, public space, terraces, pavements, alleyways, garden paths, passages, squares, footpaths with a possibility of entry up to 3.5 t and car parks and driveways with light traffic up to 3.5 t;
– rectangular concrete pavement block HOLLAND by ZIEL-BRUK with nominal surface dimensions of 10 × 20 cm and thickness of 6 cm in graphite, made in TX Active® technology with the use of TioCem® cement, according to the manufacturer it is used both on private properties, on pavements and municipal car parks, as well as on surfaces of industrial facilities.

The research material described above was divided into two parts. Half of the paving blocks were stored under laboratory conditions, while the second half was exposed to weather conditions and pollution between December 2018 and March 2019 being stored near the S8 expressway at the Radzymin South junction.

Laboratory tests were carried out in a construction laboratory of the Faculty of Civil and Environmental Engineering of the Warsaw University of Life Sciences – SGGW. The absorbency test of concrete paving stones was carried out in accordance with the PN-EN 1338:2005 standard. Samples were cleaned with a brush at the temperature of 20°C and then immersed in a vessel filled with drinking water at 20°C until mass $M_1$ was determined. The period of immersion of samples lasted for 7 days. After that two successive weighting rounds were carried out, within an interval of 24 h. The result of weighting between the above mentioned rounds showed no difference of more than 0.1%. In order to remove excess water, surface of samples was cleaned with a damp cloth before each weighing. Then the samples were placed in a dryer and dried at 105°C until constant mass $M_2$ was obtained. The samples were cooled to room temperature before each weighing.

Test of frost resistance of concrete paving stones was carried out in accordance with Annex N of the PN-B-06256:2018-10 standard (PKN, 2018). All samples were saturated with water until constant mass was obtained. For 10 days the samples were placed in a vessel filled with water at 18°C. The ones intended for freezing were wiped and placed in a freezing chamber. Freezing took place at –18°C. Each freezing period of samples lasted for 5 h, while the thawing period of samples immersed in water at 18°C lasted for 3 h. The study included 25 freeze–thaw cycles.

Abrasion measurement was performed in accordance with Annex H of the PN-EN 1338:2005 standard. The study was carried out on Boehme shield. Square cubes with side length of 71.0 ±1.5 mm were used for the test. The samples were dried at 105°C before testing to constant weight. The samples were loaded with force of 294 N and tested in 16 cycles, each of which consisted of 22 rotations. The abrasiveness was measured by volume loss according to the PN-EN 1338:2005 standard.

Measurement of the splitting tensile strength of concrete paving stones was carried out in accordance with Annex F of the PN-EN 1338:2005 standard. The test was carried out with the use of a testing machine type ZD 40 and washers with width of 15 mm and thickness of 4 mm. Before the beginning of the test, the samples were immersed in water at 20°C for 24 h, then dried and immediately tested. Correction factor for concrete paving blocks amounted to $t$ = 60 mm, thickness added up to $k$ = 0.87.

## Results

The above-described tests were carried out in March 2019. Preparation of the samples for the absorption test was carried out by systematic pouring of water in a cuvette, after maximum water saturation. The samples were graded and then dried in a dryer (Fig. 1). The obtained results are presented in Table 1.

The frost resistance tests were carried out with the use of a chamber (Fig. 2), in which 25 cycles of freezing and defrosting of the samples were performed. The obtained results are presented in Table 2.

The abrasion process was carried out on a Boehme disc (Fig. 3). The samples prepared in accordance with the standard were successively subjected to abrasion cycles. After each completed cycle, shields were cleaned, corundum was poured again and sample was rotated 90°. Each sample was measured along straight lines perpendicular to adopted base and weighted. Loss of height was given as the arithmetic mean height measured at assumed points. The results of the test and of the measurement of abrasion are presented in Table 3.

FIGURE 1. Stages of absorption testing – saturating samples, drying of samples (own photo)

TABLE 1. The results of measurements of water absorption (own study)

| Sample | Initial sample weight [kg] | Final sample weight [kg] | Water absorption [%] | Sample | Initial sample weight [kg] | Final sample weight [kg] | Water absorption [%] |
|---|---|---|---|---|---|---|---|
| Traditional paving stones | | | | | | | |
| stored in laboratory conditions | | | | stored near the S8 expressway | | | |
| 1 | 2.149 | 2.099 | 2.38 | 21 | 2.166 | 2.100 | 3.14 |
| 2 | 2.206 | 2.160 | 2.13 | 22 | 2.180 | 2.115 | 3.07 |
| 3 | 2.169 | 2.121 | 2.26 | 23 | 2.167 | 2.096 | 3.39 |
| Photocatalytic paving stones | | | | | | | |
| stored in laboratory conditions | | | | stored near the S8 expressway | | | |
| 11 | 2.572 | 2.498 | 2.96 | 31 | 2.594 | 2.504 | 3.59 |
| 12 | 2.507 | 2.430 | 3.17 | 32 | 2.613 | 2.518 | 3.77 |
| 13 | 2.490 | 2.415 | 3.11 | 33 | 2.566 | 2.468 | 3.97 |


FIGURE 2. Frost resistance test chamber (own photo)

Splitting tensile strength was tested on five specimens from each test group prepared in accordance with the requirements. The results of the breaking load and strength *T* are shown in Table 4 and the failure moment and appearance of the sample after the test are shown in Figure 4.

