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ORIGINAL PAPER

Forest road engineering in Poland: current status and development perspectives

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ABSTRACT

Forest roads not only enable the use of the productive potential of forests, but also have a significant impact on their non-productive functions, including tourism and recreation. Moreover, the density and technical condition of forest roads affect the effectiveness of forest protection and disaster prevention measures. The average density of the road network in Polish forests corresponds to the densities known from some other European countries. The main problem is the high spatial variation of this parameter and the low share of roads with paved surfaces. In Poland, a significant percentage of roads are unpaved, with often very low bearing capacity parameters. Once the optimisation of the road network is completed, these roads should be reconstructed as a priority. A wide range of road investments requires the development of fast and reliable methods for assessing the quality of construction; high hopes in this regard are associated with the development of road surface standards and the use of light falling-weight deflectometers (LFWD). Geosynthetic materials being introduced into forest road construction deserve even greater promotion. They make it possible to construct forest roads on a very weak subgrade while limiting the amount of material required to achieve the desired road parameters. By delaying the process of surface deformation, they can extend the durability of the surface many times over, thus reducing road maintenance costs and extending the periods between successive repairs. The problems to be solved in the near future are (1) the development of effective and fast techniques to inventory the engineering condition of road networks, and (2) the development of empirical linear models that allow the results of LFWD tests to be used to evaluate the value of the deformation modulus of the second static plate load.

KEY WORDS

bearing capacity, forest road network inventory, forest road operation, light falling-weight deflectometer, static plate load test

Introduction

The implementation of rational forest management necessarily requires adequate road infrastructure (Demir, 2007; Trzciński, 2011; Bitir *et al*., 2021). Forest roads make forest stands accessible and enable appropriate use of the productive potential of forests (Gumus *et al*., 2008; Stempski *et al*., 2019; Keramati *et al*., 2020). At the same time, they significantly influence the expression

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of non-productive forest functions, including tourism and recreation (Queen *et al.*, 1997; Suzuki *et al.*, 1998; Termansen *et al.*, 2008, 2013; Santiago and Loomis, 2009). The density and condition of forest roads also influence the effectiveness of forest protection and disaster response (Grajewski, 2019; Laschi *et al.*, 2019; Thompson *et al.*, 2021). Optimised forest road networks provide tangible benefits by reducing management costs, shortening distances for skidding and internal timber transport (Hrůza, 2003; Sakai, 2017), and reducing vehicle wear and fuel consumption (Gumus *et al.*, 2008), thereby reducing the negative impacts of transport on the environment (Keramati *et al.*, 2020).

According to the standard used for international assessments, the forest area in Poland currently amounts to 9,463,000 ha, which corresponds to a forest cover of 30.9% (Raport, 2020). The ownership structure is dominated by public forests comprising 80.7%, of which 76.9% are managed by the State Forests National Forest Holding (SF-NFH) (Raport, 2020).

Under the management of 430 SF-NFH forest districts, there is a total of 106,640 km of internal roads of various ranks in the networks of forest transport areas, ranging from main and secondary roads to access and technological roads (Trzciński *et al.*, 2016). Maintenance of such an extensive road network requires significant financial outlays, which amounted to almost PLN 2.3 billion in 2010-2014 (Młynarczyk, 2015).

Improving road infrastructure in Polish forests is one of the most important strategic tasks for the SF-NFH (Strategia, 2013). One of the ways to facilitate the achievement of this goal is the rational development of forest road infrastructure, the backbone of which is currently a network of fire access roads. It is estimated that currently fire access roads account for almost 50% of the length of all roads in the SF-NFH (Trzciński *et al.*, 2016). The density and geometric parameters of the fire access road network should ultimately enable rapid and safe firefighting operations in forested areas, which is particularly important in times of dramatically increasing wildfire risk (Goldammer and Nikolov, 2009; Spracklen *et al.*, 2009; De Rigo *et al.*, 2017; USGCRP, 2017; Resco de Dios and Nolan, 2021).

The aim of this study was to synthesise information on the construction technology of forest roads in Poland, the load-bearing capacity of their surfaces, and current and future problems related to the modernization and maintenance of forest road networks.

Number and quality of forest roads in Poland

Forest roads play a key role in protection activities – especially in fire protection, as all ground activities are closely linked to the presence of forest roads for access to fire perimeters. Insufficient density of the road network also leads to excessive expansion of timber skidding, which is the most expensive phase of timber transport (per m^3/km). Cost reduction can be achieved mainly by a sufficiently dense road network in the forests. The optimal road density is determined by many factors. For Polish conditions, these include fire hazard category, terrain, size and technology of timber harvesting, size of forest complexes, location of public road network and roads of other owners, and presence of protected areas (Czerniak *et al.*, 2016).

The average road density in forest areas managed by SF-NFH is 15.28 m/ha and varies from 8.87 to 23.17 m/ha in the individual regional directorates (RDSF) of SF-NFH (Table 1). Unfortunately, the variability of road density in forest districts assigned to RDSFs is much higher, ranging from 0.75 to 76.11 m/ha (Czerniak *et al.*, 2016). Nevertheless, in many cases the reported values of road density do not deviate significantly from the suggested optimal values for Polish forests (from 5.00 to 34.90 m/ha) and are in line with data from other European countries: Croatia 7-30 m/ha (Pentek *et al.*, 2011), Slovenia ~25 m/ha (Krč and Beguš, 2013), Bosnia and

Table 1.
Length, density, useful life and technical condition of forest roads in Poland (Czerniak et al., 2016)

