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Assessment of the load-bearing capacity of the state road pavement structure

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Subject review

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For the management system of modern pavements, data on the condition of the bearing capacity of the pavement, which refer to its condition during exploitation and at the end of the project period, are necessary. After the end of the project period of 20 years, it is necessary to plan reconstruction or strengthening of the pavement structure based on the parameters of the bearing capacity of the pavement. The data of the projected pavement layer thickness structures and those determined after 20 years of exploitation on samples from boreholes were compared. An example is the section of the state road D28, the northern bypass of Bjelovar, which was built and put into traffic in 2002. The deflection results of the measured falling weight deflectometer (FWD) on the subsections of the pavement, which were determined to be the most critical by visual inspection, were analysed. Based on the results of the calculated modulus of elasticity, the pavement structure was dimensioned by performing an additional cold recycled base layer with foamed bitumen. The importance of the pavement management procedure was emphasized on the example of the state road, as well as the delay in strengthening the pavement structure because the project period of 20 years has passed.

Key words:
pavement management system, asphalt pavement reinforcement, pavement structure layer thickness, deflection, modulus of elasticity

Pregledni rad

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Ocjena stanja nosivosti kolničke konstrukcije državne ceste

Za sustav gospodarenja suvremenim kolnicima neophodni su podaci o stanju nosivosti kolnika koji se odnose na njegovo stanje tijekom eksploatacije i na kraju projektnog perioda. Nakon isteka projektnog razdoblja od 20 godina potrebno je donijeti odluku o rekonstrukciji ili ojačanju kolničke konstrukcije na temelju parametara o stanju nosivosti kolnika. Na primjeru dionice državne ceste D28, sjeverne bjelovarske obilaznice koja je izgrađena i puštena u promet 2002., uspoređeni su podaci projektiranih debljina slojeva kolničke konstrukcije i onih koji su nakon 20 godina eksploatacije utvrđeni na uzorcima iz sondažnih jama. Analizirani su rezultati defleksije izmjereni uređajem s padajućim teretom (FWD) na poddionicama kolnika koje su vizualnim pregledom utvrđene kao najkritičnije. Na temelju rezultata proračunanog modula elastičnosti kolnička konstrukcija dimenzionirana je izvođenjem dodatnoga nosivog sloja od hladno reciklirane mješavine s upjenjenim bitumenom. Na primjeru državne ceste D28 istaknuta je važnost pravodobnog poduzimanja odgovarajućih mjera održavanja te su opisane uočene posljedice kašnjenja u ojačanju kolničke konstrukcije jer je prošao projektni period od 20 godina.

Ključne riječi:
sustav gospodarenja kolnicima, ojačanje asfaltnoga kolnika, debljina slojeva kolničke konstrukcije, defleksija, modul elastičnosti

1. Introduction

A pavement management system is a system that includes the identification of optimal strategies at individual management levels in maintaining pavements in appropriate condition, which includes systematic maintenance and rehabilitation activities based on optimizing benefits and costs [1].

In order for a pavement to maintain adequate load-bearing capacity and surface properties which primarily enable safe and comfortable driving during its design service life, it is necessary to regularly implement simpler or more complex pavement maintenance measures.

The lifespan of a pavement can be extended if it is systematically maintained in a timely manner before major damage occurs [2]. The closer a pavement approaches the end of its design service life, the greater the possibility that significant damage will occur to its surface due to traffic loads and environmental climatic influences. Damage on the pavement surface can have various causes and these causes must be reliably determined before undertaking any repairs. The visible surface appearance of the problem does not necessarily automatically point to the correct solution. In other words, if we want the rehabilitation of the road surface to be successful, it is necessary to analyze the behavior, determine the possible causes of such pavement behavior and find the real cause of the problem. Correctly detecting pavement damage and determining the cause of the damage is of key importance for selecting appropriate maintenance measures and strategies. In addition, it is important to know that different types of pavement do not deteriorate at the same rate. The deterioration of the pavement will be affected by various factors such as traffic loads, weather conditions, materials and thickness of the layers of the pavement structure, but also the quality of execution and the effectiveness of previous maintenance measures. It can be said that the rate of pavement deterioration increases in parallel with the intensity of its use and with the age of the pavement [3], and it is particularly important to recognize and define the right time to undertake appropriate maintenance measures.

All pavement maintenance activities must be carried out in a planned and systematic manner in order to ensure satisfactory driving safety and comfort.

It is important to monitor and know the condition of the pavement, both structurally and functionally, from the time the road is opened to traffic to the time the pavement is inspected. While functional condition assessment provides information on surface properties that directly affect the safety and comfort of users or the usability, the structural assessment of the condition provides information on whether the pavement structure behaves satisfactorily under the influence of traffic and environmental conditions. Data on the condition of the pavement can be collected in various ways: by visual inspection of the pavement condition, non-destructive or destructive testing. Visual inspection can be carried out in several ways, ranging from that performed on foot to modern automated data collection methods [4], and it is extremely important to choose an objective and repeatable visual classification procedure for the condition of the pavement. Non-destructive testing includes methods for assessing the condition of pavement that do not damage the pavement in any way and are therefore more popular than destructive methods used to assess the condition of pavements, such as coring, drilling and excavation of test pits. Numerous authors [5-18] have reported on non-destructive methods for testing pavement structures, their specific characteristics and the possibilities of using several non-destructive methods in parallel to complement each other or to obtain a more complete picture of the load-bearing capacity of the pavement structure.

An important indicator of the structural load-bearing capacity of a pavement is deflection, which represents the elastic deformation of the pavement structure. The magnitude of deflection can be determined theoretically, using the principles of the theory of elasticity and knowledge of the properties of the pavement material, or empirically, by measuring the elastic deformation generated by a known static or dynamic load on the pavement surface. Deflection can be determined using various devices, but the most common device used for this purpose is the falling weight device (FWD). The dynamic load simulates the magnitude and duration of the load transmitted through the vehicle wheels using a series of geophones – sensors for measuring deflection, and the pavement response is measured in the form of vertical deformation or deflection at different distances from the point of transmission of the impulse load [4]. Based on the determined deformations, the elastic moduli of individual layers of the pavement structure can be calculated, or conclusions can be drawn about the service life of the pavement structure [5-7].

The procedure for testing with the falling weight device has been established for years and is specified in national regulations. However, the evaluation methods used may differ from country to country [7-14]. Thus, the German regulations (AP Trag) provide two options for analyzing the results of measurements with a falling weight device: a geometry-based assessment method and a mechanistic-based approach known as the Darmstadt FWD assessment method [7]. As *Čičković* and Bald [8] point out, this method can predict the quality of interlayer bonding between the asphalt layers.

Qian et al. [9] used the falling weight device as a comparative method for determining the bearing capacity of asphalt pavement structures of different compositions on a test section. Temperature sensors were installed in each of the layers of the pavement structure. They compared the values of dynamic moduli obtained in the laboratory and the dynamic moduli obtained by measuring deflections on the test section and found that the ratio of dynamic moduli for different asphalt pavements ranged from 0.7 to 0.9. As described in the study [10], the falling weight device was used to collect data on the bearing capacity of a highway in Japan. The highway manager stored the collected data digitally, statistically continuously, and created behavior models and forecasts of the deterioration of the highway pavement bearing capacity. This study also processes the statistically estimated remaining service life of the pavement structure, considers different pavement types and recorded repairs, which are then used to make decisions on the development of repair and rehabilitation projects.