TABLE 2. Weight loss after testing for frost resistance of paving stones (own study)

| Sample | Weight of the sample before their first freezing, in a state of saturation with water [g] | Weight of samples after their last thawing, in a state of saturation with water [g] | Weight loss after the test [%] |
|---|---|---|---|
| Traditional paving stones stored in laboratory conditions | | | |
| 1 | 2 202 | 2 176 | 1.19 |
| 2 | 2 263 | 2 240 | 1.02 |
| 3 | 2 220 | 2 196 | 1.09 |
| Traditional paving stones stored near the S8 expressway | | | |
| 21 | 2 200 | 2 178 | 1.01 |
| 22 | 2 215 | 2 193 | 1.00 |
| 23 | 2 200 | 2 178 | 1.00 |
| Photocatalytic paving stones stored in laboratory conditions | | | |
| 11 | 2 633 | 2 532 | 3.99 |
| 12 | 2 583 | 2 547 | 1.41 |
| 13 | 2 606 | 2 572 | 1.32 |
| Photocatalytic paving stones stored near the S8 expressway | | | |
| 31 | 2 632 | 2 608 | 0.92 |
| 32 | 2 655 | 2 629 | 0.99 |
| 33 | 2 603 | 2 582 | 0.81 |

FIGURE 3. Abrasion test on the Boehme disk, sample before and after the test (own photo)

## Discussion of the results

The comparative analysis boiled down to presenting the differences in the results of the examined properties in two directions: between different types of paving stones (traditional and photocatalytic) and between paving stones stored under different conditions (stabilized in the laboratory and exposed to weather

TABLE 3. Loss of weight, height and volume after 16 wear cycles of paving stones (own study)

| Sample | Average height loss ($\Delta h$) [mm] | Loss of weight after 16 wear cycles ($\Delta m$) [g] | Density ($\rho$) [$g \cdot mm^{-3}$] | Loss of volume after 16 wear cycles ($\Delta V$) [$mm^3$] | Loss of volume after 16 wear cycles ($\Delta V$) [$cm^3$] |
|---|---|---|---|---|---|
| Traditional paving stones stored in laboratory conditions | | | | | |
| 7 A | 2.12 | 22 | 0.002288 | 9 615.38 | 9.62 |
| 7 B | 1.77 | 20 | 0.002288 | 8 741.26 | 8.74 |
| 10 A | 2.28 | 23 | 0.002297 | 10 013.06 | 10.01 |
| 10 B | 2.17 | 25 | 0.002297 | 10 883.76 | 10.88 |
| Traditional paving stones stored near the S8 expressway | | | | | |
| 28 A | 2.41 | 23 | 0.002294 | 10 026.16 | 10.03 |
| 28 B | 2.47 | 24 | 0.002294 | 10 462.07 | 10.46 |
| 30 A | 1.53 | 17 | 0.002313 | 7 349.76 | 7.35 |
| 30 B | 1.57 | 18 | 0.002313 | 7 782.10 | 7.78 |
| Photocatalytic paving stones stored in laboratory conditions | | | | | |
| 18 A | 1.16 | 13 | 0.002202 | 5 903.72 | 5.90 |
| 18 B | 1.22 | 14 | 0.002202 | 6 357.86 | 6.36 |
| 19 A | 1.89 | 16 | 0.002243 | 7 133.30 | 7.13 |
| 19 B | 1.62 | 16 | 0.002243 | 7 133.30 | 7.13 |
| Photocatalytic paving stones stored near the S8 expressway | | | | | |
| 36 A | 1.16 | 14 | 0.002284 | 6 129.60 | 6.13 |
| 36 B | 1.46 | 16 | 0.002284 | 7 005.25 | 7.01 |
| 39 A | 1.21 | 13 | 0.002268 | 5 731.92 | 5.73 |
| 39 B | 1.16 | 12 | 0.002268 | 5 291.01 | 5.29 |

