Original scientific paper

Estimation of carrying capacity of slag and gravel forest road pavements

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Abstract – Nactrak

The objective of the study was to estimate the carrying capacity of forest roads with slag and gravel pavements. Deformation module and elastic deflection were used as characteristic parameters of road carrying capacity. There were 9 tested sections divided into set groups. All investigated sections were measured using VSS plate (29 measurements) and deflectometer (53 measurements). Averaged results of the measurements of specific pavements were introduced in the analysis. The present study proved that the carrying capacity of slag and gravel pavements defined according to mean module M_E *is insufficient. The largest (122.87 MPa) mean deformation module was detained for gravel pavement. Two slag pavements with significant constructional differences had very similar values of deformation modules 98.26 and 94.84 MPa. Taking maximum deformation modules* M_E *into consideration, slag, gravel and gravel-broken-stone pavements comply with the requirements for low traffic intensity (*M_E *= 130–200 MPa). Only two-ply gravel pavements (about 25 cm thick) have the mean carrying capacity complying with the requirements of low traffic intensity.*

Key words: *forest road, soil basement, road carrying capacity, pavement deflection, gravel pavement, slag pavement*

1. Introduction – *Uvod*

Forest roads are characterized by low traffic intensity (Koczwański and Nowakowska-Moryl 1992, Fertal 1994, Trzciński 2001), and by hard unit pressure caused by high-tonnage transport vehicles, often exceeding 80 kN per axle. It contributes to degradation of the road pavement and forest habitat (Bień 1987, Komorowski et al. 1990). Recommended constructions of forest roads ensure the achievement of wood transport with the lowest possible deformation of pavement (Siedorowicz et al. 1990). The pavement bearing capacity, mainly, depends on its structure. However, road basement soil, its physical and mechanical attributes, and level of soil water are equally important factors affecting the pavement attributes (Pieńkos 1997, Kamiński and Czerniak 2001). Problems regarding the bearing capacity of pavements and road basement of forest roads have been analyzed in many countries (Mcfarlane et al. 1975, Kosztka 1996, Sedlak 1996, Martin et al. 1999, O'Mahony et al. 2000).

The results presented in previous Polish publications deal with the carrying capacity of forest road sections with different construction of pavement performed during the study, and include the analyses of:

- pavement made of soil stabilized with cement – cement-ground (Kamiński et al. 1997, Czerniak 2004),
- road basement stabilized with lime (Kamiński et al. 1997),
- pavement with a thick layer of tar concrete (Kamiński and Janaszek 1987),
- pavement made of soil stabilized with brown coal ash after ten years of exploitation (Kamiński et al. 1986),
- influence of soil basement on broken-stone pavement (Kamiński and Czerniak 2001, 2003).

The authors of the above studies confirm the appropriate carrying capacity of tested pavement constructions when they are constructed according to standards. At the same time, the above-cited studies confirm the significant influence of road basement on pavement bearing capacity of forest road, which, in extreme cases, can cause the decrease of deformation module up to 300 % (Kamiński and Czerniak 2001).

According to the number of vehicles a day (with 80 kN load on axle-tree) there are 3 categories of forest roads in National Forests, whose construction of pavement was described:

1. First category roads (more than 14 vehicles a day) with bituminous pavement on broken-stone and cement-ground foundation,
2. Second category roads (6–13 vehicles a day) with two-ply pavement (gravely, slag, broken-stone),
3. Third category road with low traffic (less than 6 vehicles a day) with one-ply pavement (soil, gravelly, slag).

Roads with gravel pavement account for 4 %, and with slag pavement for 3.6 % of all existing roads in the Polish National Forests. The share of this type of roads follows the predominant pavements with soil road structure, which account for 86.9 %. However, a specific road, classified during any inventory as a particular type of pavement, often has a structure not complying with forest roads standards and requirements. In such a case there is an urgent need for the analysis of the carrying capacity of the actually existing gravel and slag pavement structures of forest roads with soil basement in order to propose their improvement and to avoid such cases in road construction in future.

The objective of the study was to estimate the carrying capacity of the actually existing structures of gravel and slag pavements of forest roads built on different soil basements. The scope of the research contained a selection of tested sections, analysis of pavement structures, estimation of road basement, measurement of pavement deformation and calculation of deformation module and elastic deflection of the pavement.

2. Working methods – *Metode rada*

Deformation module M_E (MPa) is a measure of pavement or soil basement bearing capacity, determined as the ratio of a unit load increase to the increase of the tested area deformation in a certain range of unit loads, multiplied by the diameter of a loading plate (Polish Norms).