In their paper, Karbočius and Vaitkus [11] described a study using the falling weight device (FWD) conducted in Lithuania on low-volume road pavements. Nine low-volume road sections with typical asphalt pavement structures were selected to demonstrate the effectiveness of the structural condition assessment methodology used in Lithuania. The selected sections were divided into three groups according to the condition of the pavement: sections in good condition, sections in moderate condition and sections with severe pavement damage (alligator cracks, ruts). The analysis showed the applicability of this methodology on low-volume roads, however, it also showed a dispersion of results. In conclusion, the authors emphasized that a larger number of representative road sections constructed with different materials should be included and the actual thickness of the pavement layers should be determined in detail using GPR and destructive testing.

The results of the comparative application of two non-destructive methods, the falling weight device (FWD) and the ground penetrating radar (GPR), in the assessment of the bearing capacity of asphalt highway pavements were reported by Marecos et al. [12]. Structural models were established based on the deflection obtained from the FWD test, the designed layer thickness and the GPR measurements of layer thickness. The elastic moduli of the layers were determined based on the deflections, using a back-calculation procedure. The results showed that the variability of the layer thickness was large and therefore the main focus was on the sensitivity of the elastic modulus values to the layer thicknesses. It was found that the thickness of the asphalt binder courses had a major impact on the estimated elastic moduli of the asphalt layers. The importance of using GPR for continuous layer thickness estimation in conjunction with the falling weight device (FWD) for accurate structural assessment of existing pavements was emphasized. A similar study using the same two non-destructive methods GPR and FWD on three roads in New Mexico was conducted by Ahmed and Tarefder [13]. It was observed that the thickness of the asphalt layer determined by the GPR was more consistent than the thickness of the pavement structure base layer. The FWD test was also conducted at the same locations, and like the GPR, the results of back-calculation of elastic moduli showed inconsistencies in the different layers of the pavement structure. The layer thicknesses and elastic moduli were used as input parameters in the computer program used to determine traffic-related damage such as reflective cracking and rutting. The authors recommended implementing this methodology using GPR- and FWD-based pavement quality assessment at the level of individual projects as well as the entire network. The GPR and FWD methods are not exclusively used for assessing the load-bearing capacity of asphalt pavements as described so far, but also for concrete pavements. Thus, Zhao et al. [15] described the assessment of the structural condition and fatigue stress analysis of cement concrete pavements using ground penetrating radar (GPR) and falling weight device (FWD).

Liu et al. [16] described the implementation of pavement deformation analysis to calculate key mechanical index values under different operating conditions and predict the fatigue life of asphalt and bearing layers. Subsequently, ground penetrating radar (GPR) was used to quantitatively define the pavement structure condition index. The results of the study confirmed that there was a positive correlation between the internal pavement condition index (IPCI) and the remaining pavement structure life.

Regardless of the applied method or device for determining the pavement condition, all authors emphasize the importance of complete and relevant load-bearing capacity data to gain understanding of the pavement structure condition and the selection of the correct reinforcement solution.

This paper analyzes the condition of the pavement of the Bjelovar northern bypass, the 8.6-kilometer-long section of the state road D28 Predavac-Letičani. This section bypasses the center of the city of Bjelovar and is, in a broader sense, part of the road route from Zagreb to Osijek. The aforementioned section was opened to traffic in 2002. At the time of the field investigation and deflection tests, the designed life span of 20 years was at the very end, and measurements and tests were carried out to assess the condition, or rather, to propose strengthening or reconstruction of the pavement structure. Although the Main Design for the Pavement Rehabilitation was prepared in 2020, due to financial aspects, the constructions are expected to begin in 2025 at the earliest. Given the importance of the data on the basis of which the functional and structural condition of the pavement is determined, the following paper will briefly describe the methods of data collection and, in particular, the non-destructive method using the falling weight device (FWD) that was used to analyze the pavement condition of the Bjelovar northern bypass.

2. Data collection for the pavement condition assessment

Structural pavement condition assessment is used to determine the ability of a pavement structure to support and transmit traffic loads and requires detailed data on the thickness of the pavement layers, the properties of the embedded materials, the condition of the subgrade and the traffic load. When deciding to collect data on road pavements, it is necessary to collect precisely defined data with a high level of detail sufficient for an appropriate decision [19]. There are several reasons and several methods for structural pavement condition assessment. When determining the requirement for the structural capacity of a pavement, it is first necessary to monitor and measure the characteristics of the road surface. This involves analyzing the results obtained, whether it is a theoretical or empirical analysis, in order to be able to assess the load-bearing capacity of the pavement structure and the pavement service life under expected traffic conditions [20].

The integration of pavement databases with other elements of the road system is facilitated by the use of widely used referencing and relational database technologies such as geographic information systems (GIS). Given the spatial component of road infrastructure data, GIS is an ideal solution for managing road databases, as a basis for decision-making and pavement management [21]. Pavement condition data can be collected by visual inspection and/or measuring equipment, or automatically by specially equipped vehicles. When collecting visual data, so-called pavement distresses catalogues are usually used to properly classify damage and to ensure that the pavement condition assessment process is consistent in all circumstances [22]. The necessary data are the following:

- traffic data: traffic load measured for higher-ranking roads, or typically assumed for lower-ranking roads if accurate data is not available (axle counter),
- year of construction or major rehabilitation,
- number, type and width of traffic lanes,
- structure of the pavement (types and thicknesses of layers).

2.1. Visual inspection

During the visual inspection of a road, various damages and deformations are detected, recorded in the distresses catalogue, and repaired depending on the severity of the damage. Visual inspection is a simple method of pavement inspection that requires careful and systematic data collection on the condition of the pavement. It is necessary in order to determine the cause of the observed damage and identify a possible solution. However, a drawback of this method is the subjectivity of the person conducting the inspection [25]. Typical damage to the pavement structure primarily includes cracks, deformations and surface deterioration. Each type of damage manifests differently on the pavement surface. Cracks in the pavement are a common issue that arises during road usage. Depending on the direction and causes, the cracks are categorized as longitudinal cracks, transverse cracks, alligator cracks, and block cracks [26].

2.2. Pavement condition testing methods

Pavement condition testing methods are classified as destructive and non-destructive. The destructive method is one that involves core extraction from the pavement, excavating test pits, and sampling and laboratory testing of the material for complete testing of each layer. Many effective pavement condition testing techniques involve measuring deflections in combination with drilling small cores (Ø100mm) to obtain thicknesses and material samples for basic laboratory testing. These are considered non-destructive testing methods because no major physical damage to the pavement occurs [20], but more precisely, this is a combined method.

2.2.1. Destructive methods of pavement condition assessment

Although pavement condition can be assessed by measuring surface irregularities or defects, it is sometimes necessary to remove sections of the pavement structure to determine the location and cause of the problems. The term "destructive methods" refers to testing techniques that disturb the original structure of the pavement for future testing at that specific location. Such methods are generally used for pavements exhibiting surface irregularities. The techniques employed in this approach depend on the required data but typically involve cutting a single pavement layer and extracting a sample for laboratory testing. The actual cross-section of each layer of a flexible pavement structure can then be analyzed to assess its behavior and the overall functioning of the system [20]. Destructive methods involve coring or drilling test pits in the pavement structure to determine the composition and thickness of the layers. However, a drawback of these methods is that they are point-based and, therefore, provide only an approximation [24].