TABLE 4. Results of the measurement of characteristic tensile strength at splitting (own study)

| Sample | Destructive force ($P$) [N] | Cracking surface ($S$) [$mm^2$] | Correction factor ($k$) [-] | Splitting tensile strength ($T$) [MPa] |
|---|---|---|---|---|
| Traditional paving stones stored in laboratory conditions | | | | |
| 4 | 66 000 | 10 426 | 0.87 | 3.51 |
| 5 | 100 000 | 10 603 | | 5.23 |
| 6 | 85 000 | 10 541 | | 4.47 |
| 8 | 120 000 | 10 634 | | 6.25 |
| 9 | 80 000 | 10 525 | | 4.21 |

TABLE 4 cont.

| Sample | Destructive force ($P$) [N] | Cracking surface ($S$) [mm$^2$] | Correction factor ($k$) [-] | Splitting tensile strength ($T$) [MPa] |
|---|---|---|---|---|
| Traditional paving stones stored near the S8 expressway | | | | |
| 24 | 92 000 | 10 603 | 0.87 | 4.81 |
| 25 | 117 000 | 10 642 | | 6.09 |
| 26 | 120 000 | 10 698 | | 6.22 |
| 27 | 112 000 | 10 609 | | 5.85 |
| 29 | 84 000 | 10 540 | | 4.42 |
| Photocatalytic paving stones stored in laboratory conditions | | | | |
| 14 | 96 000 | 11 787 | 0.87 | 4.51 |
| 15 | 94 000 | 11 644 | | 4.47 |
| 16 | 110 000 | 11 919 | | 5.11 |
| 17 | 93 000 | 11 641 | | 4.43 |
| 20 | 95 000 | 11 769 | | 4.47 |
| Photocatalytic paving stones stored near the S8 expressway | | | | |
| 34 | 108 000 | 11 847 | 0.87 | 5.05 |
| 35 | 116 000 | 11 872 | | 5.41 |
| 37 | 109 000 | 11 850 | | 5.10 |
| 38 | 102 000 | 11 810 | | 4.79 |
| 40 | 115 000 | 11 870 | | 5.37 |

FIGURE 4. Tensile strength cracking test, sample of traditional and photocatalytic cubes after the test (own photo)

conditions and pollution). Additionally, the obtained results were confronted with the standard requirements (Table 5).

It can be observed that no sample of paving stones exceeded the 6% limit value. Traditional paving stones

TABLE 5. Comparative analysis of traditional paving stones and photocatalytic paving stones according to the PN-EN 1338:2005 standard (own study)

| Property | Traditional paving stones stored in laboratory conditions | Photocatalytic paving stones stored in laboratory conditions | Traditional paving stones stored near the S8 expressway | Photocatalytic paving stones stored near the S8 expressway | Requirements according to PN-EN 1338:2005/ /PN-B-06265:2018-10 |
|---|---|---|---|---|---|
| Average water absorption | 2.26% | 3.08% | 3.20% | 3.78% | ≤ 6.0% |
| Average weight loss after the testing for frost resistance | 1.1% | 2.2% | 1.0% | 0.9% | < 5.0% |
| Average destructive force of characteristic tensile strength at splitting | 508.17 $N \cdot mm^{-1}$ | 491.88 $N \cdot mm^{-1}$ | 590.32 $N \cdot mm^{-1}$ | 552.28 $N \cdot mm^{-1}$ | ≥ 250 $N \cdot mm^{-1}$ |
| Average strength of characteristic tensile strength at splitting | 4.73 MPa | 4.60 MPa | 5.48 MPa | 5.14 MPa | ≥ 3.6 MPa |
| Average of abrasion on Boehme disk | 9.81 $cm^3/50\ cm^2$ | 6.63 $cm^3/50\ cm^2$ | 8.90 $cm^3/50\ cm^2$ | 6.04 $cm^3/50\ cm^2$ | ≤ 18 $cm^3/50\ cm^2$ |

achieved the minimum of absorbability, both for samples stored in the laboratory and along the S8 route. It should also be stressed that the samples stored by the expressway were slightly more absorbent than those stored in the laboratory. This may be due to atmospheric factors, mainly low temperatures and precipitation. The frost resistance test of concrete paving stones, carried out in accordance with the PN-B-06265:2018-10 standard for concrete, may be a sure proof of that. This was due to the fact that it was not possible to carry out the test by the method of determining resistance to freeze/ /thawing with de-icing salt recommended by the PN-EN 1338:2005 standard. The analysis of the data from Tables 2 and 5 shows that there has been a loss of mass, which may result in greater absorbability. Regardless of the type and place of storage of the cubes, the loss in mass is 1%, which is negligible in relation to the allowed 5%.

The wear resistance of paving blocks according to the standard for class 4 should be less than 18 $cm^3$ per 50 $cm^3$ sample. For all samples the loss in volume shall not exceed the maximum value. Interestingly, samples exposed to weathering show less volume loss after 16 abrasion cycles than samples from the laboratory. The weight of the samples of traditional paving stones after 16 test cycles decreases on average by 22 g, while that of photocatalytic paving stones by 14 g.

