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Recycling of concrete pavements – assessment criteria for load-bearing capacity

Abstract: The article outlines the development of concrete road pavements in Poland and the experiences related to the recycling of such pavements constructed in the 1930s. It presents typical damage to concrete pavements and describes a method for the evaluation of such damage with the use of the Road Pavement Condition Diagnostics system developed by the General Directorate for National Roads and Highways in Poland. The article observes that the system lacks criteria for the assessment of the recyclability of concrete road pavements. The results of tests performed for the actual concrete pavements and numerical analyses of stress distributions within pavement joints served to propose such recyclability criteria. These criteria include pavement slab modules and load transfer efficiencies in the joints. The paper also presents in situ methods for recycling concrete road pavements and for the use of the recycled material as base course for concrete or flexible pavements.

Keywords: concrete pavements, load-bearing capacity evaluation criteria, recycling, road pavement condition assessment.

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1. INTRODUCTION

Concrete pavements are not a common road-construction solution in Poland. Until 1990s such pavements were built at airports, parking sites, on roads in industrial areas etc. They include *in situ* wet or prefabricated pavements. A small number of such pavements were constructed in the first half of the twentieth century (before World War II). In the mid-1990s, Polish roads administration decided to recycle such pre-war concrete pavement from a 12-kilometer stretch of highway A18 and to use the old material crushed in stationary crushing mills. The new concrete pavement consisted of slabs connected with dowels and anchors. Fig. 1 shows destressed slabs ready for transport to stationary crushers.

Fig. 1. Broken pavement slabs in the A18 highway; photo by the author

The aggregate from the crushed old slabs was added to the lower layers of the pavement slabs (19 cm thick), and new aggregate was added to the upper layer (7 cm thick). The new pavement has been now in service for approx. 30 years. Since that time, more than 2000 km concrete pavement roads have been built in Poland, of which approx. 1200 km are highways and freeways. Their pavements are currently in good condition and do not require recycling. Experiences gained during the operation of pre-war road and airport concrete pavements allowed the development of methods for recycling old deteriorated concrete pavements. These recycling methods can be classified into two groups [1] which will be defined in the article as option 1 and option 2.

Option 1 – tests of material from the degraded pavement layers crushed into appropriate aggregate size fractions to be reused in the construction of different road layers, e.g.: unbound aggregate base courses, improved subgrade layer, filtration and freeze-resistant layers, cement- and asphalt-bound base courses, upper embankment layers, reinforced embankment subgrades and road embankments.

Option 2 – tests of the layers and of the material from the *in situ* crushing process of the degraded concrete pavements performed with the impact and resonance methods, as well as their compacting and shaping in order to reuse them as base courses in flexible and rigid (concrete) pavements.

This article will focus on option 2 and discuss the experiences of using this method in Poland and abroad. It will present criteria for evaluating the load-bearing capacity of concrete pavements, which allow the pavement to be assessed for its recyclability with the use of the *in situ* breaking methods. These criteria will supplement the set of criteria for pavement condition assessment as part of the method employed in the Road Pavement Condition Diagnostics (RPCD) system.

2. TYPICAL DEFECTS OF CONCRETE PAVEMENTS AND THEIR ASSESSMENT

Typical defects of concrete pavements include:

- Single longitudinal/lateral cracks – extending in the direction parallel or diagonal to the road axis (travel direction); can be caused by thermal or shrinkage cracks due to the setting of concrete.
- Single transverse cracks – extending transversely to the road axis (travel direction); can be caused by factors similar as in the case of longitudinal cracks.
- Fractured slab – the pavement slab is broken into four or more fragments by intersecting fracture lines due to fatigue loads or low load-bearing capacity of the subgrade.
- Near-edge fractures – fractures approximately parallel to the slab edge or at a maximum distance of 0.5 m from the slab edge; can be caused among others by dowel misalignment or fatigue cracks.
- Sealant faults – torn, pushed or pulled sealant, vegetation growth, hardened sealant, sealant detached from the slab edges, displacement of the slabs.
- Corner damage – fracturing or fracturing and spalling across the slab edges at a maximum distance of 1 m from the corner; can be caused by lack of dowels or lack of slab support.

- Joint spalling – chipping and cracking at a distance up to 0.1 m from the edge of the fracture.
- Surface defects (surface cracks, holes, scaling) – defects to the structure of the upper part of the slab, such as alligator cracks, small holes in the material, scaling down to a maximum of 2 cm, bumps.
- Network of surface crazing – alkaline cracks.

Figs. 2-4 show examples of defects to concrete pavement.

Many countries have systematic methods for classifying concrete pavement defects, assessing pavement condition and applying recommended remedy techniques. The first such system, widely implemented and still used in some countries, was the *PSI* (Present Serviceability Index) – AASHO, USA, 1950 0. It includes a 0 to 5 degradation scale.