RDSF[1]	Length [km]	Density [m/ha]	Useful life [years]					Technical condition[2]			
			0-10	11-20	21-30	31-40	>40	I	II	III	IV
Białystok	11845	21.01	6157	1077	636	345	3630	2555	5405	3131	741
Gdańsk	3642	12.97	3303	196	87	48	9	1678	1283	395	286
Katowice	13606	23.17	6866	2367	1053	394	2930	3289	6243	622	3453
Kraków	1802	10.78	813	218	247	147	376	915	555	204	127
Krosno	3518	8.87	1918	505	555	341	200	1536	1028	416	537
Lublin	7523	19.35	5802	869	408	165	279	1852	4022	281	1367
Łódź	4539	16.23	3590	101	646	159	44	1109	2105	194	1128
Olsztyn	5977	10.71	5072	484	288	84	49	2090	2676	701	510
Piła	5610	16.94	4263	798	522	27	1	2714	1908	355	634
Poznań	5687	14.15	2669	1568	163	288	996	2520	2378	366	423
Radom	4786	15.61	3808	554	208	109	107	856	1936	512	1481
Szczecin	7064	11.21	4804	1343	375	123	412	2279	2238	1210	1336
Szczecinek	7869	14.01	6202	621	773	251	28	2595	3314	360	1599
Toruń	5613	13.59	4735	171	436	54	217	1710	2682	527	579
Warszawa	2372	13.19	1981	99	113	12	168	918	1045	59	349
Wrocław	10360	20.15	5523	2951	416	298	1172	2193	4583	1199	2385
Zielona Góra	4827	11.58	3585	639	341	5	257	861	1970	1143	852
SF-NFH	106640	15.28	71090	14561	7266	2850	10873	31671	45371	11677	17788

[1]RDSF: regional directorate of State Forests – National Forest Holding; [2]technical condition of forest roads: I – good, II – average, III – satisfactory, IV – poor

Herzegovina 8-10 m/ha (Petković and Potočnik, 2018), Finland 4-20 m/ha (Płotkowski *et al.*, 2012), France 30-40 m/ha (Piekutin *et al.*, 2015), and Austria 45 m/ha on average (Ghaffaria *et al.*, 2009). Moreover, the actual density of forest roads accessible to heavy transport vehicles is lower than the indicated overall density of the road network, because a significant proportion of roads have insufficient carrying capacity (see next section).

More optimistic data concern the lifespan of forest roads (Table 1). According to the data collected, 74% of all forest roads in SF-NFH are used within 10 years. It is also encouraging that 72% of forest roads were classified as being in good and medium technical condition.

Technologies for forest road construction

A large majority of forest roads in Poland have an earthen surface (71%; Fig. 1a, 2a, 2b). Surfaces consisting of gravel, crushed stone, slag, cobblestones, etc. (so-called unpaved roads) are found on about 20% of the total length of all forest roads (Fig. 1a, 2c, 2d, 2e), while paved roads (mainly bitumen or concrete, Fig. 1a, 2f) account for only 9% of their length (Trzciński and Czerniak, 2017). Unfortunately, detailed information on the proportion of each surface type on SF-NFH roads is not available. Published data cover less than 25% of forest roads classified as fixed assets by forest districts. This group of roads is dominated by road surfaces made of crushed stone and gravel (Fig. 1b).

Out of almost 57,000 km of forest roads with natural earthen surface, 28% of roads are in a technical condition that does not require repairs, while 25% are in poor technical condition (Trzciński and Czerniak, 2017). In this respect, the situation is better for roads with a solid surface (unpaved and paved). In this group, about 65% of roads are in a technical condition that does not require rehabilitation, while a total of 1,754 km of roads are in a poor technical condition (Trzciński and Czerniak, 2017).

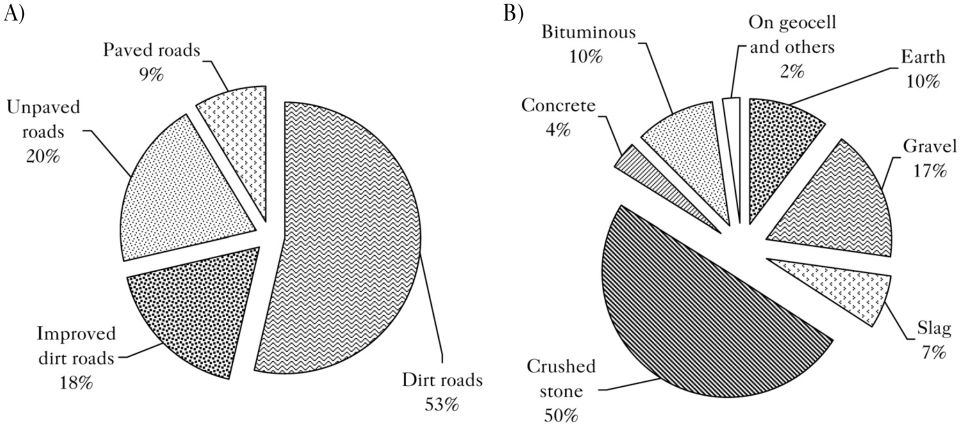

Fig. 1.

A. Types of forest roads in areas managed by SF-NFH (total length 106,640 km) (Trzciński and Czerniak, 2017). B. Basic surface types of forest roads in areas managed by SF-NFH (only roads classified as fixed assets by SF-NFH with total length 25,816 km are listed) (Czerniak *et al.*, 2016).