Elastic deflection value U_s (mm) is calculated as a double difference between deflection of a loaded pavement and the deflection after its complete relief. It indicates the ability of the pavement construction to endure loads.

The tested sections were selected on the basis of a pavement construction, type of road basement (determined on the basis of a forest district soil map, and confirmed in laboratory studies), and forest site type. All tested sections were 10 meters long, and located in places characterized by homogeneous pavement and road basement. Laboratory studies included the determination of the soil granulometric composition in accordance with the requirements of the Polish Norms (PN).

An actual pavement construction of a particular test section of the road was determined using 0.5 m deep pavement outcrops, recorded in photographs with the determined outcrop measure.

The determination of a deformation module M_E of the pavement and road basement was made using VSS plate 30 cm in diameter, in accordance with the requirements of the Polish Norms BN-64/8931-02, using unit load up to 0.55 MPa. M_E was calculated in the range of unit loads from 0.25 to 0.35 MPa. The measurements performed with the use of VSS plate were made on the road rut surface, where the vehicles wheels move. At least 3 measurements were made on each test section. When the results showed considerable differences, additional measurements were made. The measurements were performed using VSS plate together with a Benkelman's deflectometer with automated data collection. High-tonnage vehicles designed for wood transport were used as counterweight (Fig. 1). A total of 29 measurements were made using VSS plate on all tested sections. The obtained results of measurements and calculated deformation modules were arranged according to the pavement construction, type of soil base-

Figure 1 Set of measuring apparatus to VSS tests

Slika 1. *Mjerna oprema za određivanje modula deformacije VSS testom* ment, and forest site type. Further, the results were characterized by mean values and presented with a minimum and maximum value together with a graph of mean deformations.

Figure 2 Measurement of the pavement deflection using Benkelman's deflectometer

Slika 2. *Izmjera elastičnoga progiba kolničke konstrukcije primjenom Benkelmanova deflektometra*

The measurements of the pavement deflection using Benkelman's deflectometer were made in accordance with the requirements of the variant I of the Polish Norms BN-70/8931-06: a load and elastic deflection during moving downhill was calculated. Six measurements were made on each experimental section. The distance between the testing points was 6 m, so that the vehicle could cross the required distance in accordance with PN. The measurement was performed between identical wheels of the rear axle of a Volvo transport vehicle on the area of a pavement rut (Fig. 2). Elastic deflection was calculated for all six measurements, and than the mean value of the deflection for the whole section was used for further analyses and comparisons. The significance of difference of the deformation module and elastic deflection between groups was tested using ANOVA and multiple range tests performed in Statgraphics® Plus for Windows software.

3. Research area – *Područje istraživanja*

For research purpose 9 test sections were established and marked in the forest road network of Gidle forest district in south Poland. Four test sections were located on roads with slag pavement, 4 on roads with gravel pavement, and one on gravel-broken stone pavement. The detailed characteristics of the tested sections are presented in Table 1.

The tested sections S1 and S2 were on the road with slag pavement with the thickness of construction layers up to a standard second category road with increased traffic. The construction of the section S4 pavement was carried out in compliance with the requirements of the applicable standards for roads with low traffic intensity. The thickness of the pave-

Table 1 Detailed characteristics of the tested points

Tablica 1. *Detaljan opis pokusnih dionica šumskih cesta*

Tested section *Oznaka pokusne dionice*	Road number/ forest district *Šumska cesta/ šumsko područje*	Sector/ separation *Odjel/odsjek*	Forest site type *Tip sastojine*	Pavement type *Vrsta kolničke konstrukcije*	Pavement thickness *Debljina kolničke konstrukcije*	Road basement (from a soil map) *Posteljica ceste (sa pedološkog zemljovida)*
S1	51 / Gidle	156/ i	FMC*	Slag *Šljaka*	10 cm of slag, 15 cm of sand *10 cm šljake, 15 cm pijeska*	Loose and poorly clayey sands, deep *Slabo glinoviti duboki pijesak*
S2	51 / Gidle	155/ a	MC*	Slag *Šljaka*	18-20 cm of slag *18-20 cm šljake*	Loose and poorly clayey sands, deep *Slabo glinoviti duboki pijesak*
S3	70 / Dabrowa	40/ h	FC*	Slag *Šljaka*	5-7 cm of slag with addition of gravel *5-7 cm šljake s dodatkom šljunka*	Loose and poorly clayey sands, deep *Slabo glinoviti duboki pijesak*

Table 1 Detailed characteristics of the tested points (continued)