Fig. 2. Transverse cracks in the slabs and corners [1]

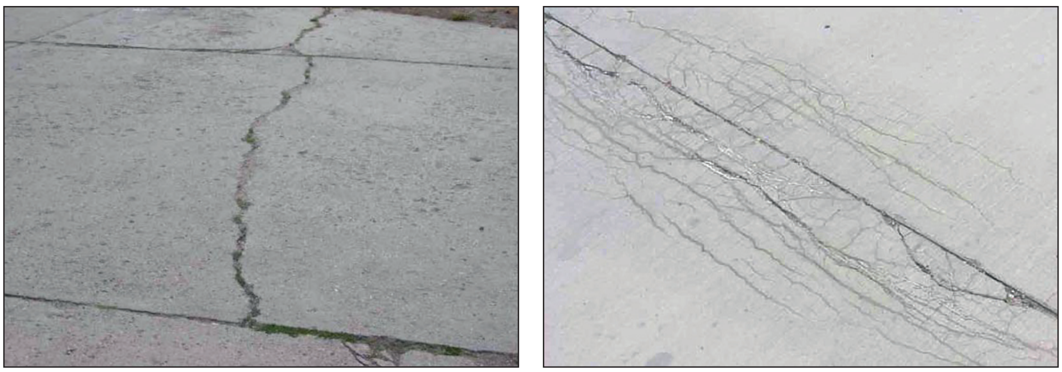

Fig. 3. Longitudinal and transverse cracks (fractured slab) and near-edge cracks [1]

Fig. 4. Surface defects, alkaline cracks [1]

After 1960 various US states and other countries have introduced indicators related to different types of damage, e.g. Pavement Condition Index *PCI*, Pavement Condition Rating *PCR*, Maintenance Control Index *MCI*, Pavement Structural Condition *PSC*. These indexes use various scales (1-5, 0-100, 1.0-9.0, 0.0-4.0) to quite precisely identify the condition of the pavement [4-6]. They typically describe various types of surface cracks and defects. Depending on the extent of damage, they recommend different repair techniques, from surface and texture repair methods to the replacement of entire concrete slabs and lower layers. They are employed solely for the data managed by road administration institutions and do not address the possibility to rehabilitate concrete pavements with the use of material recycled *in situ*. Another system for assessing pavement condition and forecasting potential repair costs is the Pavement Management System (PMS). Its main elements include: pavement degradation models, repair costs, rehabilitation methods, industry requirements, management policies, users, designers, road network requirements, and a module supporting the decision-making process regarding pavement condition monitoring and repairs 0.

In Poland, the Road Pavement Condition Diagnostics (RPCD) system has been used since 2015 to identify and assess the servicing parameters of asphalt and concrete pavements 0. This document regulates the standards for setting the measuring ranges, performing measurements and processing the results of technical and operating conditions within the national road network. It was developed as a response to the dynamic technological progress in the field of pavement condition diagnostics and to the need for adjusting the existing diagnostic regulations to the new conditions. In comparison do the previous diagnostics system, RPCD has an increased number of technical and operating pavement parameters, and is based on new diagnostic technologies.

In RPCD, the pavement condition is assessed by calculating individual condition parameters based on the measurement results. Each of the pavement characteristics is assigned basic condition parameters and supplementary parameters. The notion "pavement characteristics" refers to the properties which change as the pavement remains in use. The basic pavement characteristics include 0:

- load-bearing capacity (fatigue-life), understood as the ability of the pavement to carry repeatable loads due to vehicle traffic, valid only for flexible pavements (made of mineral-asphalt mixes), not assessed for concrete pavements,
- evenness (longitudinal and transverse) which defines the degree to which the surface of the pavement is consistent with the required parameters,
- skidding resistance, which describes the tractive adhesion between the pavement and the tire,
- surface characteristics, which describe pavement defects (longitudinal and transverse cracks, corner defects, edge defects, as well as other properties important for the management of road maintenance activities, visible on its surface, including the macrotexture and surface imperfections (small individual holes, spalls etc.),
- vertical displacement of slab edges.

Importantly, at present RPCD does not allow the assessment of the condition of concrete structures by measuring deflection (*U*, *SCI*), and only identifies cracks, edge and corner defects, pavement evenness and macrotexture. This is a significant problem particularly in the context of qualifying concrete pavement for recycling.

3. PROPOSED CRITERIA FOR THE ASSESSMENT OF THE RECYCLABILITY OF CONCRETE PAVEMENTS

As mentioned in Section 2, the RPCD system does not allow for the parameters of the pavement structure layers measured in tests based on the full displacement (deflection) basin which enables the identification of layer modules. These modules provide information on structural changes in the layers. Moreover, the RPCD system does not assess the engagement between the slabs in the joints. Here the author proposes criteria for evaluating the load-bearing capacity of old deteriorated concrete pavements with respect to their potential *in situ* recyclability. The criteria have been developed on the basis of concrete pavement model parameters identified in tests performed on pavements remaining in service. The criteria relate to concrete slab modules *E* and to load transfer efficiencies in the joints *LTE*. For this purpose, the tests included concrete layer modules identified on pavements having various deterioration degrees and load transfer efficiencies identified on slab joints. These parameters were identified with a falling weight deflectometer (FWD). Fig. 5 shows a schematic diagram of the deflection tests.

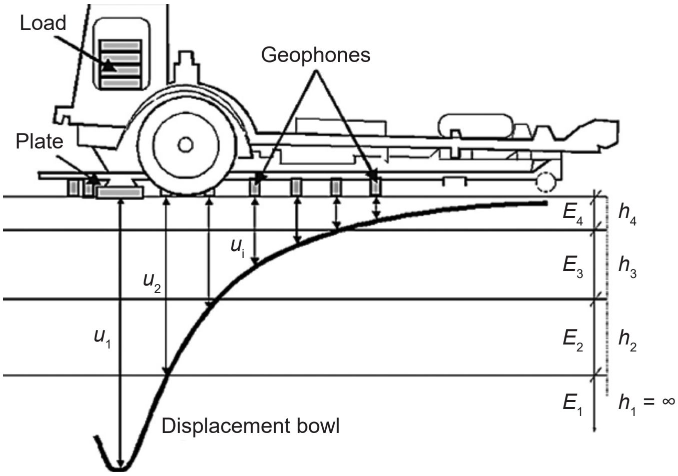

Fig. 5. Schematic diagram of the tests performed with the FWD

The load was adjusted to the type of the tested structure. The deflectometer was used to measure deflection with the use of geophones.