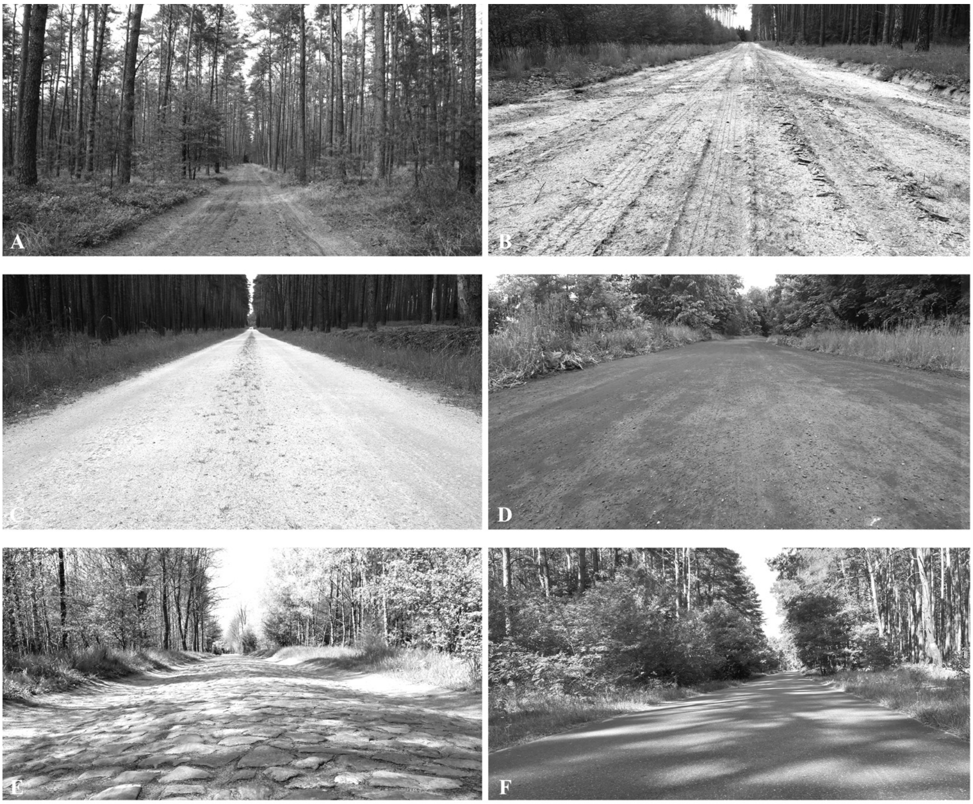

Fig. 2.

A. Unprofiled dirt road in the Oborniki Forest District. B. Profiled dirt road in the Oborniki Forest District. C. Macadam forest road in the Oborniki Forest District. D. Forest road with slag coating in the Oborniki Forest District. E. Forest road with cobblestones in the Szubin Forest District. F. Forest road with bituminous surfacing in the Wronki Forest District (photos: S.M. Grajewski).

Nowadays, Polish forest road construction is dominated by technologies based on different types of aggregates, which are most often incorporated into construction based on the McAdam concept (Fig. 2c, 3, 4). To minimise the negative impact of road infrastructure on the natural environment, materials of natural origin are preferred in the construction of forest roads; they are safe for the ecosystem and offer the possibility of more effective harmonisation of the road with the forest environment. Therefore, natural aggregates from crushing of solid rock of 0-4 mm, 4-31 mm, 31.5-63.0 mm (alternatively road aggregates of 0-31.5 mm and 0-63.0 mm, which are slightly cheaper to purchase) and other natural aggregates such as gravel, sandy gravel, and sand are most commonly used. Nevertheless, approved substitutes for natural aggregates obtained from recycled construction materials such as bricks or concrete are increasingly used in forest road construction (Grajewski, 2019).

Since the costs of purchasing and transporting aggregates and the associated loads on access roads are high, it is advisable to use solutions that allow the thickness of construction layers to be reduced without risking a loss of load-bearing capacity of the road surface. An important aspect is also the isolation of the costly material from the road subgrade, in the case of laying aggregate sub-base on weak bearing soils, which makes it possible to keep the thickness of the layers constant and maintain the required bearing capacity throughout the life of the road (Zhang and Hurta, 2008; Elleboudy *et al.*, 2017). In Polish forests, different types of solutions have been used so far, such as fascine layers, sandy separation layers, or non-woven geotextile fleeces (Dzikowski *et al.*, 2006; Trzciński, 2011; Kozakiewicz and Trzciński, 2020; Fig. 3). Recently, modern planar and spatial geosynthetics (woven geotextiles, biaxial or triaxial geogrids, geocells) have become very helpful, as they are much better at reinforcing the pavement than geotextiles and geogrids that have been on the market for a long time (Ashmawy and Bourdeau, 1996; Latha *et al.*, 2010; Hegde, 2017; Fig. 4, 5, 6a).

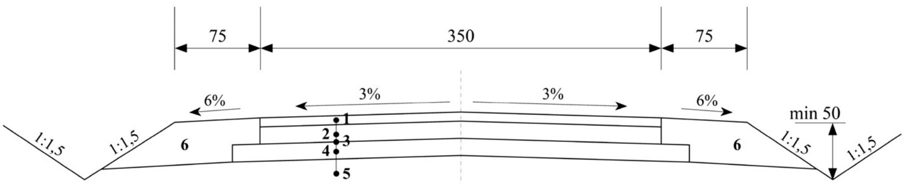

Fig. 3.

Construction of a forest road from aggregates laid on non-woven geotextile in the Oborniki Forest District

1. Quarry aggregate 0/31.5 mm with quarry aggregate seal 0/4 mm – 8 cm. 2. Quarry aggregate 0/63.0 mm – 15 cm. 3. Non-woven geotextile (tensile strenght ≥10 kN/m, CBR static puncture resitance ≥1600 N,water permeability ≥90 mm/s) – width 450 cm. 4. Composite sand – 15 cm. 5. High bearing capacity road subgrade (non-frost sensitive soils), aligned and without humus. 6. Road shoulders from original soil.

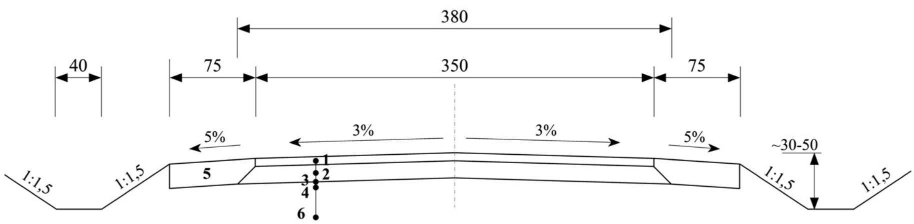

Fig. 4.

Construction of a forest road from aggregates reinforced with biaxial geogrids and non-woven geotextile in the Dąbrowa Forest District

1. Quarry aggregate 0/31.5 mm or 4/31.5 mm with quarry aggregate seal 0/4 mm – 7 cm. 2. Quarry aggregate 0/63.0 mm or 31.5/63.0 – 15 cm. 3. Biaxial geogrid made of polypropylene (mesh size ≤40×40 mm, tensile strenght ≥20 kN/m). 4. Non-woven geotextile (tensile strenght ≥10 kN/m, CBR static puncture resitance ≥1600 N,water permeability ≥90 mm/s). 5. Road shoulders made of soil from profiling and bedding construction. 6. High bearning capacity road subgrade (non-frost sensitive soils), aligned and without humus.