2.2.2. Non-destructive methods of pavement condition assessment – falling weight deflectometer (FWD)

As noted by the authors [6], the assessing pavement structural capacity is a challenge for every engineer. Measurements are conducted using various devices, ranging from beams to falling weight deflectometers. However, regardless of the device or measurement method used, pavement structural properties are determined indirectly by measuring pavement deflection.

As previously mentioned, non-destructive testing refers to methods of assessing pavement condition without causing any damage, making them more popular than destructive methods. Deflection results can be used to calculate the structural load-bearing index, which is integrated into the pavement management system to predict the remaining life of the pavement and to determine the need for pavement reinforcement or rehabilitation [27]. Deflection measurement techniques are well-established methods for assessing pavement load-bearing capacity. Compared to destructive methods, they offer advantages such as lower cost, minimal traffic disruption, reduced pavement damage and the ability to conduct a sufficient number of measurements to quantify variability. It is a widely accepted principle that the load-bearing capacity of pavement structure is inversely proportional to deflection – the deformation of the pavement surface under a given load. In a properly designed and constructed structure, deflection is minimal and exhibits an almost elastic response, i.e. after unloading, the surface returns to its original, nearly undeformed shape. In weak, deteriorated pavements, deflection under load is significantly higher, and after unloading, only a portion of the deformation is recovered (elastic deflection) while the remaining deformation is permanent (plastic deflection) [28]. The falling weight deflectometer (FWD) is one of the most commonly used devices for evaluating and understanding the structural behavior of pavements. Measuring pavement deflection with this device is not an end in itself, but rather one of several methods available for assessing pavement condition. The results should be interpreted to provide meaningful insights into pavement performance. The measured deflections can be used to determine the elastic modulus of different pavement layers, including asphalt layers, binder-stabilized base layers, base layers composed of unbound materials, and the subgrade [29].

The test is based on the principle of dynamic loading and measuring the deflections of the pavement, whether rigid or flexible. The load is applied to the pavement surface using a falling weight, and the deflection results are obtained using sensors placed at a certain distance. The deflection results obtained in this way are used to calculate the stiffness of the pavement and other structural properties such as the modulus of elasticity of the pavement layers. Using the deflection results tested with the falling weight device, it is necessary to calculate the modulus of elasticity using an appropriate method in order to determine the stiffness of the existing layers [30].

There are several factors that affect the magnitude of the measured deflections, making the interpretation of the results difficult. The main factors that affect deflection can be grouped into the following categories: pavement thickness, pavement loading (size and type) and climate (temperature and seasonal influences) [31].

Parameters used as guidelines for assessing the structural condition of individual pavement layers are derived from the deflection curve. These parameters are simple to use and require minimal input data, enabling an efficient and rapid assessment of pavement condition. They serve as basis for further assessment of the strength of individual layers. The most common parameters used are:

- SCI (surface curvature index) represents the difference between the central deflection and the deflection measured at a distance of 30 cm (d30) from the central load. The specified parameter defines the quality of surface asphalt layers;
- BDI (base damage index), represents the difference between the deflection measured at a distance of 30 cm (d30) and the deflection measured at a distance of 60 cm (d60) from the central load. This parameter defines the condition of the lower bearing layers of the pavement, and
- BCI (base curvature index), represents the difference between the deflection measured at a distance of 60 cm (d60) and the deflection measured at a distance of 90 cm (d90) from the central load. The specified parameter defines the condition of the pavement structure subgrade.

The index d0 represents zero deflection, i.e. the deflection measured under the central load [32]. It is recommended to observe the value of the BDI index to distinguish reflective cracks from thermal cracks [33].

In the multilayer elastic model, the pavement structure is considered linearly elastic, with materials characterized by Young's modulus of elasticity (E) and Poisson's ratio (ν). It is assumed that the materials are homogeneous and isotropic, and that the layers extend infinitely in the horizontal direction. Similar to the finite element technique, the accuracy of the output results depends on the precision of the input data. The data required for the calculation include the peak deflections and their locations, peak load values, the number of layers in the pavement structure, and their thicknesses. The purpose of this procedure is to assess the existing structural condition of the pavement by determining the "in situ" modulus of elasticity of all layers of the pavement structure [34].

3. Measuring and testing the condition of state road D28 pavement structure

The 8.6-kilometer-long section of the state road D28 Predavac-Letičani, which is the subject of analysis in this paper, is part of the road route from Zagreb to Osijek and also the northern bypass of the city of Bjelovar. The visual method for determining damage and deformation of the road surface, the non-destructive method for determining deflections (falling weight deflectometer) and field excavations were used to obtain complete data on the condition of the section in question for the selection of an appropriate reinforcement solution. The overview map in Figure 1 shows the position of the state road D28 and the length of the intervention.

3.1. Traffic load

The traffic counters installed provide information on the structure and number of vehicles by vehicle groups on the observed section. The axle counters on the section in question are located in the immediate vicinity of the planned intervention zone (Figure 1). There are two counting points with automatic continuous counting, marked 2102 Predavac (west of the intervention, approximately 350 m from the start of the route) with an average daily annual traffic (ADAT) of 8,883 vehicles and the counting point marked 2140 Kupinovac (east of the intervention, approximately 500 m from the end of the route in question) with an ADAT of 5140 vehicles. In addition to the above, relevant data is also available from the counting point marked 2123, which is located on the county road Ž3300 in Klokočevac, with data on an ADAT of 5402 vehicles (Figure 1).

Figure 1. Overview map of the narrow area of D28 Bjelovar bypass with the locations of traffic counters [35]

Analyzing traffic by vehicle groups, i.e. observing heavy goods vehicles, heavy goods vehicles with trailers and tractors, it can be concluded that transit traffic prevails on the observed section in the direction D10 (Gradec junction) – Sv. Ivan Žabno – Bjelovar – Hampovica – D2 (Đurđevac).

Figure 2. Structural cracks on D28 Bjelovar bypass from km 0+800 to km 2+100

Figure 3. Ruts on D28 Bjelovar bypass from km 2+900 to km 3+300

The input data for dimensioning the reinforcement of the pavement structure from the Predavac counting point was reduced by half, while the traffic values from the counting point in Klokočevac also represent input data and were taken into account in the traffic load analysis for dimensioning the reinforcement of the existing pavement structure [35].

3.2. Visual inspection of the section

A visual inspection of the road surface of the D28 state road and its sub-sections revealed typical damage, including structural cracks, ruts and temperature cracks, as well as localized road surface repairs.

From km 0+800 to km 2+100 on the D28 Bjelovar bypass, structural cracks are prominent, appearing at regular intervals of approximately every ten meters (Figure 2). It is estimated that the primary cause of these structural cracks lies in the cement-stabilized base course, where transverse cracks form during cement hydration. These cracks, influenced by traffic loads and temperature fluctuations, propagate into the upper layers [36].

Ruts are caused by shear failure in the asphalt layer at the wheel track locations (Figure 3). This type of failure is recognized by the ridges that have formed along the depression [37].