Fig. 6 shows a model of concrete pavement structure used in the identification of concrete pavement modules.

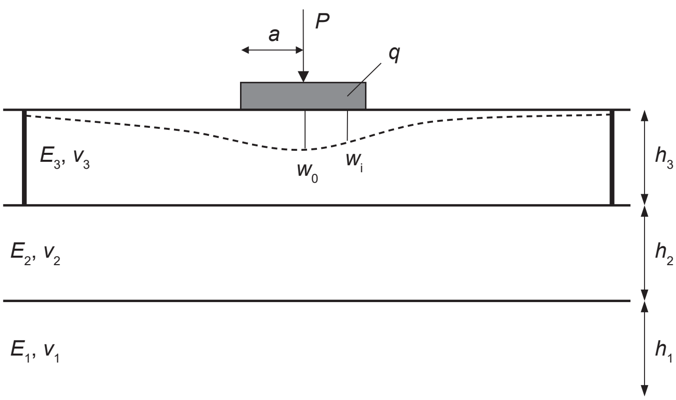

Fig. 6. Model of concrete pavement structure

The layer having the thickness h_3 is the concrete slab, the h_2 layer – base course, and the h_1 layer – subgrade. Fig. 7 shows a schematic diagram of the deflection measurement process in the concrete slab.

The principle behind module identification is to minimize the objective function described with the following eq. (1):

$$\Delta = \frac{\sqrt{\frac{F}{k}}}{\frac{\sum_{j=1}^{k} w_j}{k}}, \tag{1}$$

where:

$$F = \sum_{j=1}^{k} (w_j - u_j)^2 , \tag{2}$$

w_j – theoretical deflection calculated from the model,

u_j – measured deflections,

k – number of deflections measured at one point, forming the deflection basin.

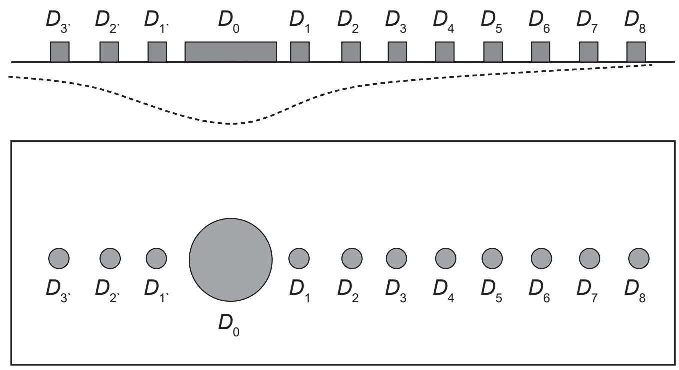

Fig. 7. Schematic diagram of the deflection measurement in the slab

For identification purposes, the calculations were performed with the use of the CZUG software 0. The identification process results in module values E_i for individual layers. The layer thicknesses are selected on the basis of in-depth identification (drill holes). The Poisson ratio ν_i has no significant influence on the obtained module value.

On the pavement, additional identification was performed for load transfer conditions within the joints. These conditions are described by the so-called load transfer efficiency *LTE*. Fig. 8 shows a schematic diagram of *LTE* measurement.

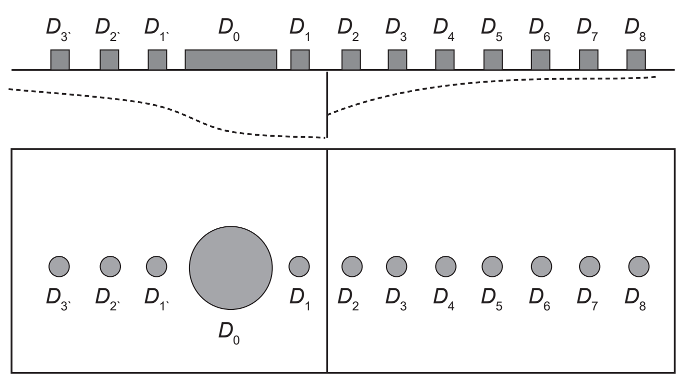

Fig. 8. Schematic diagram of *LTE* measurement

LTE is calculated from relationship (3):

$$LTE = D_2 / D_1, \tag{3}$$

where:

D_2 – deflection under geophone 2, load-free slab,

D_1 – deflection under geophone 1, loaded slab.

Fig. 9 is a graph showing examples of dowelled concrete slab modules in the A4 highway. The slabs did not show structural damage. The modules for the dowelled pavement are above 35,000 MPa. The tests were performed annually over a period of two years after the highway was open to traffic. The RPCD system classified the pavement as category A.

Fig. 10 shows the results of module tests on the pavement comprising cracked slabs on the A18 highway. The RPCD system classified the pavement as category D. The modules did not exceed 14,000 MPa.

Fig. 11 shows the *LTE* test results for the pavement on the A4 highway. The results are presented for a two-year period. The tests were performed two years after the pavement was constructed. The observed *LTE* is not lower than 0.8. The RPCD system classified the pavement as category A.

Fig. 12 shows *LTE* values identified on the A18 highway. The pavement is not dowelled. The observed *LTE* coefficient varies from 0.2 to 0.5.