Tablica 1. *Detaljan opis pokusnih dionica šumskih cesta* (nastavak)

S4	91 / Dabrowa	154/ h-j	FMC*	Slag *Šljaka*	12-14 cm of slag *12-14 cm šljake*	Loose and poorly clayey sands, deep *Slabo glinoviti duboki pijesak*
Gr1	near 33 / Gidle	68/ i-69/ c	FC*	Gravel *Šljunak*	25 cm of gravelly *25 cm šljunka*	Loose and poorly clayey sands, deep *Slabo glinoviti duboki pijesak*
Gr2	near 35 / Gidle	60/ c - 61/ a	FC*	Gravel *Šljunak*	22-25 cm of gravelly *22-25 cm šljunka*	Loose and poorly clayey sands, deep *Slabo glinoviti duboki pijesak*
Gr3	Continuation of road number 94	192/ a	FMC*	Gravel *Šljunak*	12-15 cm of gravelly *12-15 cm šljunka*	Loose and poorly clayey sands, up to 1.6 m on clayey sand *Slabo glinoviti pijesak dubine 1,6 m*
Gr4	71 / Dabrowa	41/ c - 36/ a	FC*	Gravel *Šljunak*	10-12 cm of gravel *10-12 cm šljunka*	Loose and poorly clayey sands, deep *Slabo glinoviti duboki pijesak*
GrBn	73 near forester's Dabrowa	68/ f	FMC*	Gravel-broken-stone *Šljunak-tucanik*	5 cm of gravel 12-15 cm of broken-stone *5 cm šljunka 12-15 cm tucanika*	Loose and poorly clayey sands, up to 1.6 m on medium and consistent clay *Slabo glinoviti pijesak dubine 1,6 m na glinencima*

FMC*- fresh mixed coniferous forest, MC*- moist coniferous forest, FC*- fresh coniferous forest

FMC – mješane šume četinjača, MC* – vlažne šume četinjača, FC* – šume četinjača*

ment of section S3 was small and failed to comply with the requirements for one-ply constructions. Sections Gr3 and Gr4 had one-ply gravel pavement designed for roads with low traffic load. Pavement thickness of sections Gr1 and Gr2 was designed for forest roads of the second category.

4. Results and discussion – *Rezultati i rasprava*

4.1 Deformation module using VSS plate – *Modul deformacije određen VSS pločom*

The least 2.03 mm deflection was observed under maximum load (0.55 MPa) for slag one-ply pavement (S4), which was simultaneously characterized by the least constant 0.67 mm deformation after the load removal (Table 2).

When two-ply slag pavements with better construction were tested, similar results were obtained (2.32 and 1.39 mm, respectively) only for section S2. Measurements of slag pavement on a sand basement (S1) demonstrated the largest deformations (2.96 and 1.69 mm) in the group of slag pavements.

The analysis of graphs of slag pavements deformations show that their structure is not dependent on the number and thickness of construction layers (Fig. 3). Soft and regular shape of the graph was obtained for the pavement S4 located in FMC habitat. The slag pavement (S3) with 50 mm slag thickness showed a significant increase of deformation (0.52 mm) under loads between 0.10 and 0.15 MPa.

The observed considerable increase of deformation (ranging between 0.25 and 0.05 mm) under the load of 0.05 MPa for the pavements S1 and S3 indicate poor condensation in comparison with the results obtained for S2 and S4.

The tested section with the gravel layer of the largest thickness Gr1 showed the lowest values of deformation (1.78 and 0.99 mm) obtained for gravel pavements. In case of gravel pavement on clayey sand basement (Gr3-one-ply) in FMC habitat, a maximum deformation 2.72 and 1.73 was established after the completed research (Table 3).

There were two gravel pavements (Gr1 and Gr2) located on loose and poorly clayey sand basement with a similar pavement thickness. The obtained mean results of pavement deformation varied 0.4 mm at the maximum (Fig. 4). The large growth of deformation under increasing load was observed for one-ply gravelly pavement Gr3.