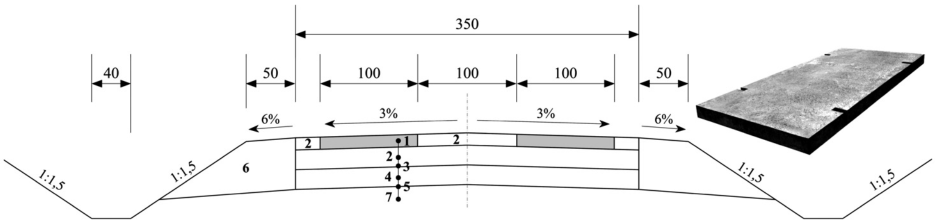

Fig. 5.

Construction of a forest road made of reinforced concrete slabs on an aggregate reinforced with biaxial geogrids and woven geotextile in the Sieraków Forest District

1. Reinforced concrete road slab (300×100×15 cm). 2. Quarry aggregate 0/31.5 mm – 15 cm. 3. Biaxial geogrid of polypropylene (mesh size 35×35 mm, tensile strenght ≥48 kN/m). 4. Medium sand, all-in aggregate or gravel. 5. Woven geotextile (tensile strenght ≥25kN/m, CBR static puncture resistance ≥3000 N, water permeability ≥70 mm/s). 6. Road shoulders of load bearing soil (sand, all-in aggregate, gravel). 7. Non-bearing road subgrade, aligned and without humus.

Fig. 6.

A. Construction of a forest road in the Dąbrowa Forest District – aggregates on a layer of biaxial geogrid and non-woven geotextile. B. Forest road with rolled concrete technology in the Warcino Forest District. C. Forest road with road slabs in the Sieraków Forest District. D. Forest road with openwork concrete slabs in the Oborniki Forest District. E. Forest road with PDTP concrete slabs (120×80×16 cm) in the Sieraków Forest District. F. Modernised slag forest road in the Włocławek Forest District: 0/4 cm double dressing with stone chippings 2/5 mm and 8/11 mm, 4-12 cm gravel or crushed limestone 0/31.5 mm, 12-37 cm furnace slag mixed with crushed limestone or crushed concrete 16/31.5 mm to improve grading, 37-80 cm embankment for non-structural purposes, 80-300 cm fine sand (photos: S.M. Grajewski).

In the 21st century, forest managers are increasingly using much more expensive, but also more efficient, methods of forest road construction on particularly heavily used sections. For example, bituminous or concrete surfaces – made of poured or rolled concrete – are increasingly used in Polish forests (Fig. 6b). An alternative to these costly solutions are technologies using prefabricated concrete elements (Fig. 5, 6c, 6d, 6e, 7) or single/double surface treatment of existing forest road pavements with asphalt emulsions (Fig. 6f).

To address the growing interest of SF-NFH in the construction of roads with concrete slabs, a new type of self-draining concrete slab for the construction of permanent and temporary roads was recently developed and filed for patent (Czerniak *et al.*, 2019).

Load-bearing capacity of road surfaces

The bearing capacity of a pavement can be defined as its ability to carry traffic loads without excessive deformation that would interfere with the normal use of the pavement or shorten its life. In other words, the pavement should have a bearing capacity that will provide the durability required by the regulations, or assumed by the designer and desired by the developer under current and projected traffic loads. In Poland, the bearing capacity of forest roads is most often measured by determining the modulus with a static plate (deformation modulus at the 1st – E_1 and the 2nd – E_2 loading), or increasingly with a light falling-weight deflectometer (dynamic deformation modulus – E_{vd}). A detailed description of static plate tests can be found in the articles by Mackiewicz and Krawczyk (2015) and Czerniak *et al.* (2021).

The results of static plate tests on 86 forest road sections show that the lowest values of E_2 are characteristic of pavements made of natural soils (I, II, III*, IV) (Fig. 8; Trzciński, 2011; Grajewski, 2019), which due to their high susceptibility to permanent deformation lead to significant pavement damage even at low traffic intensity (Trzciński and Kaczmarzyk, 2006; Grajewski, 2019). On the other hand, surprisingly, the highest bearing capacity was demonstrated for pavements made of optimal mixtures of natural aggregates (XI). Also noteworthy are the significantly better bearing capacity parameters obtained for classical gravel pavements with macadam technology compared to pavements made of other aggregates (XIV vs XIII, Fig. 8, 9). The relatively low efficiency of geosynthetics (XVI, XVII, XVIII*) is the result of their use on extremely low load-bearing road subgrade, which does not exclude this type of solution from use on forest roads (Fig. 8). According to Kamiński (2007), forest road surfaces reinforced with flat and spatial geosynthetics are characterised by high resistance to deformation despite low values of the deformation modulus. This means that they can be successfully used to maintain

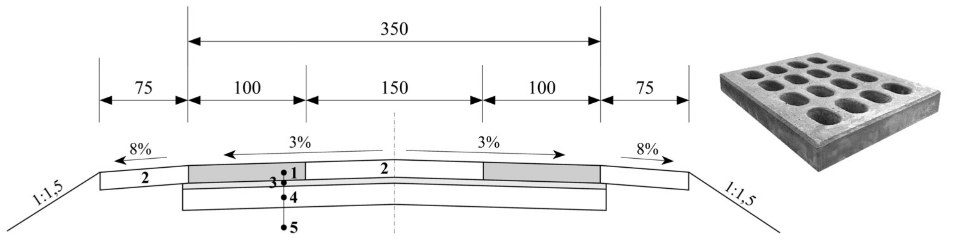

Fig. 7.

Construction of a forest road made of openwork reinforced concrete slabs laid on aggregates in the Oborniki Forest District

1. Openwork reinforced concrete road slab (100×75×15 cm). 2. Quarry aggregate 0/31.5 mm – 15 cm. 3. Cement-sand laying layer – 5 cm. 4. Quarry aggregate 0/63.0 mm – 18 cm. 5. High bearing capacity road subgrade (non-frost sensitive soils), aligned and without humus.