The test results indicate that the slab modules have varying values. The values are significantly lower for cracked slabs. Analogically, the *LTE* coefficient for slabs without dowels in the joints is below 0.5, and for slabs with dowels it is approximately 0.8.

Subsequent numerical calculations allowed the defining of conditions for the reinforcing and recycling the concrete pavement depending on the slab engagement expressed as *LTE*.

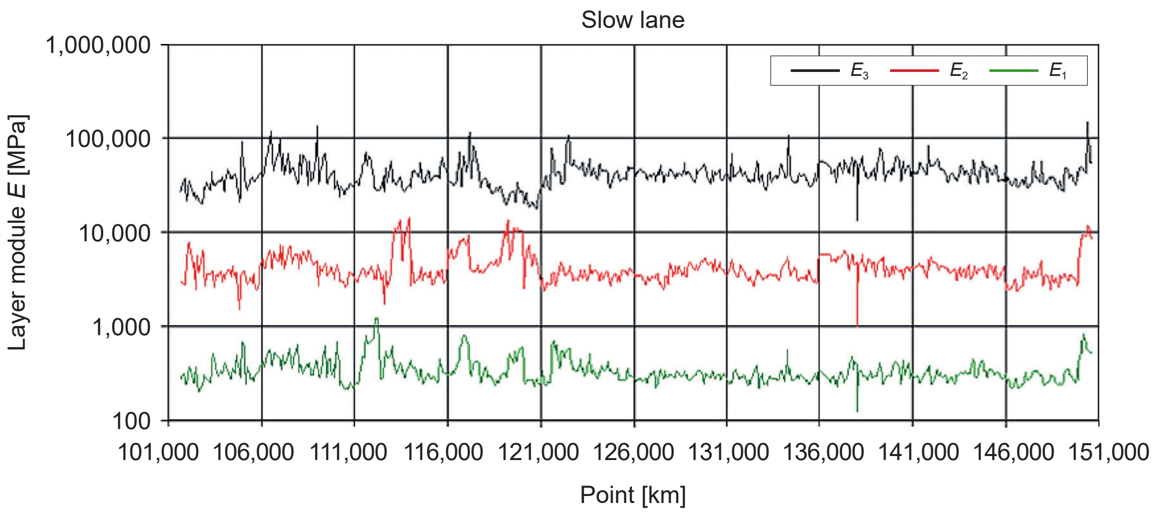

Fig. 9. Identification of layer modules for dowelled concrete pavement in highway A4; (E_3 – concrete pavement module, first curve from the top)