Figure 4. Temperature cracks on D28 Bjelovar bypass from km 7+000 to km 7+500

Figure 4 shows a typical example of temperature cracks caused by fatigue in the asphalt layer on the D28 Bjelovar bypass. During the winter months, asphalt concrete tends to shrink due to low temperatures, which, in principle, is not possible. As a result, tensile stresses develop as temperature drops. The magnitude of these stresses depends on the cooling rate and the type of asphalt mixture, particularly the rheological properties of bitumen. If the tensile stress becomes too high, the pavement will crack at the weakest point. Further cooling of the pavement will lead to additional cracking and the widening of existing cracks. Low-temperature cracks are often the primary reason for pavement maintenance, typically addressed by filling the cracks. When a heavy-duty vehicle passes over a crack, high tensile stresses form at the crack edges due to the absence of load transfer. This issue can worsen in the spring when moisture infiltrates the cracks, weakening the base layers. These factors indicate that traffic can accelerate the expansion of existing cracks, even though cracks caused by traffic loads are not the primary issue [37].

During regular pavement maintenance on sections of the D28 road, a new thin asphalt layer was applied to replace the existing worn-out layer of the pavement, which had been degraded by temperature microcracks, driving surface with poor grip and pronounced rutting. However, after applying the new thin asphalt layer in smaller segments to replace the old pavement layer affected by structural cracks, poor longitudinal evenness, and pronounced rutting, the new asphalt driving surface quickly developed deformations identical to those in the underlying layer (Figure 5).

Figure 5. Repairs of local damage to the pavement of D28 Bjelovar bypass from km 5+000 to km 5+500

3.3. Investigation works – field sampling and laboratory tests

3.3.1. Field sampling – test pits

To assess the actual condition of the pavement layers on the analyzed section, investigation works were carried out according to the plan. According to the study [38], test pits were excavated in the outer wheel track at five locations (Figure 6) along the route to determine the type and thickness of the layers. The excavation was conducted down to the subgrade, revealing that the thickness of the asphalt layers ranges from 12.5 to 14.5 cm, while the cement-stabilized layer has an average thickness of 19 cm, varying between 16 and 21 cm. The diagram in Figure 7 shows that the thickness of the mechanically compacted base layer and the subgrade made of stone materials is inconsistent. This leads to the conclusion that the embankment and subgrade are composed of the same gravel material, and the unbound base course (UBC) is also made of gravel.

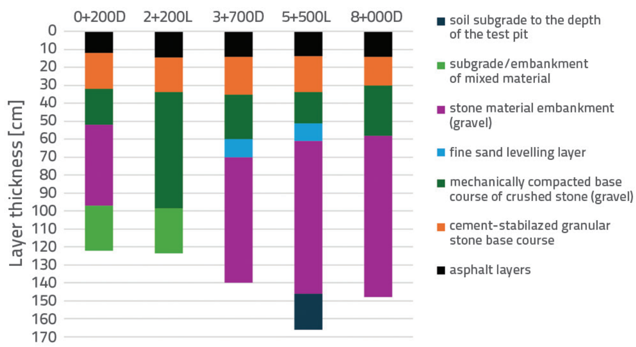

Figure 7. Graph of layer thickness and composition of pavement structure [38]

3.3.2. Laboratory tests

During the excavation of the test pits, samples of the UBC layer were taken to determine the granulometric composition of the granular material and silt content. The material composition should meet the requirements for the degree of grain unevenness, the diameter of the largest grain, the proportion of grains smaller than 0.02 mm, all according to the requirements

Figure 6. Photodocumentation of exploratory drilling on the state road [38]

of the General Technical Conditions for Road Works (GTC) [39]. In order to perform the UBC sampling, it was necessary to remove the asphalt layers and the CBC pavement structures.
In order to determine the optimal moisture content and maximum dry bulk density, a sample of granular stone material extracted from the exploratory pits is compacted using the energy of the modified Proctor method. The result of the test is the optimal moisture content, i.e. the amount of water in the sample that allows for maximum compaction of the material with the specified energy, at which the maximum dry bulk density is obtained. It is important that the installation of granular stone material (of the appropriate granulometry) into the base layer takes place at optimal moisture content. The bearing capacity of the UBC layer is assessed based on the laboratory-determined California Bearing Capacity Index – CBR (California Bearing Capacity Index). CBR is determined on test specimens compacted at optimal moisture according to the HRN EN 13286-47:2012 standard [40].
Based on the test results and the specified conditions from the General Technical Conditions for Road Works (GTC), a conclusion is made on the suitability of each individual layer of the existing pavement structure for its further use [19].

Table 1. Determining the California Bearing Capacity Index of the UBC layer [38]

Penetration [mm]	Referent force [kN]	Standard force [kN]	CBR [%]	Minimum CBR [%] acc. GTC
2.5	11.5	13.2	87.4	80.0
5.0	18.2	20.0	91.0	

Table 2. Analyzed subsections A, B, C and D

Subsection name	Station	Visual inspection	Deflection
A	0+800-2+100	transverse cracks	high
B	2+300-2+900	transverse cracks	low
C	2+900-3+300	ruts	high
D	7+000-7+500	temperature cracks	high

4. Results of measurements and testing D28 pavement construction layers

4.1. Granulometric composition

The granulometric composition of the samples of gravel and stone material was tested and the California Bearing Capacity Index (CBR) of the mechanically compacted layer and the embankment of stone materials was determined.
The granulometric composition test was carried out according to (HRN EN 933-1:2012) [41] and was compared with the limit values according to GTC [39]. The granulometric curve of the mechanically compacted UBC is within the prescribed limit range (Figure 8)..

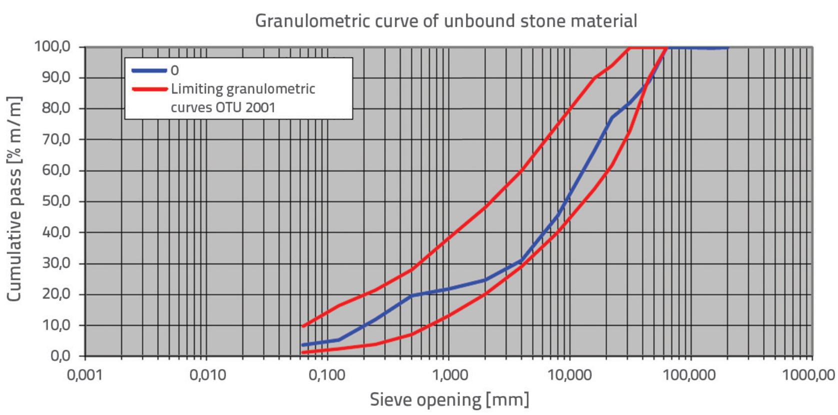

Figure 8. Graphic representation of the UBC granulometric composition, km 2+200 left [38]

4.2. CBR bearing capacity values

The optimum moisture content and maximum dry density according to modified Proctor on two samples of UBC were tested according to HRN EN 13286-2:2013 [42]. The result of the optimum moisture content is 7.7%, and the maximum dry density is 2.24 t/m3. Based on the results obtained, the UBC was determined according to the HRN EN 13286-47:2012 standard [40]. The results met the requirements of the General Technical Conditions for Road Works (Table 1).