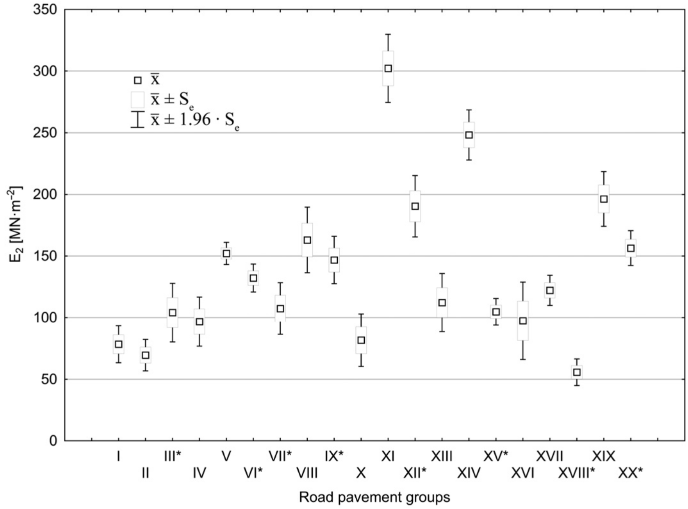

Fig. 8.

Values of the deformation modulus after the 2nd loading cycle of the static plate (E_2) in relation to the pavement groups: I – natural non-profiled dirt roads, II – profiled dirt roads, III* – dirt roads, IV – improved dirt roads, V – sandy gravel or gravel roads, VI* – single layer gravel roads, VII* – double layer gravel roads, VIII – roads with furnace slag, IX* – roads with furnace slag, X – roads with recycled aggregates (concrete rubble, construction debris, brick rubble, track bed mix), XI – roads with optimal aggregate mix, XII* – roads with natural aggregate, XIII – roads with crushed stone, XIV – roads with crushed stone in macadam structure, XV* – roads with basalt aggregate, XVI – roads with crushed stone on woven geotextile or geogrid, XVII – roads with geocells, XVIII* – roads with geocells, XIX – roads with double dressing pavement, XX* – bituminous roads (Grajewski, 2019; *Trzciński, 2011).

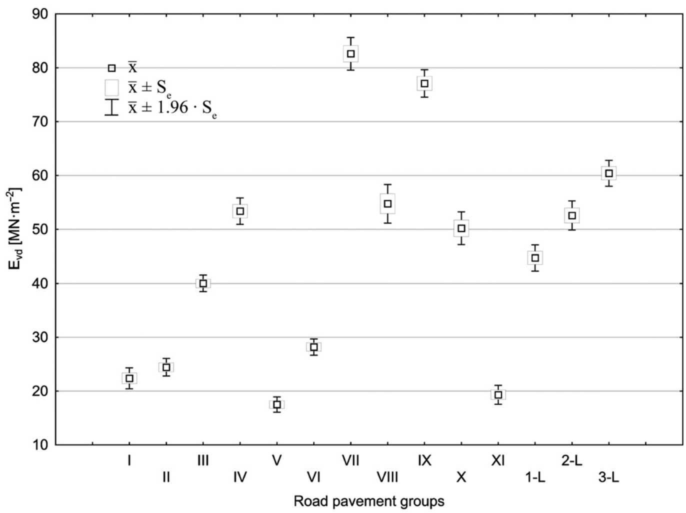

Fig. 9.

Statistics for dynamic deformation modulus E_{vd} (Zorn, ZFG 3000, 300 mm pressure plate, 10 kg drop weight) for pavement variants of forest roads: I – natural, non-profiled dirt roads, II – profiled dirt roads, III – improved dirt roads, IV – sandy gravel or gravel roads, V – roads with furnace slag, VI – roads with recycled aggregates (concrete rubble, construction debris, brick rubble, track bed mix), VII – roads with optimal aggregate mix, VIII – roads with crushed stone, IX – roads with crushed stone and macadam structure, X – roads with crushed stone on geogrids, XI – roads with geocells, 1-L – roads with one-layer surface, 2-L – roads with two-layer surface, 3-L – roads with three or more layers (Grajewski, 2019).

the passability of forest roads, especially those that have an important function as fire access roads.

The LFWD tests of 52 forest road sections lead to similar conclusions (Fig. 9). In this case, the low E_{vd} values for pavements made of slag (V), geocells (XI) and recycled aggregates (VI) are also related to the construction of roads on extremely low load-bearing road subgrades (marshy areas). In this study, the expected increase in bearing capacity with the increase in the number of applied layers of the road structure was confirmed (Fig. 9).

Construction and operational problems

Adaptation of road networks to economic, natural, and social conditions has recently become an important need of forestry in many countries of the world (*e.g.* Hrůza, 2003; Kašková, 2004; Olsson and Lohmander, 2005; Demir, 2007; Henningsson *et al.*, 2007; Gumus *et al.*, 2008; Ghaffariyan *et al.*, 2010; Sosa-Pérez and MacDonald, 2017; Petković and Potočnik, 2018; Kazama *et al.*, 2021). In Poland, forest road network optimization was carried out in all SF-NFH units. This process reduced the length of forest roads to the minimum necessary, while rationalising the costs of their construction, repair and maintenance in individual units and prioritising the needs in this area (Instrukcja, 2018).

Practise shows that a newly built forest road does not always meet the investor's expectations. The soundness of the soil and water conditions in the investment area, the correctness of the accepted design solutions, the correctness of road construction, and the appropriate quality of the construction materials used guarantee that the final result will be correct. An objective measure of the quality of road works can be measured objectively by evaluating the bearing capacity parameters of the road surface.