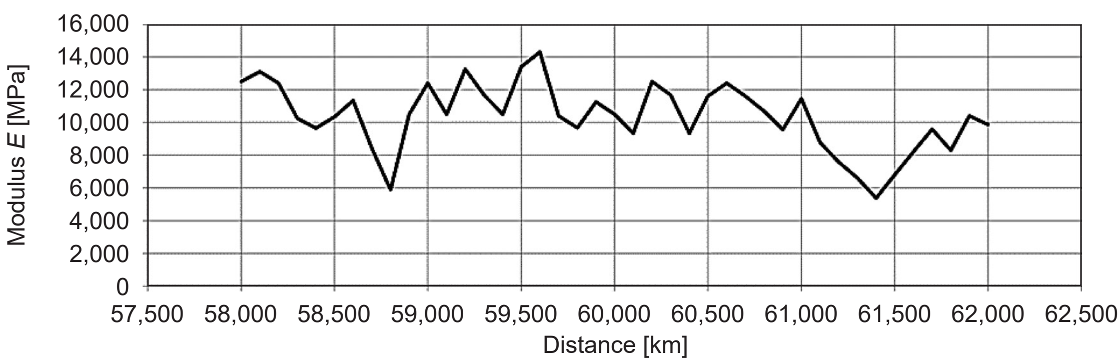

Fig. 10. Modules identified for concrete slabs in highway A18

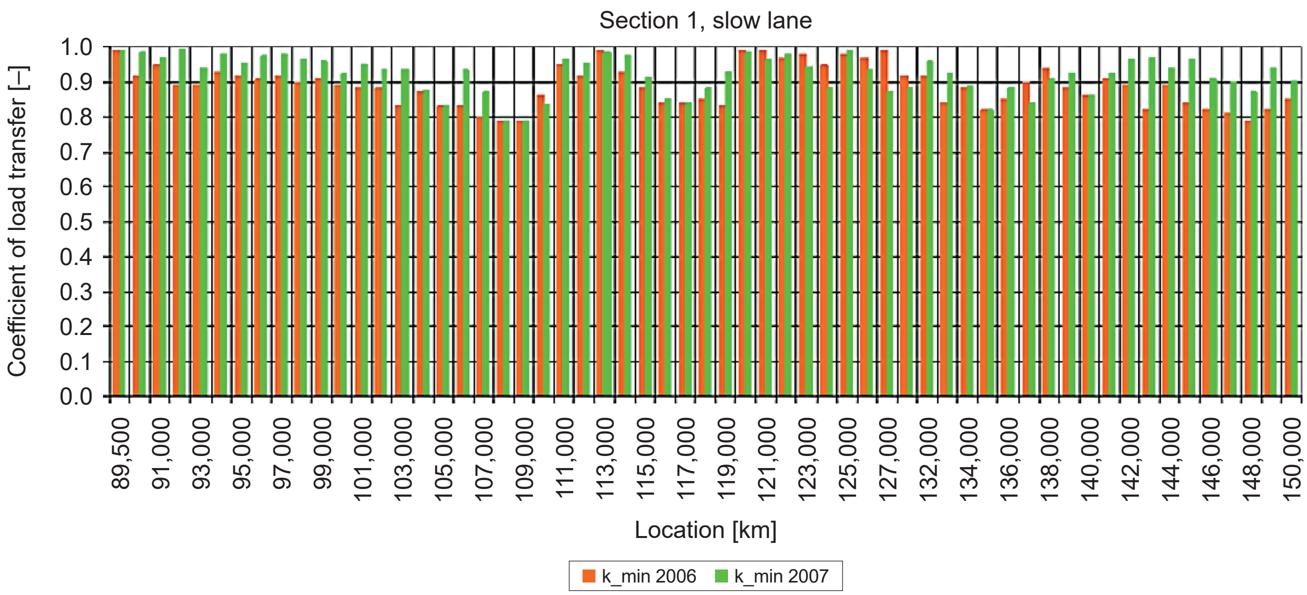

Fig. 11. *LTE* values identified on highway A4

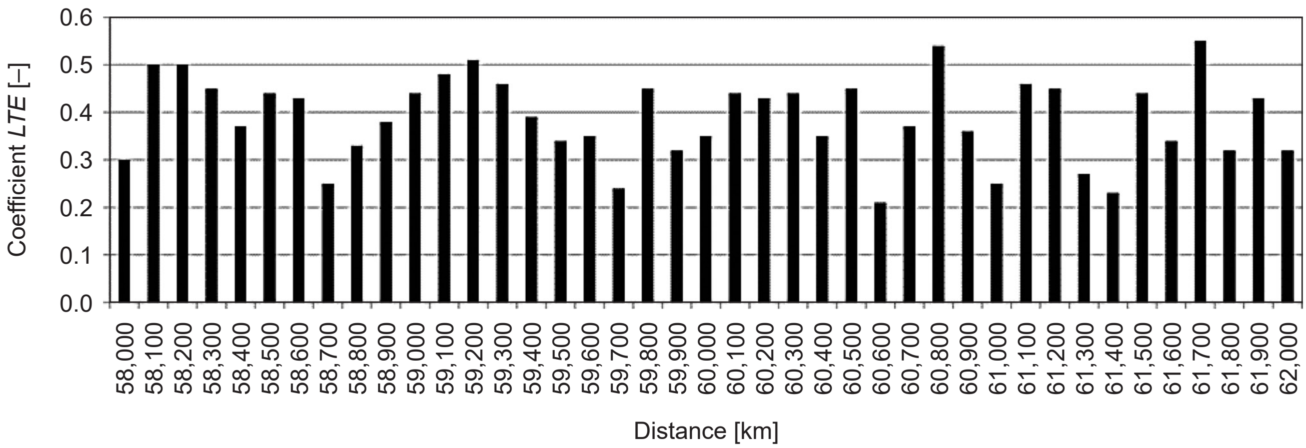

Fig. 12. *LTE* test results for the pavement on the A18 highway

The calculations included the reinforcement of the existing undowelled concrete pavement with a module of 20,000 MPa, a thickness of 20 cm, and a varying (40%-95%) *LTE* coefficient. As regards the reinforcement, the new concrete slab layer with a module of 35,000 MPa was allowed for with three slab thicknesses: 20, 25, 30 cm.

The calculations were performed with the finite element method. The concrete pavement model was developed in a three-dimension xyz coordinate system (Fig. 13). The calculations were performed for an assumed linear elastic model and for the slab size of 4.0 × 5.0 m. In the assumed conditions, the existing and the new slab were allowed to slide against each other on a layer of asphalt concrete having a module of 10,000 MPa and a thickness of 6 cm. The assumed load had a field of 28 × 31 cm and a force of 57.5 kN. It was located above the joint in the concrete slab and in the sliding layer. An additional allowance was made for the influence of a positive temperature difference of 12°C. The analysis included the concentrated load state in the new concrete slab under the existing joint.