With regard to the tensile strength at splitting, the test material met the standard expectations. In all types of the samples the average strength was greater than 3.6 MPa and no single result was less than 2.9 MPa. The average breaking load was twice as high as the mini-

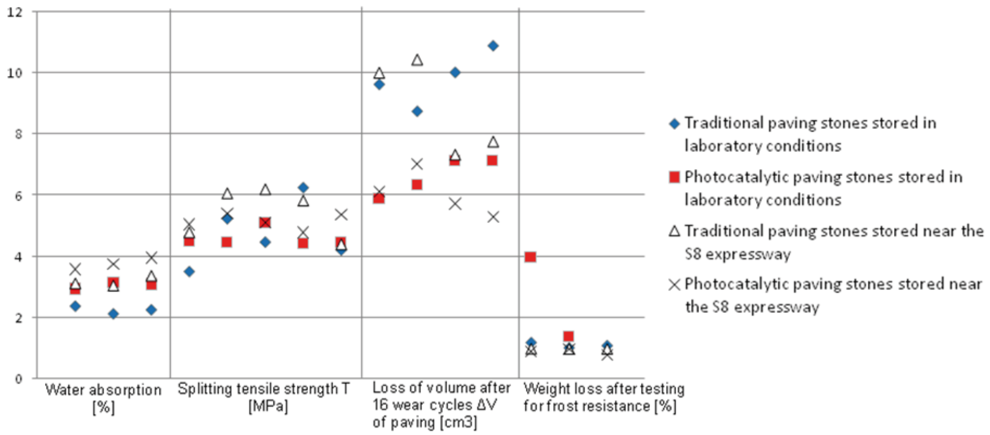


FIGURE 5. Summary of test results depending on the type of paving blocks and their storage method (own study)

mum required by the PN-EN 1338:2005 standard. The strength of traditional paving stones and of photocatalytic paving stones were very similar.

The studies carried out and, above all, the obtained results confirmed the views expressed so far. Compared to the tests carried out by Sokołowski (2010), slightly less absorbability, better abrasiveness, but also less destructive load was obtained when testing tensile strength in splitting. Similarly, in comparison with the experimental results presented by Adamus, Janic and Pietrzak (2016), also the absorbability of the analysed subjects was about 1.5% lower, and the weight loss after frost resistance testing was about 0.5% lower. The authors did not check abrasiveness and tensile strength at splitting in these tests. It should be stressed that research on real material, not experimental material, produced better results. This shows that current manufacturers of paving blocks, including those using TioCem® cement, try to meet the conditions for such products at a high level.

## Conclusions

On the basis of the carried out research synthetic conclusions can be drawn:

- traditional paving stones in the abrasion test were characterized by a higher volume loss than photocatalytic paving stones about 32%;
- based on the average values of split tensile strength, slight increase in the values of strength of the samples used in the vicinity of the S8 expressway can be observed compared to paving blocks stored in the laboratory conditions, regardless of their type;
- the frost resistance of traditional and photocatalytic paving stones is at comparable level, oscillating around 1% weight loss after 25 freeze–thaw cycles;

– the absorbability of the samples that were exposed to weather and pollution between December 2018 and March 2019 increased by about 1% in comparison to the test material stored in the laboratory.

Environmental problems contributed to the creation of a modern product containing nanometric titanium dioxide with photocatalytic properties that reduce harmful substances present in the air and have self-cleaning properties. The production technology of photocatalytic products is identical to the standard version of the products. TX Active® production technology is definitely the technology of the future. The aim of the article, which was to compare selected properties of traditional paving stones and photocatalytic paving stones, was achieved. The laboratory tests show that in analogous storage methods photocatalytic paving blocks slightly exceed the properties of traditional paving blocks. Therefore, it can be assumed that, taking into account the additional properties of pollution reduction and self-cleaning, photocatalytic paving block will replace the traditional one as walking and driving on roads material.

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## Summary

**Comparative analysis of selected features of traditional and photocatalytical paving stones.** Nature friendly technologies in today's world are the subject of scientific research and the interest of local authorities and the residents themselves. In the context of the city, one of the most important issues is the neutralization of air pollution generated by transport and heating of the premises with the use of solid fuels. The article analyses differences of the response of traditional and photocatalytic paving stones. We analysed water absorption, frost resistance, tensile strength at splitting and abrasion of paving stones. It has been proved that paving stones exposed to atmospheric factors and pollution during one heating season met the assumed quality criteria. In addition, the results obtained for the characteristics analysed were higher than the results of samples tested in laboratory conditions. The results also indicate a slight advantage of photocatalytic cubes in terms of their resistance to abrasion and tensile strength at splitting. Traditional and photocatalytic paving stones withstand well the operating conditions. It seems that products based on TioCem® cement are the future implementation of pedestrian and traffic routes.

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