One of the biggest problems related to the construction and subsequent operation of forest roads in Poland is their insufficient bearing capacity (Kamiński and Czerniak, 2001, 2003; Miler *et al.*, 2008; Trzciński, 2011; Grajewski, 2019). Among the most common reasons for the lack of correct values for the bearing capacity parameters are (Grajewski, 2019):

– incorrect recognition of geotechnical conditions and lack of adaptation of technical solutions to them, *i.e.* pavement construction, drainage elements;
– improper compaction of the layers of the pavement structure and the road subgrade;
– unsuitable choice of the pavement structure for the geotechnical conditions, *e.g.*, aggregate layers that are too thin;
– paving without removing the organic layer of soil;
– surface courses of inferior construction materials – in particular improperly graded aggregate, dusty road aggregate;
– failure to use materials that separate the weak road subgrade from the surface courses.

Intensively invested road networks require large-scale, careful inspections of the correctness of the construction work, *e.g.*, with regard to the load-bearing capacity and degree of compaction of the road materials used. Therefore, the monitoring authorities must have suitable equipment that allows a simple, quick and authoritative assessment of the quality of the work. In this regard, high hopes rest on the appearance of the LFWD on the market, whose use in the units of SF-NFH is becoming increasingly popular.

The use of geosynthetic materials in forest road construction sometimes causes problems in the operation of forest roads (Grajewski, 2019). Namely, insufficient thickness of the aggregate layer covering the geosynthetic material and subsequent migration of the rock material from the geocells lead to the destruction of the geosynthetic, for example, during maintenance and repair

(Fig. 10). It is worth noting that the application of a cellular geogrid must be accompanied by backfilling with suitable and properly compacted aggregate, because errors in this respect can lead to a reduction in load-bearing capacity by up to 30% (Kamiński and Czerniak, 2003).

In Poland, it is illegal for unauthorised persons to drive a motorised vehicle on a forest road. However, the growing interest in forest recreation leads to the need to make forest roads accessible to public traffic. Special marking is needed to ensure the safety of users of such roads and to improve traffic circulation. Currently, the units of SF-NFH are in the process of implementing a system for standardised marking of forest roads, with special emphasis on roads accessible to public traffic (Fig. 11).

Perspectives of forest road engineering

The results of research on road density in forest areas show that the investment focus of SF-NFH in the coming years should be on optimising their road networks, taking into account conditions related to fire hazard category, terrain, size and technologies of timber harvesting, size and number of forest complexes, location of public roads or roads of other owners, and the presence of protected areas. It will also be important to increase the share of hard-surfaced roads on which high tonnage vehicles can travel (Trzciński, 2011).

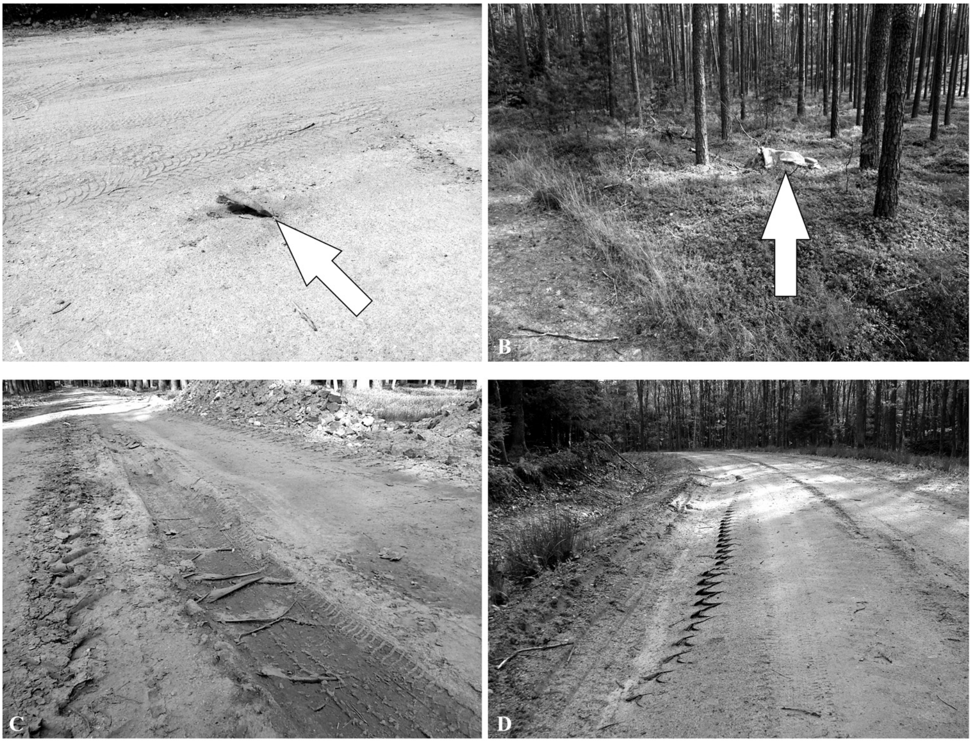

Fig. 10.

Damage to the pavement of forest roads reinforced with geosynthetics. A. An insufficiently thick top layer of gravelly sand as the cause of damage to the non-woven geotextile during the levelling of the pavement. B. Non-woven geotextile removed from the road structure during the levelling of the pavement and deposited in the forest. C. Lack of a top layer as a cause of destruction of the geocell reinforced subgrade. D. Vehicle traffic and roadside erosion on a curve as a cause of destruction of the edge of the geocell reinforced pavement (photos: S.M. Grajewski).

Fig. 11.

Standardised marking of forest roads in the units of SF-NFH. A. Sieraków Forest District – marking of a forest road open to public traffic with the speed limit. B. Wronki Forest District – sign reminding that use of forest roads by motor vehicles is prohibited (photos: S.M. Grajewski).

Road surfaces made of native soil, which are otherwise the most natural, can have a resistance to traffic that varies greatly in time and space, depending on soil characteristics and weather conditions. During periods of intensive use, even when weather conditions are favourable, these roads are heavily stressed, degrade easily, and often become impassable. Increasing the carrying capacity of such areas will be a priority for forest owners and managers in the near future. Especially given the projected increase in forest fire risk, it will be important to further reduce the time it takes fire engines to reach the source of the fire. This time is partly determined by the parameters of the access roads used in rescue operations (Hulida *et al.*, 2017). At the same time, this does not mean that all roads in SF-NFH must have a surface other than dirt.