4.3. Interpretation of deflection results

A non-destructive deflection test method with a KUAB brand falling weight device (FWD) was used to determine the modulus of elasticity. The test was carried out in the right wheel track for left and right driving directions. The distance of individual measurements in one direction was 100 m, measurements in the opposite direction were offset by 50 m. The sensors were placed at a distance of 20(d1), 30(d2), 45(d3), 60(d4), 90(d5) and 120(d6) cm relative to the central load.
On the D28 Bjelovar bypass, four typical sub-sections were analyzed, where significant damage was visually observed in the form of rutting, temperature and structural cracks, and one section with extremely low deflections (Table 2).
The diagram in Figure 9 shows areas with pronounced high deflection results (km 0+900, 2+050, 3+050, 3+300). Extremely low deflection levels are observed from km 2+300 to km 2+900.
By analyzing subsection A, where transverse or reflective and low-

temperature cracks were observed, using the SCI, BDI and BCI parameters described in (2.2.2), it can be concluded that the parameters are also higher at locations with high deflections (d0 above 160 μm) than in the rest of the observed subsection (Figure 10). The SCI parameter, which is higher than in the rest of the section, indicates the presence of microcracks in the asphalt, which was also visually observed. The microcracks have transferred to other layers, reducing the load-bearing capacity of the pavement structure. On subsection A, the BDI parameter has also increased, meaning that the load-bearing layer has also been weakened, which indicates the possible presence of active cracks that will very quickly reflect on the asphalt layer. It can be concluded that stations with higher deflections (d0 above 160 μm, d2 above 135 μm) are the locations of reflective cracks. Locations of reflective cracks have higher deflection results than those permeated by temperature cracks.

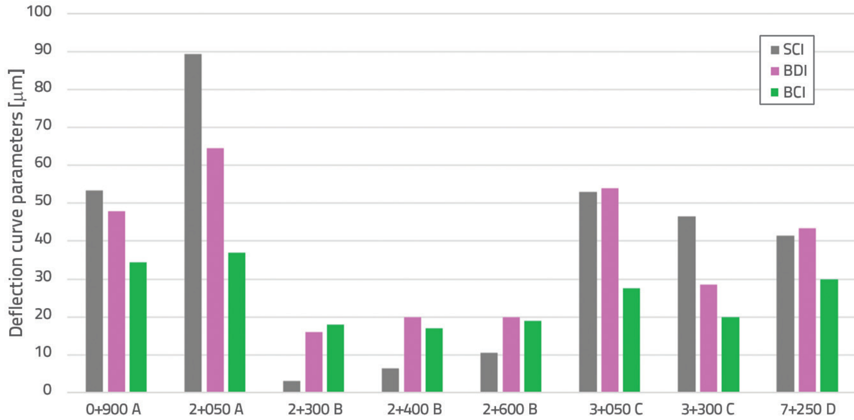

Figure 11. Deflection curve parameters with low and high deflections in analyzed subsections (A, B, C and D)

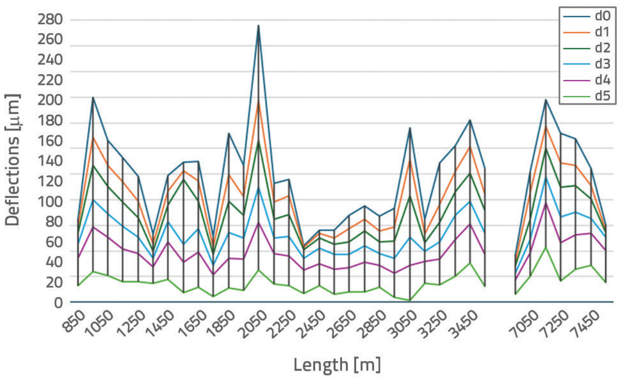

Figure 9. Deflection results, left driving lane, direction Zagreb

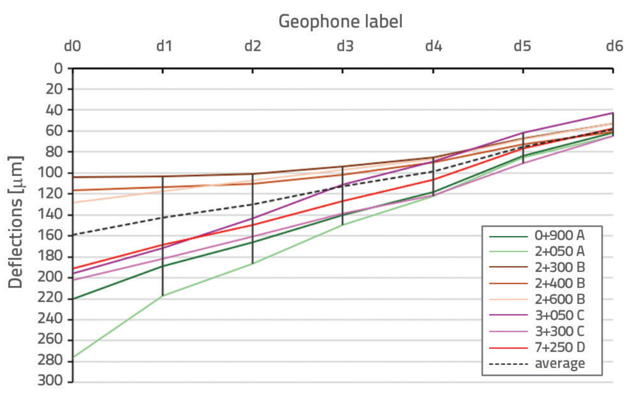

Figure 10. Values of pronounced high and low deflections in analyzed subsections (A, B, C and D)

The parameters on subsection B are extremely low, as are the deflections (d0 below 120 μm, d2 below 105 μm, d4 below 90 μm), with observed transverse cracks on the route. The relationship among BDIs indicates that the base layer has been weakened by structural cracks. Certain deviations in quality might have occurred during the construction of the pavement layers.

Permanent deformations or rutting were observed on subsection C. This can be attributed to the increased share of heavy traffic vehicles that slow down in that section as they approach the roundabout, and it is logical that the SCI parameter is increased (d0 above 160 μm, d2 above 140 μm). According to the results, the CBC base course is also weakened.

Subsection D is full of temperature cracks, while the deflection results (d0 above 160 μm, d2 above 135 μm, d4 above 105 μm) show a possible reduced load-bearing capacity of the base courses, formed in the asphalt layers and spread over time to the lower base courses.

Figure 11 shows the deflection parameters that indicate the difference in the subsections (A, B, C and D) in the observed stations according to the SCI, BDI and BCI indices (chapter 2.2.2.).

After processing the deflection and layer thickness data (from test pits and cores), uniform homogeneous pavement sections (according to AASHO Appendix J) were determined for asphalt layers, cement-stabilized base course (CBC) and unbound base course mixes (UBC) [43].

5. Determining the modulus of elasticity using the computer program ELMOD

The calculation of the modulus of elasticity was carried out using the computer program ELMOD, which automatically calculates elastic moduli using the back-calculation method. The calculation is performed based on the deflection results obtained from FWD testing using the cumulative difference method. Homogeneous sections are aligned with sections of equal layer thicknesses. When determining homogeneous sections, they should have approximately the same load-bearing capacity and be aligned with the data on the layer thicknesses as these vary along the route [45].

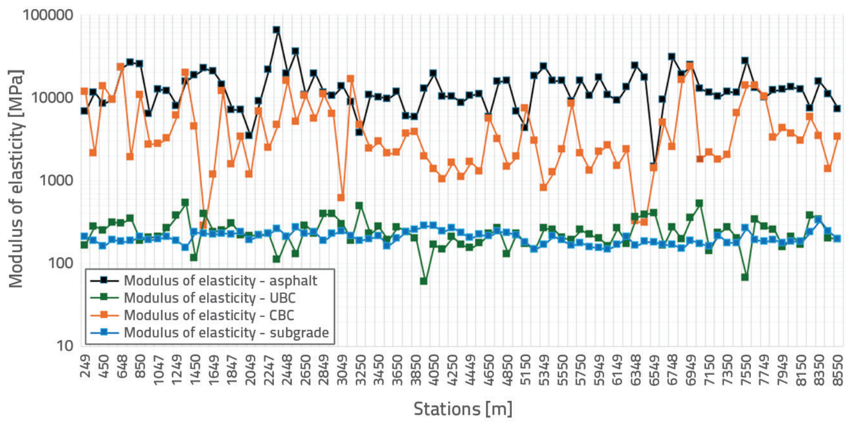

Figure 12. D28 pavement modulus of elasticity D28 [37]

After calculating the elastic modulus for each individual homogeneous section, the stresses and deformations of the pavement structure can be calculated at critical points. The diagram (Figure 12) shows the elastic modulus of the entire section D28 Bjelovar bypass for asphalt layers, CBC, UBC and subgrade. The modulus of elasticity values of the subgrade in all subsections (A-D) range from 150 to 270 MPa.