Table 2 Mean values of deformations for slag pavements

Tablica 2. *Srednje vrijednosti deformacije kolničke konstrukcije izvedene od šljake*

Pressure, MPa *Tlak, MPa*	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55
Tested section *Oznaka pokusne dionice*	Deformation under pressure, mm *Deformacija zbog opterećenja, mm*											
S1	0.00	0.24	0.60	0.94	1.21	1.54	1.81	2.08	2.29	2.54	2.73	2.96
S2	0.00	0.37	0.70	0.98	1.15	1.35	1.50	1.68	1.82	1.94	2.19	2.32
S3	0.00	0.38	0.64	1.16	1.43	1.65	1.87	2.10	2.28	2.43	2.58	2.73
S4	0.00	0.25	0.48	0.70	0.90	1.10	1.24	1.41	1.58	1.72	1.89	2.03
Deformation under relief, mm *Dubina kolotraga, mm*												
S1	1.69		2.40		2.75		2.88		2.93			2.96
S2	1.39		2.07		2.27		2.33		2.33			2.32
S3	1.73		2.41		2.65		2.71		2.72			2.73
S4	0.67		1.21		1.81		2.00		2.06			2.03

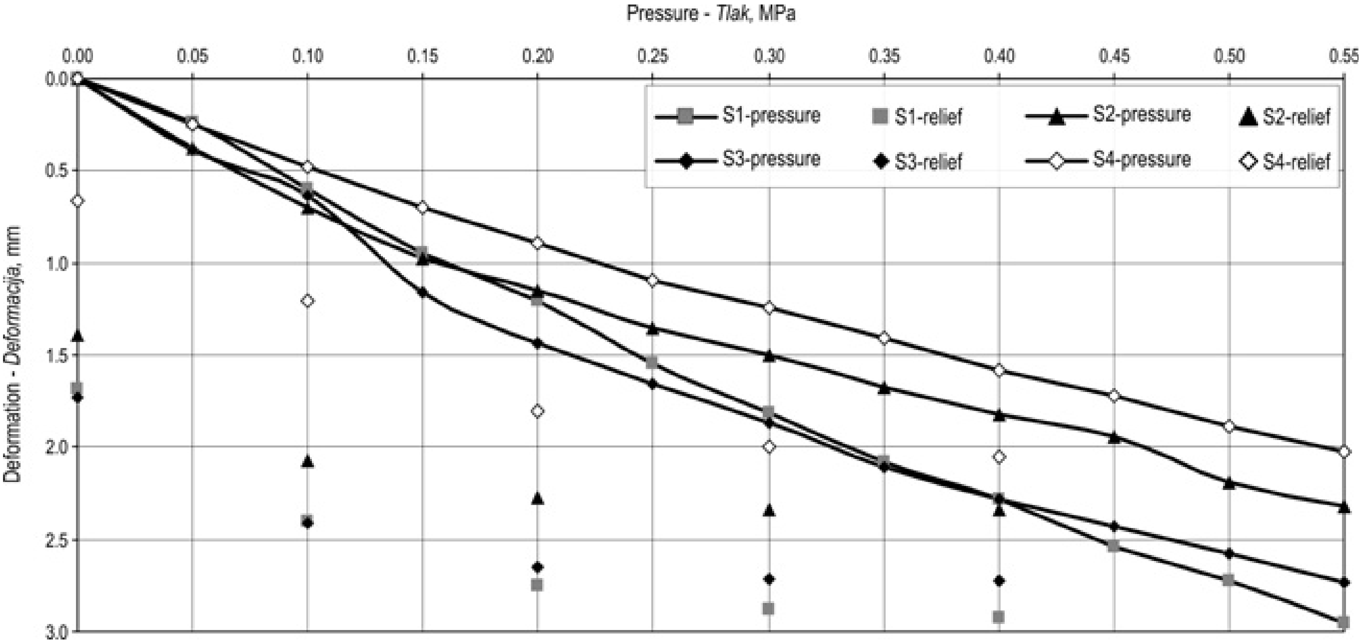

Figure 3 Deformations for slag pavements

Slika 3. *Deformacije kolničke konstrukcije izvedene od šljake*

The values of deformation for gravel pavements Gr3 and Gr4 indicate the influence of road basement on parameters of the pavement bearing capacity. Also, gravel–broken stone (GrBn) pavement was characterized by greater deformation under less favorable soil conditions.

Mean, maximum and minimum values of deformation module were calculated for particular pavements based on results of studies performed using VSS plate. These values are presented in Table 4. The largest 122.87 MPa mean deformation module was detained for gravel pavement Gr1. Two slag pavements S2 and S4 with significant constructional differences had very similar values of deformation modules, 98.26 and 94.84 MPa, respectively. Statistic analysis (ANOVA) demonstrated no significant difference between deformation modules of the tested pavements, and multiple range tests demonstrated a significant difference between the results obtained for Gr1 and Gr2, Gr3 and slag pavement S1 and S3.