So far, neither requirements for bearing capacity of road surfaces nor catalogues of typical road designs for forest road construction have been developed in Poland. Therefore, minimum bearing capacity criteria are adopted based on scattered information, mainly applicable to public roads (PN-S-96023:1984; OST D-05.02.01:1998; Rolla, 1985; Kamiński, 2012). Only recently, a first attempt was made to develop a set of guidelines (Czerniak *et al.*, 2021). There is an urgent need to continue research to develop standards for the bearing capacity of typical pavement structures recommended for use in forestry.

Measurements, surveys, and evaluations accompany road investments throughout their life cycle, beginning with the collection of site information. Inspections of the integrity of road works are necessary and should be carried out not only after completion of the investment, but also at each stage of its implementation. The methods used to check bearing capacity in Polish forests have required appropriate preparation and have been time-consuming or expensive. One possibility for change is seen in the use of LFWD. Unfortunately, the use of this device has not yet been officially standardised in Poland. Therefore, the results of LFWD measurements usually have to be referenced to other accepted methods. Previous research has not led to the development of simple, universal, and at the same time sufficiently strong correlations between the dynamic deformation modulus and other geotechnical parameters (Livneh and Goldberg, 2001; Fleming *et al.*, 2002; Nazzal *et al.*, 2004; Alshibli *et al.*, 2005; White *et al.*, 2007; Tompai, 2008; Abulkareem, 2018). The main reason for this is that the result of the LFWD measurement depends not only on the properties of the layer under test, but also, to varying degrees, on a number of other factors related both to the way the measurement is made and to the design of the device used (how the test site is prepared, the position and type of sensor measuring the plate displacement, the value of the contact stress, the stiffness of the compression plate, the radius of the compression plate). Therefore, correlations from the literature are of rather limited use, as they require a high degree of similarity in the performance of the test with respect to the material tested, the measurement conditions, or the device used and its configuration.

Hope for building inspectors can found in the results of a comparison of 245 measurements between LFWD and static plate (Fig. 12). The great variability of the results does not support a strong correlation between the two test methods. Nevertheless, the fact that less than 10% of the results are lower than the value of the E_2 modulus calculated by doubling the value of the dynamic deformation modulus justifies the use of this device in the quality control of road works. However, it should be kept in mind that before obtaining reliable LFWD test results, it is always necessary to establish correlations with static plate tests for a given road section. At the same time, it should be remembered that LFWD is perfect for diagnostic testing, in that it allows numerous measurements to be taken in a relatively short time and provides the ability to mark the weakest areas of the structure where tests can be carried out using one of the recognised methods, if required.

Given the still significant need for investment in forest road infrastructure, there is a need to promote the wider use of geosynthetic materials (Sakai, 2017). Geosynthetics allow forest roads to be constructed on a very weak subgrade while reducing the amount of material needed to achieve the required pavement performance (*e.g.* Leonardi and Buonsanti, 2012; Dewangan *et al.*, 2013; Ingle and Bhosale, 2017). By reducing rutting or increasing the resistance to fatigue cracking in bituminous layers, geosynthetics also allow the life of road pavements to be extended by up to several times (Berg *et al.*, 2000; Zhang and Hurta, 2008; Al-Qadi *et al.*, 2011; Calvarano *et al.*, 2016). This alternative can reduce the cost of road maintenance and significantly extend the intervals between overhauls (Leonardi *et al.*, 2012).

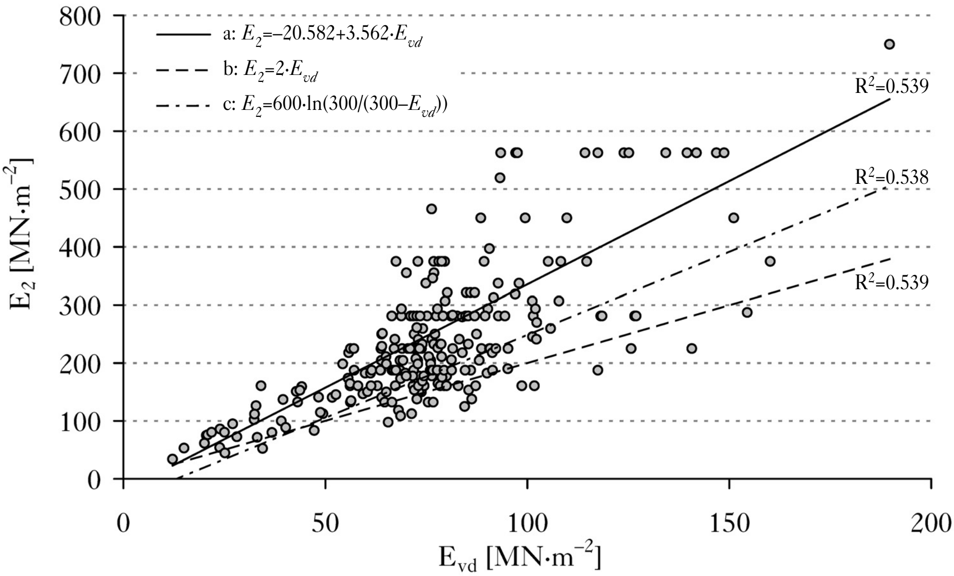

Fig. 12.

Estimation of the static constraint modulus during secondary compression (E_2) based on the values of the dynamic deformation modulus (E_{vd}) according to: (a) the original linear regression model proposed by Grajewski (2019), (b) the simplified conversion from E_{vd} to E_2 sometimes used in practise, (c) the formula allowed in the absence of data on other dependencies between E_{vd} and E_2 (Livneh and Goldberg, 2001), in view of bearing capacity measurements carried out with a static plate on 245 forest road sections (Grajewski, 2019; modified).

Another important problem that needs to be addressed in the future is the development of effective and rapid techniques for inventorying the technical condition of forest roads. Up-to-date information on the condition of roads will allow forest managers to properly organise economic work and conduct efficient and safe rescue and firefighting operations. The technical condition of forest roads is threatened not only by economic activities (*e.g.*, timber harvesting), but also by deteriorating weather phenomena (Sakai, 2017; Aruga *et al.*, 2021). Nowadays, the assessment of the technical condition of roads is largely carried out in the context of visual inventories, which are not only burdened with the subjectivity of observers, but are also time-consuming. Previous attempts to automate this process have given rise to high hopes for success (Zuo and Yao, 2013; Wyczałek and Pożarycki, 2014; Waga *et al.*, 2020; Buján *et al.*, 2021; Lei *et al.*, 2021).