Subsection A: UBC moduli of elasticity range from 115 to 230 MPa, CBC moduli of elasticity range from 300 to 19000 MPa, which is an extremely large range, just like asphalt layers from 3500 to 22000 MPa. The section is full of transverse cracks, and in certain points of high deflections, the moduli of elasticity are low in the asphalt layers and the CBC layer.

Subsection B: The analysis of the subsection B with extremely low deflections showed extremely high values of the elastic moduli in asphalt layers (10500-36000 MPa) and CBC (5000-11000 MPa). The pattern repeats, so the CBC moduli and asphalt layers have almost equal values every 200 meters.

Subsection C: Subsection C with pronounced ruts at critical points of deflection showed a lower modulus of elasticity of the CBC (600-4600 MPa) as well as lower elasticity modulus of the asphalt layers compared to the rest of this section, due to permanent deformations in the asphalt layers.

Subsection D: Characterized by temperature cracks, has low CBC moduli of elasticity (1600-2000 MPa) compared to the rest of the section, which indicates that the stabilization layer is in a worse condition and should be repaired first before any construction of the layers above it.

According to the obtained elasticity modulus results for each individual layer, it can be concluded that the CBC is the critical layer in the analyzed sections of the pavement structure and it needs to be strengthened, which is confirmed by the oscillations of the value of the CBC modulus of elasticity (shown in Figure 12). The main reason for the poor condition of the CBC is gravel as a constituent material; by using crushed stone material, the layer retains its properties for a longer period in exploitation conditions, despite oscillations in initial compressive strengths..

6. Strengthening the pavement structure

The pavement structure of the state road D28 consists of a wearing course and a base course of asphalt concrete, a cement-stabilized bearing course (CBC), and the compacted base course of crushed stone (UBC).

During the construction of the state road route, or rather its pavement, in the period from XI/2001 to XII/2002, technological supervision of the execution of the works was carried out, including all the necessary control-investor tests, as well as ongoing-execution sampling and measurements according to the requirements of the main design and the General Technical Conditions for Road Works (GTC) [39]. According to the asphalt control test report [38], the designed thickness of the AB 11s wearing course is 5 cm, the BNS 32s base course is 8 cm, the cement-stabilized layer is 20 cm, and the UBC is 30 cm (Figure 13).

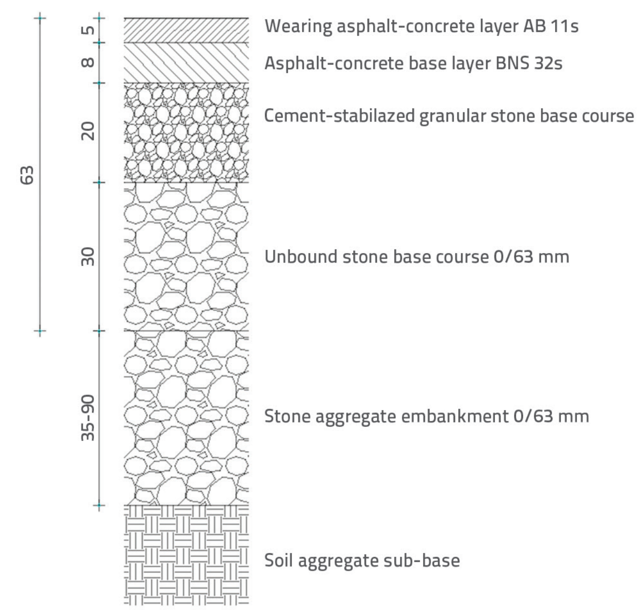

Figure 13. Layers of the existing state road structure D28 [35]

Based on the results of the measurements and laboratory tests carried out as part of the control tests, it is concluded that the composition and physical-mechanical properties of the asphalt base course layer (BNS 32s) and the asphalt wearing layer (AB 11s) are in accordance with the prescribed requirements according to the General Technical Specifications and the design requirements, with deviations within the tolerance limits that should not affect essential requirements for the structure.

State road construction projects and control tests of the constructed layers should be archived and made available in the process of determining the pavement bearing capacity. The designed condition should be compared with the existing one in order to enter into further calculations and reinforcement design with more accurate information on the type of asphalt layers and thicknesses. It would be easier to reach conclusions as to why some of the sub-sections are more damaged than other sections and whether there were any deviations during the construction process.

In May 2020, field investigation works were carried out on the Bjelovar bypass, during which the thickness and type of layers were determined, and samples of unbound mixtures were tested. The assessment of the bearing capacity of the pavement structure included processing of the results of the deflection measured with a falling weight deflectometer (FWD), obtaining the values of elastic moduli and preparing a proposal for a solution for the rehabilitation, or strengthening, of the pavement of the state road D28.

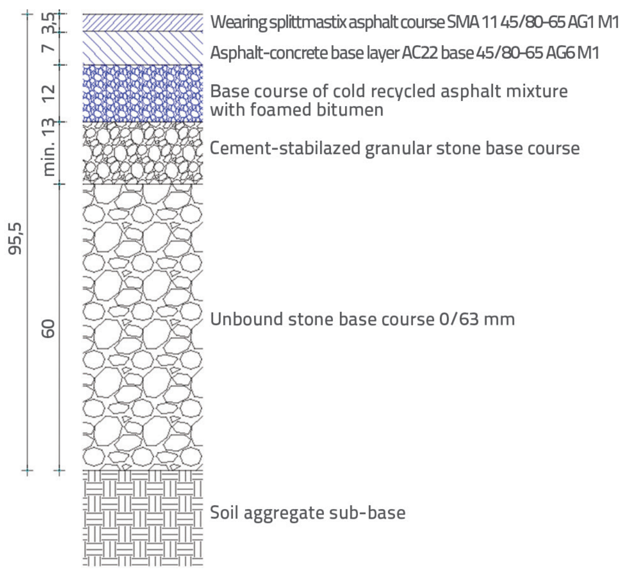

Figure 14. Layers of strengthened pavement structure of D28 Bjelovar bypass state road [35]

Laboratory tests concluded that the (gravel) stone base course meets the conditions given for the specified layer. The same was shown by deflection tests conducted by non-destructive testing method using the FWD. Visual inspection revealed deformations and cracks in the sub-sections that could have reduced load-bearing capacity. In cement-stabilized layers, it is expected that after a certain time, due to tensile stress and deformations caused by traffic loads, cracks appear at the bottom of the layer and spread to the pavement surface. Areas with structural cracks showed higher deflection results than areas with temperature cracks. The elasticity moduli of all layers of the pavement structure were calculated using the above data and knowledge of the materials in the layers used to determine the modulus of elasticity and Poisson's coefficient. The required thickness of the pavement reinforcement was determined based on the results obtained and the calculation of stresses and deformations in the layers of the existing pavement structure. It was determined that a 12 cm thick base course of cold recycled mix with foamed bitumen will be installed on the previously prepared CBC layer. Prior to this, the existing asphalt layers will be milled and used as aggregate in the base course of the recycled layer.