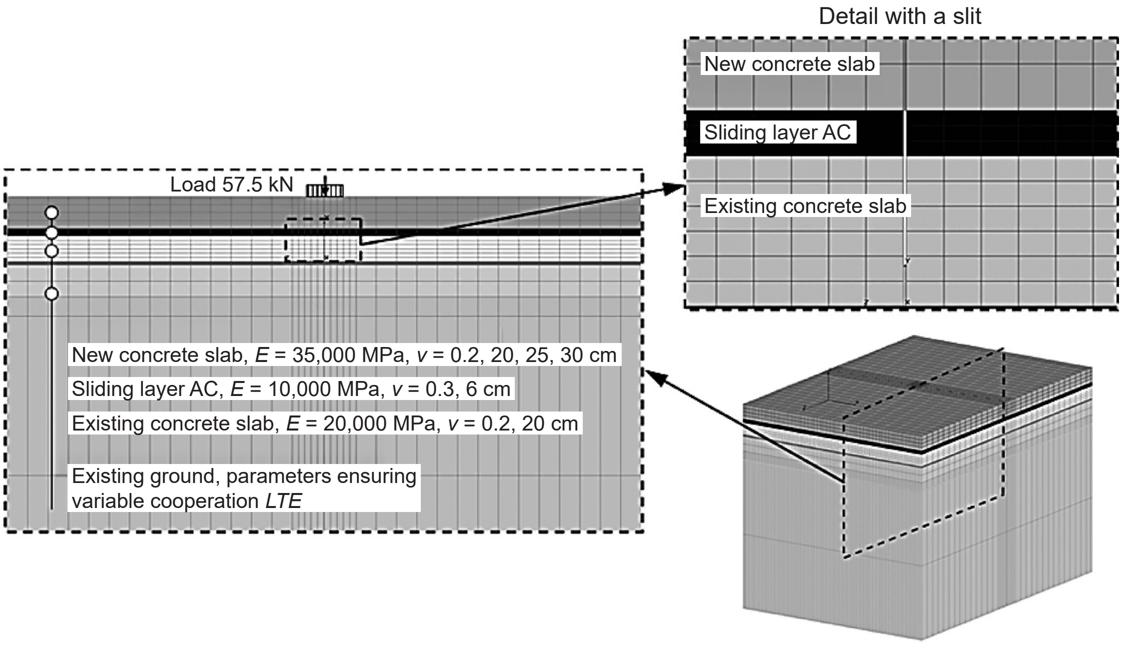

Fig. 13. Pavement model for slab engagement analysis

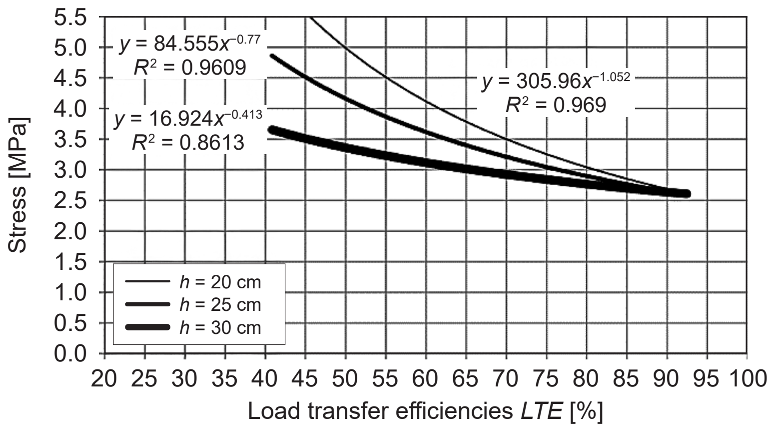

Fig. 14. Tensile stresses SZ for different slab thicknesses depending on the *LTE* coefficient

Fig. 14 shows the calculated tensile stresses SZ for different slab thicknesses depending on the *LTE* coefficient.

It was observed that 20 cm thick slabs resting on a pavement having a 45% *LTE* coefficient are prone to reflection cracking due to significant stress values which exceed the tensile strength. Regardless of the slab thickness, low stress values at *LTE* approx. 95% provide a sufficient margin of tensile strength (half of the value). By calculating stress values depending on the slab thickness relative to *LTE* and by allowing for the fatigue criteria for concrete pavements, it was possible to find the fatigue life of the pavement (Fig. 15).

The analyzed relationship between fatigue life and *LTE* allows a conclusion that the required fatigue life can be ensured for the KR7 traffic category (>38 million of 115 kN axle loads) at *LTE* = 75% and with a 30 cm thick reinforcement. Reinforcements 25 and 20 cm in thickness allow the 38 million of 115 kN axle load criterion to be met at LTEs 82% and 86%, respectively. However, in the case of *LTE* = 65% and with a 30 cm thick reinforcement, the achievable fatigue life is 16 million, which corresponds to category KR5. In order to ensure an identical life with 25 cm thick reinforcement, the existing pavement would need to have *LTE* = 75%, and with 20 cm reinforcement – *LTE* = 80%.

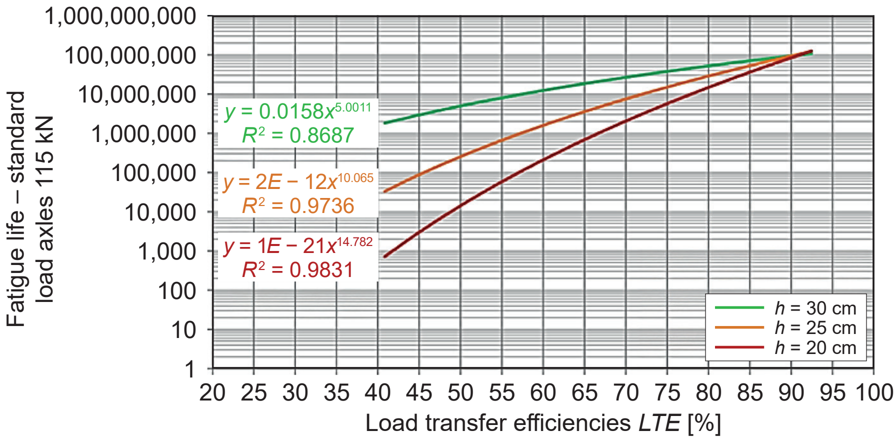

Fig. 15. Fatigue life of reinforced pavement for different slab thicknesses depending on *LTE*

The above results demonstrate that depending on the required service-life for roads of higher technical categories it is necessary to recycle the existing concrete pavement if the *LTE* is below 65%. In such conditions, the achievable life will be on the level of at least category KR5.

The existing pavements with *LTE*s above 85% may require reinforcement of minimum thickness depending on the module, so as to ensure the highest durability, on the level of Polish traffic intensity category KR7.

The analyses and tests performed on the roads discussed above as well as on other concrete roads and pavements, have allowed the following criteria which aid the assessment and qualification of the pavement for *in situ* recycling.