Table 3 Mean values of deformations for gravelly pavements

Tablica 3. *Srednje vrijednosti deformacije kolničke konstrukcije izvedene od šljunka*

Pressure, MPa *Tlak, MPa*	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55
Tested section *Oznaka pokusne dionice*	Deformation under pressure, mm *Deformacija zbog opterećenja, mm*											
Gr1	0.00	0.23	0.46	0.69	0.90	1.07	1.19	1.33	1.44	1.57	1.67	1.78
Gr2	0.00	0.18	0.48	0.78	1.01	1.27	1.48	1.63	1.79	1.93	2.07	2.22
Gr3	0.00	0.40	0.88	1.24	1.46	1.73	1.91	2.09	2.25	2.44	2.57	2.72
Gr4	0.00	0.31	0.60	0.90	1.10	1.37	1.59	1.75	1.95	2.18	2.36	2.56
GrBn	0.00	0.32	0.68	0.97	1.21	1.46	1.64	1.81	1.98	2.12	2.27	2.46
Deformation under relief, mm *Dubina kolotraga, mm*												
Gr1	0.99		1.48		1.72		1.76		1.78			1.78
Gr2	1.34		1.88		2.11		2.18		2.21			2.22
Gr3	1.73		2.47		2.66		2.73		2.74			2.72
Gr4	1.46		2.20		2.44		2.54		2.57			2.56
GrBn	1.34		1.86		2.03		2.13		2.22			2.46

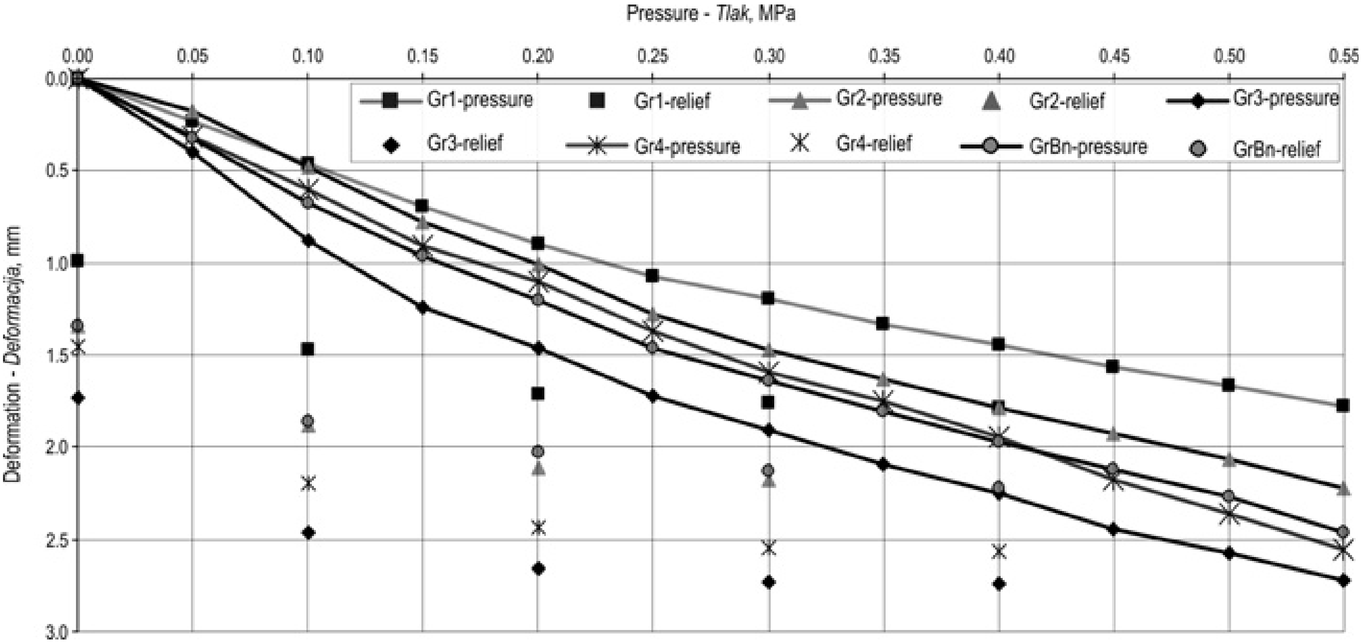

Figure 4 Deformation of gravel pavements

Slika 4. *Deformacije kolničke konstrukcije izvedene od šljunka*

The lack of significant difference between deformation modules of pavements with different thickness (for example Gr1, Gr4 and S4) may indicate the influence of other factors such as road basement or proper pavement construction, on the carrying capacity. This phenomenon was also observed in other studies by Kamiński and Czerwiński (2001, 2003). Taking maximum deformation modules M_E into consideration, six pavements: S2, S4, Gr1, Gr2, Gr4 and GrBn comply with the requirements for low traffic intensity (M_E =130–200 MPa). Taking the mean value of deformation into consideration, only Gr1 pavements comply with the requirements for this type of traffic.