As part of the detailed design [35], the calculation of the axis elements, the vertical alignment, the calculation of the pavement edges and the road axis at intervals of 5m, and the dimensioning of the pavement structure reinforcement were made (Figure 14). The determination of the total equivalent traffic load was carried out in accordance with HRN U.C4.010., and the approach is discussed in Chapter 3.1. of this article. Heavy traffic load was determined, the dimensioning of the pavement layers was carried out according to the AASHTO method, and the calculated layers of the reconstructed pavement are shown in Figure 14. Due to the fact that this is a standardized calculation principle and due to space limitations, the numerical calculation is not an integral part of the article. The design period for the observed section is 20 years. When determining the total equivalent traffic load, a traffic growth rate of 4 % was assumed according to the data from Chapter 2, and thus heavy traffic load was determined. The design decision to reinforce the pavement structure with a recycled base layer is environmentally and economically justified, as confirmed by research [46].

7. Conclusion

On the section of the state road D28 built in 2001/2002, field surveys and sampling, as well as laboratory tests, were carried out in 2020 to assess the pavement bearing capacity and make a decision on the rehabilitation of the pavement structure. The section is full of cracks and some parts have pronounced ruts, which reduces driving comfort and affects traffic safety. Sounding excavations were carried out to determine the composition and thickness of the layers and deflection tests, as primary tools for determining the pavement bearing capacity.

It was determined that the CBC layer and the locations where it lost its bearing capacity were critical, as indicated by the results of deflection tests (d2 below 105 μm) and calculated elastic moduli (600-4600 MPa). The locations on which the CBC layer was completely destroyed or cracked will be repaired by installing a new layer or using geogrids.

The section of the state road D 28 studied in this paper can be a good example of the approach to pavement management, because the rehabilitation design process was initiated before the end of the 20-year project period. However, regardless of the investigation work conducted, laboratory tests and preparation of project documentation, pavement reinforcement works are not expected to start for several years. In the five years since the tests were conducted, the condition of the pavement has changed significantly. The information provided suggests that, regardless of the timely conduct of the pavement condition testing procedure at the end of the project period, this is still a deviation from timely rehabilitation within the framework of modern road management. The solution for strengthening the pavement structure itself is satisfactory according to today's priorities for saving new materials and recycling existing material, because milled asphalt layers are used in the share of up to 60% for the new bearing layer of cold recycled mixture.

REFERENCES

[1] Sršen, M.: Terminološki četverojezični rječnik cestovnog inženjerstva s pojmovnikom, 1. izdanje Zagreb: AspeCta - Udruga za promicanje socijalnih i okolišnih aspekata održivog razvoja cesta, 2011.

[2] Asphalt in pavement maintenance Asphalt institute ISBN 10: 0614232945 ISBN 13: 9780614232943, 1996.

[3] Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D.Y., Kennedy, T.W.: Hot Mix Asphalt Materials, Mixture Design, and Construction, 2nd ed., NAPA Education Foundation: Lanham, MD, USA, (1996), pp. 286-304. ISBN 953-6686-07-5.

[4] Rukavina, T., Ožbolt, M.: Sustav gospodarenja kolnicima - prikupljanje podataka // Gospodarenje prometnom infrastrukturom. Zagreb: Zavod za prometnice Građevinskog fakulteta Sveučilišta u Zagrebu, (2009), pp. 95-176

[5] Domitrović, J., Rukavina, T.: Application of GPR and FWD in assessing pavement bearing capacity Romanian Journal of Transport Infrastructure, 2 (2013), pp. 11-21, https://doi.org/10.1515/rjti-2015-0015

[6] Cuculić, M., Pranjić, I., Deluka Tibljaš, A., Stanić, I. : Analiza asfaltnih kolničkih konstrukcija na temelju podataka strukturalne nosivosti, GF - Zbornik radova UDK 625.7, https://doi.org/10.32762/zr.23.1.3, 2020.

[7] Scheidig, M., Uzara, K., Kempfa, D., Harriesa, L., Böhma, S., Liu, J.: Load-Bearing Capacity Assessment of Traffic Superstructures for Roads and Tramways, SMAR 2024 - 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, ScienceDirect Procedia Structural Integrity, 64 (2024), pp. 301-310, https://doi.org/10.1016/j.prostr.2024.09.251

[8] Čičković, M., Bald, J.S.: Rückrechnung der charakteristischen mechanischen Parameter von Verkehrsbefestigungen aus FWDMessungen, In: Straße und Autobahn, 68 (2017) 12, pp. 950-957.

[9] Qian, F., Shanqiang, L., Xinquan X.: Bearing capacity evaluation of asphalt pavement based on dynamic deflection equivalent, REES2019, IOP Conf. Series: Earth and Environmental Science 300-052041, IOP Publishing, https://doi.org/10.1088/1755-1315/300/5/052041, 2019.

[10] Araki, S., Kazato, T., Kaito, K., Kobayashi, K., Akihiro Tanaka, A.: Evaluation for Load Bearing Capacity of Each Layer of Pavement in Japan Expressway, Internet Journal of Society for Social Management Systems, 11 (2017) 1, sms17-8813.

[11] Karbočius, M., Vaitkus, A.: Falling-weight-deflectometer-based structural condition assessment of low-volume road pavements: practices and challenges, 8th International Conference on Road and Rail Infrastructure - CETRA 2024, pp. 709-716, https://doi.org/10.5592/CO/cetra.2024.1613

[12] Marecos, V., Simona Fontul, M., de Lurdes, A., Solla, M.: Evaluation of a highway pavement using non-destructive tests: Falling Weight Deflectometer and Ground Penetrating Radar, Construction and Building Materials, 154 (2017), pp. 1164-1172, https://doi.org/10.1016/j.conbuildmat.2017.07.034.

[13] Mesbah, U.A., Rafiqul, A.: Tarefder. Incorporation of GPR and FWD into pavement Mechanistic-Empirical design, Construction and Building Materials, 154 (2017), pp. 1272-1282, ISSN 0950-0618, https://https://doi.org/10.1016/j.conbuildmat.2017.06.105.

[14] Zhao, M., Liu, Y., Wu, C., Xu, X., Pei, Y., Zhang, C.: Pavement bearing capacity evaluation during pavement-fracturing using falling-weight impact acceleration, ScienceDirect Case Studies in Construction Materials, 21 (2024) 12, https://doi.org/10.1016/j.cscm.2024.e04002.

[15] Zhao, M., Yang, Q., Wu, W., Liu, J.: Structural condition assessment and fatigue stress analysis of cement concrete pavement based on the GPR and FWD, Construction and Building Materials, 328 (2022), 127044, https://doi.org/10.1016/j.conbuildmat.2022.127044

[16] Liu, Z., Yang, Q., Gu, X.: Assessment of Pavement Structural Conditions and Remaining Life Combining Accelerated Pavement Testing and Ground-Penetrating Radar, Remote Sens., 15.