Owing to the above analyses, concrete pavement modules and *LTE* have been assigned limit values which may serve as an indicator for deciding between reinforcing or recycling such concrete pavements. Importantly, *LTE* is here viewed as the decisive parameter. Based on the identified modules *E* and coefficients *LTE*, the criteria for concrete pavement reinforcement or recycling are thus as follows:

a) if *LTE* is greater than or equal to 0.8 (80%) and if the concrete slab modules are greater than or equal to 30,000 MPa, corresponding to the RPCD class A/B, the concrete pavement can remain in service;
b) if *LTE* is greater than or equal to 0.8 (80%) and if the concrete slab modules are below 30,000 MPa, corresponding to the RPCD class C/D, reinforcement is possible depending on the slab condition;
c) if *LTE* is within the range $0.65 \leq LTE \leq 0.8$ and if the concrete slab modules are above 10,000 MPa, corresponding to the RPCD class A/B/C, limited fatigue-life reinforcement is possible due to reflection cracks within the joints;
d) if *LTE* is below 0.65 and if the concrete slab modules are below 30,000 MPa, corresponding to the RPCD class C/D, the slabs should be recycled;
e) if *LTE* is below 0.65 and if the concrete slab modules are above 30,000 MPa, corresponding to the RPCD class B/C, the slabs should be recycled.

The proposed criteria can be included in the RPCD system as an aid in the decision-making process regarding the *in situ* recycling of concrete pavements. The current version of the RPCD system does not include such information.

4. METHODS FOR *IN SITU* RECYCLING OF CONCRETE PAVEMENTS

4.1. *IN SITU* RECYCLING TECHNOLOGY

The previous section focused on the recyclability criteria based on selected pavement parameters, i.e. on layer modules and on *LTE* in joints. This section describes the technology for the *in situ* recycling of concrete pavements. The idea behind *in situ* recycling is to break (destress) concrete pavement in order to eliminate reflection cracks after the reinforcement procedure. It is also required to ensure an adequate load-bearing capacity of such a crushed layer. Nowadays, there are practically two methods employed worldwide for the *in situ* recycling of concrete pavements. Both were developed in the USA in the early 1990s [9].

They are the high-impact drop hammer method and the resonant method, both described in detail below (Fig. 16).

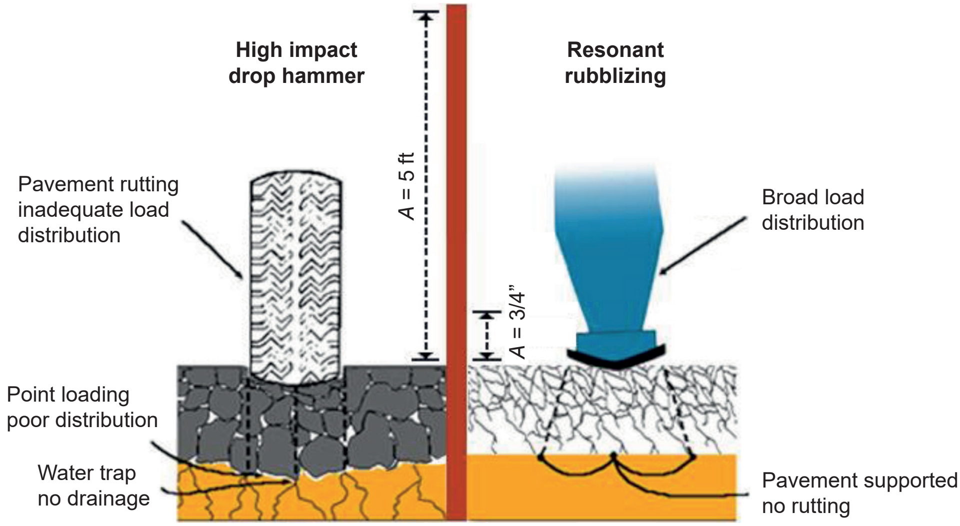

Fig. 16. Concrete pavement destressing (breaking) methods 0 [9]

The experiences gathered on the two methods in the USA are described in 0 and in 0. The numerical and analytical models of defects occurring in concrete subjected to dynamic loads are shown in 0.

The description below presents two *in situ* recycling methods:

- multi-head breaker (MHB), shown in Fig. 17, and
- resonant pavement breaker (RPB), shown in Fig. 18.

American experiences indicate that both rehabilitation methods are highly effective and obviously generate significant savings in comparison to a scenario with complete replacement of cement concrete overlay.

4.2. MULTI-HEAD BREAKER (MHB)

The multi-head breaker (MHB) method (Fig. 17) consists in the mechanical crushing of the pavement with the use of typically 12 to 16 hammers 500-900 kg in weight, which impact the pavement from a set height of 0.3-1.5 m. This method allows stress to be relieved from a strip 0.8-3.5 m in width, depending on the number of hammers. With the use of MHB, it is possible to crush 1.6 running kilometer of pavement per day (or 3.5 running kilometers if the pavement is crushed into large blocks).

This method proves particularly useful in crushing concrete pavements 18-40 cm in thickness. One machine has an efficiency that is sufficient to unstress and crush up to 10,000 m^2 per shift. Concrete is broken/crushed with the use of steel hammers which are lifted upwards and allowed to fall freely from a height adjusted to a maximum of 1.5 m. The hammers are 20 cm in thickness and are arranged in two diagonally shifted rows. The hammer from the first row is in a pair with the hammer from the second row. Each pair is lifted to an individually adjusted height. Depending on the lift height, the frequency varies in the range of 30-35 impacts per minute. The crushing energy is controlled by adjusting the vehicle speed, the hammer height and the hammer mass.