Table 4 Value of pavements deformation module (M_E) on tested sections

Tablica 4. *Vrijednosti modula deformacije (M_E) kolničke konstrukcije na ispitivane pokusnim dionicama*

Tested section *Oznaka pokusne dionice*	Value of deformation module, MPa *Vrijednosti modula deformacije, MPa*		
	Minimum *Najmanja*	Maximum *Najveća*	Mean *Srednja*
S1	46.15	78.95	58.94
S2	69.77	125.00	98.26
S3	55.56	81.08	68.27
S4	90.91	100.00	94.84
Gr1	85.71	157.89	122.87
Gr2	43.48	111.11	76.67
Gr3	65.22	96.77	84.57
Gr4	60.00	130.43	86.73
GrBn	75.00	103.45	89.23

4.2 Elastic deflection – *Elastični progib*

According to the methodology, mean deflection (out of 6 measurements) was calculated for each experimental section, and then the mean value was calculated for a particular group of pavement. Among slag pavements, the lowest mean value of elastic deflection (0.65) was obtained for the group S2, and among gravel pavements – for the group Gr1 (1.42 see Table 5). Significant difference was observed between the results of elastic deflection for particular pavements. Only the results for the sections Gr2, Gr3 and Gr4 are similar, as well as single results for slag pavement S1–S2, S1–S3, and S3–S4.

Table 5 Value of pavement elastic deflection

Tablica 5. *Vrijednosti elastičnog progiba kolničke konstrukcije na ispitivanim pokusnim dionicama*

Tested section *Oznaka pokusne dionice*	Value of elastic deflection, mm *Vrijednosti elastičnog progiba, mm*		
	Minimum *Najmanja*	Maximum *Najveća*	Mean *Srednja*
S1	0.74	1.92	1.43
S2	0.06	1.14	0.65
S3	1.38	3.58	2.26
S4	2.00	4.46	2.91
Gr1	0.06	1.26	0.79
Gr2	1.50	1.90	1.67
Gr3	1.50	2.44	1.85
Gr4	1.30	2.86	2.04

5. Conclusions – *Zaključak*

This study proved that the carrying capacity of slag and gravel pavements defined according to mean module M_E is insufficient. Two-ply gravel pavements (about 25 cm thick) have the carrying capacity complying with the requirements of low traffic intensity.

The mean carrying capacity of the tested pavements indicates the necessity of verification of forest road pavements construction with respect to the type of the road basement.

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Sažetak

Procjena nosivosti šumskih cesta s kolničkom konstrukcijom izrađenom od šljake (troske) i od šljunka (tucanika)

Za šumske je ceste karakteristična niska frekvencija (intenzitet) prometa, glavnina se prometa tijekom godine odvija u određenom kraćem razdoblju, a najveći udio u prometnom opterećenju zauzimaju teški šumski kamioni osovinskoga opterećenja često većega i od 80 kN (Nowakowska-Moryl 1992, Fertal 1994, Trcinski 2001). Poradi što manjih troškova održavanja šumskih cesta zbog oštećenja kolničke konstrukcije šumske je ceste potrebno graditi sukladno preporučenim tehničkim značajkama i propisanomu postupku izgradnje za određenu kategoriju šumske ceste (Siedrowicy i dr. 1990).

U državnim se šumama u Poljskoj šumske ceste prema dnevnoj frekvenciji prometa šumskih kamiona osovinskoga pritiska od 80 kN dijele u tri kategorije. Prva kategorija šumskih cesta (s više od 14 teških vozila dnevno) ima bitumenski gornji stroj kolničke konstrukcije izrađen na cementom poboljšanoj posteljici i podlozi od drobljenoga kamena. Druga kategorija šumskih cesta (s dnevnim prometom teških šumskih kamiona između 6 i 13) ima dvoslojnu kolničku konstrukciju izrađenu od šljunka (tucanika), šljake (troske) ili drobljenoga kamena. Za treću je kategoriju šumskih cesta (šumske ceste sa slabim prometom), uz dnevni promet šumskih kamiona do 6, propisana jednoslojna kolnička konstrukcija od šljunka (tucanika), šljake (troske) ili zemlje.