[17] Rasol, M., Pais, J., Pérez-Gracia, V.: Solla, M., Fernandes F.M., Fontul, S. David Ayala-Cabrera, D. Schmidt, F. Hossein Assadollahi, H, GPR monitoring for road transport infrastructure: A systematic review and machine learning insights, Construction and Building Materials, 324 (2022), 126686, https://doi.org/10.1016/j.conbuildmat.2022.126686.

[18] Domitrović, J., Bezina, Š., Stančerić, I., Rukavina, T.: 3D modelling of asphalt concrete overlay based on GPR data. International Journal of Pavement Engineering, 24 (2021) 1, https://https://doi.org/10.1080/10298436.2021.2004413

[19] Keller, M.: Gospodarenje cestovnim kolnicima, Zbornik radova: Četvrto hrvatsko savjetovanje o održavanju cesta, pp. 41-52, 2009.

[20] Haas, R, Hudson, W.R., Zaniewski, J.P.: Modern Pavement Management. Malabar, Florida, USA: Krieger Publishing Company, 1994.

[21] Zagvozda, M, Dimter, S, Moser, V., Barišić, I.: Application of GIS technology in Pavement Management Systems, Građevinar, 71 (2017) 4, pp. 297-304. https://doi.org/10.14256/JCE.1980.2017

[22] Moser, V., Barišić, I., Rajle, D., Dimter, S.: Comparison of different survey methods data accuracy for road design and construction , 4th International Conference on Road and Rail Infrastructure - CETRA 2016, pp. 847-852, 23-25 May, 2016, Šibenik, Croatia.

[23] Babić, B.: Projektiranje kolničkih konstrukcija. Zagreb: Hrvatsko društvo građevinskih inženjera, 1997.

[24] Kuvačić, B., Rukavina, T.: Sustav gospodarenja kolnicima na hrvatskim prometnicama - postavke i principi, Zbornik radova: Četvrto hrvatsko savjetovanje o održavanju cesta, Šibenik, pp. 33-44, 2009.

[25] Zekušić, M., Črljenko, M.: Vizualni pregled, istražni radovi i varijante rješenja obnove kolnika, Seminar: Projektiranje obnove asfaltnih kolnika, Zagreb, 2017.

[26] Sun, L.: Structural Behaviour of Asphalt Pavements. Imprint Butterworth-Heinemann, ISBN 978-0-12-849908-5, 2016.

[27] Buttlar, W.G.: Mechanisms of Cracking and Debonding in Asphalt and Composite Pavements, vol. 28. Springer Cham, Hardcover ISBN 978-3-319-76848-9 Published: 05 June 2018 https://https://doi.org/10.1007/978-3-319-76849-6

[28] Rukavina, T.: Korištenje deflektografa s padajućim teretom i georadara za utvrđivanje postojeće i projektiranje potrebne nosivosti kolnika, Zagreb: Seminar Asfaltni kolnici, 2014.

[29] COST 336 Use of Falling Weight Deflectometers in Pavement Evaluation, Final Report of the Action, European Cooperation in the Field of Scientific and Technical Research, The Netherlands, Apr. 2005.

[30] Harshdutta, I.P., Ayman, A.A., Yusuf, A.M.: Enhancing Falling Weight Deflectometer (FWD) Testing: Comprehensive Review and Development of Robust Procedure in the United States, J Test. Eval, 52 (2024) 4, pp. 2039-2054, https://https://doi.org/10.1520/JTE20230389.

[31] Enhanced Analysis of Falling Weight Deflectometer Data for Use With Mechanistic-Empirical Flexible Pavement Design and Analysis and Recommendations for Improvements to Falling Weight Deflectometers, Research Development and Technology Turner-Fairbank Highway Research Center, U.S. Department of Transportation Federal Highway Administration, Georgetown Pike, Mar. 2017.

[32] Talvik, O., Aavik, A.: Use of FWD deflection basin parameters (SCI, BDI, BCI) for pavement condition assessment, The Baltic Journal of Road and Bridge Engineering, 4 (2009), pp. 196-202. https:// https://doi.org/10.3846/1822-427X.2009.4.196-202.

[33] Fu, G., Zhao, Y., Wang, G., Wei, J.: Evaluation of the effects of transverse cracking on the falling weight deflectometer data of asphalt pavements, International Journal of Pavement Engineering, 23 (2021) 5, pp. 1-14, https://doi.org/10.1080/10298436.2021.1886295.

[34] Drenth, K.P.: ELMOD 6: The design and structural evaluation package for road, airport and industrial pavements, San Francisco: 8th International Conference on Concrete Block Paving, pp. 721-730, 2006.

[35] Izvedbeni projekt izvanrednog održavanja asfaltnog kolnika D28 sjeverna obilaznica Bjelovara, Labos Varaždin, studeni 2020.

[36] Zvonarić, M., Dimter, S.: Mjere prevencije i sanacije reflektirajućih pukotina u savitljivim kolnicima, Građevinar, 74 (2022) 3, pp. 189-197. https://doi.org/10.14256/JCE.3427, 2021.

[37] Molenaar, A.: Lecture Notes: Design of Flexible Pavements. Nootdorp https://www.asphalt.de/fileadmin/user_upload/downloads/EAPA-Brosch%C3%BCren/17-Flexible-Pavement-Design.pdf, pristup 3.11.2024, 2018.

[38] Privremeni elaborat o provedenim terenskim istražnim radovima i laboratorijskim ispitivanjima materijala iz kolničke konstrukcije s prometnice D28, poddionica 3, svibanj 2020.

[39] Opći tehnički uvjeti za radove na cestama: Knjiga III - Kolnička konstrukcija, Institut građevinarstva Hrvatske, Zagreb, 2001.

[40] HRN EN 13286-47:2012: Unbound and hydraulically bound mixtures - Part 47: Test method for the determination of California bearing ratio, immediate bearing index and linear swelling (EN 13286-47:2012), Brussel, Belgium 2012.

[41] HRN EN 933-1:2012: Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method (EN 933-1:2012), Brussel, Belgium 2012.

[42] HRN EN 13286-2:2010/Ispr.1:2013: Unbound and hydraulically bound mixtures - Part 2: Test methods for laboratory reference density and water content - Proctor compaction (EN 13286-2:2010/AC:2012), Brussel, Belgium 2012.

[43] American Association of State Highway and Transportation Officials: AASHTO Guide for Design of Pavement Structures. Washington D.C., 1993.

[44] Izvještaj - ocjena nosivosti kolničke konstrukcije (strukturalni kapacitet) državna cesta D28, poddionica 003, obilaznica Bjelovara od km 0 + 000,00 m do km 8 + 600,00 m, TRIKprojekt j.d.o.o., Zagreb, 2020.

[45] Izvješće o kontrolnim ispitivanjima asfalta i hidroizolacije na sjevernoj zaobilaznici grada Bjelovara, Institut građevinarstva Hrvatske d.d. Zavod za prometnice Cestograđevni laboratorij - Odjel za tehnološki nadzor, Zagreb, 2002.

[46] Vaitkus, A., Gražulyte, J., Kravcovas, I., Mickevic, R.: Comparison of the Bearing Capacity of Pavement Structures with Unbound and Cold Central-Plant Recycled Base Courses Based on FWD Data, Sustainability, 13 (2021), 6310. https://doi.org/10.3390/su13116310, MDPI 2021.