Fig. 17. Multi-head breaker 0 [13]

The MHB method allows two rubblization technologies: full and modified 0. They differ in the size of the final lumps of crushed concrete. In the first case, concrete is crushed in a uniform manner across the entire width of the roadway into grains/lumps no larger than 310 mm. At the same time, at least 75% of the grains is no larger than 0:

- 230 mm in the lower half of the slab,
- 75 mm in the upper half of the slab,
- 50 mm on the surface of the slab.

The size of the crushed lumps translates into the rigidity of the obtained layer: the greater the size, the higher the effective modulus of rigidity, but also the higher the risk of reflection cracks. Larger pieces of the crushed slabs, 30-45 cm in size, are advantageous in the case of inadequate load-bearing capacity of the subgrade. In such case, modified rubblization is preferred, as it requires less energy to crush concrete and obtain a load-bearing base course for new asphalt layers. Rubblization technologies 0 are considered an adequate solution when the concrete pavement has reached its service life, i.e. when vertical displacements are observed between the slabs.

4.3. THE RESONANT PAVEMENT BREAKER (RPB) METHOD

The resonant pavement breaker (RPB) method, shown in Fig. 18, originated in 1980s as a preparatory means for the removal of cement concrete. It was first used to destress concrete pavement prior to preparing a reinforcement overlay in New York in 1986 [1]. It consists in crushing the pavement with the use of a resonant beam which vibrates at a frequency of 44 Hz and is finished with a foot which has a width of 23 cm and a mass of 900 km. The low vibration amplitude (12.5-25 mm, typically 20 mm) prevents the degradation of lower pavement and subgrade structure layers or the damage of underground infrastructure. At the same time, the grain size of the crushed concrete is more uniform in RPB than in MHB. The pass speed of 6-8 km/h and the limited width of the weighing foot allow 5000 m^2 of pavement to be broken into fractions <50 mm during one work day.

In the RPB method, pavement is crushed using a single hammer with a high impact frequency of 44 Hz. The amplitude of the hammer may be up to 20 mm, and the crushing depth reaches 60 cm. The weight of the hammer is 4,080 kg, and the crushing surface is 20.3 cm. The working speed of the machine is within the range of 6-13 km/h, and the noise level is below 90 dB. The surface of the crushed pavement is even and optionally requires two or three passes of a roller. Due to the high hammer frequency and low amplitude, cement-bound base is not damaged during the rubblization process, and the vibration does not affect the installations and buildings located near the road. Therefore, RPB is particularly advantageous in the case of rubblizing concrete street pavements.

Fig. 18. Resonant pavement breaker; photo by the author

Fig. 19 shows pavement broken with a resonant pavement breaker.

Fig. 19. Broken pavement; photo by the author

The two above-presented methods allow *in situ* breaking of degraded pavements and their usage as base courses in the construction of new pavements. The methods can be employed in the case when the subgrade under the recycled slabs is freeze-resistant and load-bearing. In the other case, the layers recycled *in situ* can be used as subgrade reinforcement.

5. SUMMARY AND CONCLUSIONS

This article proposes assessment criteria for concrete pavement recyclability. Based on the considerations carried out, the following conclusions were drawn:

1. The current Polish RPCD system does not allow assessment of concrete pavements in terms of reinforcement needs or recycling potential.
2. New assessment criteria are proposed, based on evaluating concrete slab modulus *E* and joint load-transfer efficiency *LTE*.
3. These criteria were tested on concrete pavements used in the Polish national road network and can be incorporated into the RPCD system.
4. Defined value ranges for *E* and *LTE* support classification of pavements for continued service, reinforcement, or recycling.
5. Deteriorated concrete pavements can be recycled using two methods:
   - Option 1 – to disassemble the pavement, crush the material in stationary crushers, and use the material in different layers of the pavement structure. The material can be used as aggregate not improved with binding agents, or as aggregate improved with hydraulic, asphalt or other binders;
   - Option 2 – in this case recycling can be performed *in situ*, and the broken material can be compacted and shaped, and then used as a base course or a subgrade reinforcement layer. Option 2 is more economical and significantly reduces the construction time.

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Recykling nawierzchni betonowych – kryteria oceny nośności

Streszczenie: W artykule przedstawiono zarys rozwoju nawierzchni betonowych w kraju oraz doświadczenia zdobyte w zakresie recyklingu tych nawierzchni, które zostały wybudowane w latach trzydziestych ubiegłego wieku. Zaprezentowano typowe uszkodzenia nawierzchni betonowych oraz scharakteryzowano metodę oceny powyższych uszkodzeń z wykorzystaniem systemu Diagnostyki Stanu Nawierzchni funkcjonującego w Generalnej Dyrekcji Dróg Krajowych i Autostrad. Stwierdzono, że brak jest w tym systemie kryteriów oceny nawierzchni betonowych pod kątem przydatności do technologii recyklingu. Wykorzystując badania wykonane na istniejących nawierzchniach betonowych oraz analizy numeryczne rozkładu naprężeń w obrębie szczelin nawierzchni zaproponowano kryteria oceny nawierzchni pod kątem przydatności do wdrożenia technologii recyklingu. Tymi kryteriami są moduły płyt nawierzchni oraz współczynniki współpracy płyt na szczelinach. Zaprezentowano metody recyklingu nawierzchni betonowych in situ i wykorzystanie recyklowanego materiału jako podbudowy nowych nawierzchni betonowych bądź podatnych.

Słowa kluczowe: diagnostyka stanu nawierzchni, kryteria oceny nośności, nawierzchnie betonowe, recykling.