U ukupnoj strukturi vrsta kolničkih konstrukcija prevladavaju zemljani kolnici sa 86,9 %, slijede šljunčani kolnici s 4 %, dok kolnici izrađeni od šljake imaju udio od 3,6 %. Inventura šumskih cesta često upućuje na nižu razinu kvalitete nego što je propisano važećim propisima. Tada je nužno što prije popraviti kolničku konstrukciju temeljem rezultata dobivenih procjenom njezine nosivosti.

Svrha je ovoga rada procijeniti nosivost kolničke konstrukcije šumskih cesta izgrađenih na različitim tipovima tla uz ove ciljeve (faze) istraživanja: odabir testnih dionica šumskih cesta, raščlamba kolničke konstrukcije, procjena matičnoga tipa tla (uz kasniju laboratorijsku potvrdu procjene), određivanje deformacije kolničke konstrukcije te izračun modula deformacije i elastičnoga progiba kolničke konstrukcije.

Za istraživanje je odabrano i obilježeno devet pokusnih dionica šumskih cesta u šumskom području Gidle na jugu Poljske. Četiri pokusne dionice imaju kolničku konstrukciju izvedenu od šljake, na četiri je pokusne dionice kolnička konstrukcija šljunčana, dok se na jednoj pokusnoj dionici nalazi kolnička konstrukcija izgrađena od kombinacije šljunka i drobljenoga kamena. Struktura je kolničke konstrukcije precizno određena na prokopu šumske ceste dubine 50 cm uz fotodokumentiranje. Sve su testne dionice duljine 10 metara i smještene su na onim djelovima šumske ceste koji su karakterizirani homogenom strukturom kolničke konstrukcije i dobrim općim stanjem tijela ceste. Za svaku je pokusnu dionicu temeljem geološko-pedološkoga tematskoga zemljovida istraživanoga područja određen tip tla (uzeti su uzorci poslije ispitivani u pedološkom laboratoriju), kao i vrsta sastojine. Detaljan je opis pojedine testne dionice prikazan u tablici 1.

Testne dionice S1 i S2 imaju kolničku konstrukciju izvedenu od šljake s debljinom kolničke konstrukcije većom od propisane za drugu kategoriju šumskih cesta. Pokusna dionica S3 ima debljinu kolničke konstrukcije manju od preporučene za jednoslojne kolničke konstrukcije šumskih cesta najniže (treće) kategorije. Na dionici S4 kolnička je konstrukcija izgrađena u suglasju s preporukama za treću kategoriju šumskih cesta. Debljina šljunčane kolničke konstrukcije pokusnih dionica Gr1 i Gr2 odgovara preporukama tehničkih značajki za drugu kategoriju šumskih cesta, dok pokusne dionice Gr3 i Gr 4 imaju jednoslojne kolničke konstrukcije debljine na razini šumskih cesta niskoga prometnoga opterećenja.

Modul deformacije (M_E) kolničke konstrukcije i posteljice šumske ceste izmjeren je okruglom pločom VSS promjera 30 cm prema preporukama Poljskih normi. Norma BN-64/8931-02 pruža mogućnost opterećenja do 0,55 MPa. Mjerenje je obavljeno u području kolotraga šumske ceste, i to najmanje tri mjerenja na svakoj pokusnoj dionici. Ako su odstupanja u dobivenim rezultatima bila značajna, provodila su se i dodatna mjerenja. Ukupno je obavljeno 29 mjerenja modula deformacije. Način je mjerenja modula deformacije prikazan na slici 1.

Usporedo s izmjerom za potrebe izračunavanja modula deformacije određivan je i elastični progib kolničke konstrukcije primjenom Benkelmanova deflektometra u suglasju s Poljskim normama BN-70/8931-06. Na svakoj je pokusnoj dionici šumske ceste obavljeno šest mjerenja potrebnih za izračun elastičnoga progiba, a udaljenost između mjernih točaka iznosila je 6 metara. Za svaku je dionicu određena srednja vrijednost šest mjerenja koja je korištena pri daljnjim raščlambama i usporedbama. Postupak je mjerenja prikazan na slici 2. Statistička je analiza provedena u okruženju Windows programom Statgraphics®Plus metodom ANOVA i testom multiple regresije.

Rezultati izračuna modula deformacije kolničke konstrukcije (srednje vrijednosti) pri izmjeri različito opterećenom kružnom VSS pločom prikazani su u tablici 2 i na slici 3 (za kolničku konstrukciju izvedenu od šljake) te u tablici 3 i na slici 4 (za kolničku konstrukciju izvedenu od šljunka odnosno šljunka i drobljenoga kamena kod testne dionice GrBn).

Najmanja je deformacija pri najvećem opterećenju kružne VSS ploče od 0,55 MPa za jednoslojnu kolničku konstrukciju izvedenu od šljake određena na testnoj dionici S4 i iznosila je 2,03 mm uz napomenu kako je za ovu testnu dionicu vezana i najmanja deformacija od 0,67 mm nakon prestanka opterećenja. Na ispitivanoj dionici šumske ceste S1 zabilježene su najveće deformacije pri opterećenju (2,96 mm) i nakon prestanka opterećenja (1,69 mm).

Na ispitivanoj dionici šumske ceste sa šljunčanom kolničkom konstrukcijom najveće debljine (Gr1) zabilježene su najmanje vrijednosti deformacije kolničke konstrukcije pri najvećem opterećenju VSS kružnom pločom (0,55 MPa) od 1,78 mm, ali i nakon prestanka opterećenja od 0,99 mm. Najveće su vrijednosti dobivene na ispitivanoj dionici šumske ceste Gr3 (2,72 mm i 1,73 mm). Vrijednosti deformacije za šljunčane kolničke konstrukcije pri opterećenju i nakon prestanka opterećenja pokazuju kako kvaliteta materijala koji je ugrađen u tijelo šumske ceste (lokalni materijal) utječe na nosivost kolničke konstrukcije. Također se kolnička konstrukcija izgrađena od kombinacije šljunka i lomljenoga kamena (GrBn) pokazala kao najlošija u uvjetima nenosivih tala.

Najmanje, srednje i najveće vrijednosti modula deformacije kolničke konstrukcije određene ispitne dionice šumske ceste izračunate su temeljem rezultata VSS testa i prikazane su u tablici 4. Najveći modul deformacije izračunat je za pokusnu dionicu Gr1 (122,87 MPa). Dvije pokusne dionice s kolničkom konstrukcijom izvedenom od šljake, ali značajnih razlika u debljini (sukladno kategoriji šumske ceste), imaju vrlo slične izračunate vrijednosti modula deformacije (98,26 MPa i 94,84 MPa). Statistička analiza (ANOVA) nije pokazala statistički značajne razlike između izračunatih modula deformacije kolničke konstrukcije na različitim testiranim dionicama šumskih cesta. Test je multiple regresije pokazao značajne

razlike između rezultata dobivenih za pokusne dionice Gr1, Gr2 i Gr2 kod šljunčanih kolničkih konstrukcija te za pokusne dionice S1 i S3 kod kolničkih konstrukcija izrađenih od šljake. Izostanak statistički značajnih razlika između modula deformacije kolničkih konstrukcija različite debljine (npr. Gr1, Gr4 i S4) pokazuje kako na modul deformacije snažno utječu i ostali čimbenici, kao što su materijal ugrađen u tijelo šumske ceste, postupak izradbe šumske ceste i dr. Takvu tvrdnju svojim radovima potkrjepljuju Kamínski i Czerwínski (2001, 2003). Modul deformacije kolničke konstrukcije za šumske ceste treće kategorije (šumske ceste s niskim prometnim opterećenjem) iznosi od 130 do 200 MPa.

Vrijednosti su elastičnoga progiba kolničke konstrukcije prikazane u tablici 5. Najmanja je srednja vrijednost elastičnoga progiba dobivena za pokusnu dionicu S2 (0,65 mm) među šumskim cestama s kolničkom konstrukcijom izvedenom od šljake, odnosno za pokusnu dionicu Gr1 (1,42 mm) među ispitivanim dionicama šumskih cesta sa šljunčanom kolničkom konstrukcijom. Među većinom testnih dionica utvrđene su statistički značajne razlike glede izračunatoga elastičnoga progiba kolničke konstrukcije.

Općenito se može zaključiti da je nosivost kolničke konstrukcije istraživanih dionica šumskih cesta, definirana srednjom vrijednosti modula deformacije, nedostatna. Tek bi se dvoslojnim kolničkim konstrukcijama ukupne debljine oko 25 cm postigla nosivost sukladna tehničkim zahtjevima treće kategorije šumskih cesta. Rezultati istraživanja upućuju na nužnost provjere nosivosti kolničke konstrukcije svih šumskih cesta, kontrolu izvedbe kolničke konstrukcije pri gradnji šumske ceste, poboljšanje nosivosti već izvedenih šumskih cesta, a sve u suglasju s matičnim tlom i materijalom koji se ugrađuje u tijelo (posteljicu) šumskih cesta.

Ključne riječi: *šumska cesta, matično tlo, nosivost šumske ceste, progibanje kolničke konstrukcije, šljunak, šljaka*

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