Conclusions

The development of forests through a forest road network is a costly part of the forestry investment process. The economic issue of building and developing forest roads is closely related to the design of road density, the cost of construction and maintenance, and the amount of timber harvested from a unit of forest land. The units of the SF-NFH will have to make efforts to adapt their road network to the optimal density envisaged for them, while the main investment burden is not so much related to the construction of new roads as it is to the need to increase the percentage of hard-surfaced roads to allow for the movement of high tonnage vehicles, both for timber transport and for rescue and fire-fighting operations.

The load-bearing capacity of forest roads is not always sufficient. This problem mainly affects earthen surfaces and structures constructed on subgrades with low load-bearing capacity. The passability of a road section for occasional traffic may be insufficient if the road is to be used permanently for timber transport with heavy trucks. In such a situation, it is necessary to raise the bearing capacity to the values required for this type of transport.

The results of the studies on the bearing capacity of forest roads show that the bearing capacity parameters of these roads are very variable. Not only do they depend on the type of road construction and the road base used, but their variability is likely to be determined to a large extent by the quality of the construction work and the design errors made. Therefore, there is an urgent need to intensify monitoring on the part of investors, both at the stage of preparing the construction project and during the actual construction.

As the use of LFWD to assess the bearing capacity and compaction quality of road subgrade and road structure layers is becoming more common on SF-NFH, it is advisable to continue the search for correlations between LFWD test results and static plate measurement results for various types of forest road surfaces. The outcome of this research should be the development of empirical models that allow the results of LFWD tests to be used to evaluate the values of the primary and secondary strain modulus. The use of geosynthetics in forest road construction is likely to become more widespread, not only for reinforcing low-performing soils or for constructing drainage facilities, but also for erosion control, for which biodegradable materials are particularly suitable.

The need to update comprehensive databases on the technical condition of forest road infrastructure requires continuating research to develop fast, efficient, and reliable, but not necessarily fully autonomous, methods for collecting information on geometric parameters and the load-bearing capacity of forest roads. Only with up-to-date data is it possible to properly organise road traffic in connection with economic activities or rescue and fire-fighting operations.

Conflicts of interest

The author declares no conflict of interest.

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STRESZCZENIE

Drogownictwo leśne w Polsce: stan obecny i perspektywy rozwoju

Współcześnie w Polsce zdecydowana większość dróg leśnych ma nawierzchnie gruntowe (ryc. 1, 2a, 2b). Nawierzchnie ze żwiru, tłucznia, żużla, bruku itp. (twarde nieulepszone) występują na około 20% sumarycznej długości wszystkich dróg leśnych (ryc. 2c, 2d, 2e), a twarde ulepszone, głównie bitumiczne, względnie betonowe, stanowią tylko 9% ich długości (ryc. 2f). Z prawie 57 tys. km dróg leśnych o nawierzchni gruntowej naturalnej w stanie technicznym niewymagającym żadnych zabiegów remontowych jest 28% dróg, natomiast w stanie technicznym złym aż 25% (tab. 1). W grupie nawierzchni twardych w stanie technicznym niewymagającym żadnych zabiegów remontowych sklasyfikowano około 65% dróg, natomiast w złym stanie technicznym jest łącznie 1754 km dróg. Średnia gęstość sieci dróg w polskich lasach (15,28 m/ha) wpisuje się w deklarowane gęstości znane z niektórych krajów europejskich (tab. 1). Głównym problemem jest znaczne zróżnicowanie przestrzenne tego parametru oraz niewielki udział dróg o nawierzchniach utwardzonych. Poprawa infrastruktury drogowej jest jednym z ważniejszych zadań strate-

gicznych stojących przed Państwowym Gospodarstwem Leśnym Lasy Państwowe (PGL LP). Realizacji tego celu ma sprzyjać m.in. racjonalny rozwój drogowej infrastruktury leśnej, której szkieletem jest obecnie sieć dróg leśnych pełniących rolę dojazdów pożarowych. Zagęszczenie oraz parametry geometryczne sieci dojazdów pożarowych mają docelowo umożliwiać szybkie i bezpieczne prowadzenie akcji gaśniczych na terenach leśnych, co jest szczególnie ważne w czasach dramatycznego wzrostu zagrożenia pożarowego lasów.

W polskim leśnym budownictwie drogowym dominują technologie bazujące na różnego rodzaju kruszywach wbudowywanych zazwyczaj wg klasycznej koncepcji McAdama (ryc. 2c, 3, 4), a minimalizowanie negatywnego oddziaływania infrastruktury drogowej na środowisko skutkuje preferowaniem materiałów pochodzenia naturalnego. Stąd najczęściej korzysta się z kruszyw naturalnych, pochodzących z kruszenia skał litych oraz innych kruszyw, m.in. żwirów, pospółek i piasków. Niemniej w konstrukcjach nawierzchni coraz częściej znaleźć można zamienniki kruszyw naturalnych, pochodzące z recyklingu materiałów budowlanych, np. cegły czy betonu. Wprowadzane do budownictwa drogowego materiały geosyntetyczne zasługują na propagowanie (ryc. 3, 4, 5a). Umożliwiają one budowanie dróg na bardzo słabych podłożach, ograniczając jednocześnie ilość materiału niezbędnego do osiągnięcia wymaganych parametrów nawierzchni. Dodatkowo, opóźniając proces deformacji nawierzchni, pozwalają na nawet kilkukrotne wydłużenie jej trwałości, dzięki czemu możliwa jest redukcja kosztów utrzymania dróg i wydłużenie okresów między kolejnymi remontami. Na odcinkach szczególnie intensywnie eksploatowanych coraz częściej stosowane są droższe, ale i efektywniejsze metody budowy dróg leśnych. Stąd w polskich lasach coraz częściej spotkać można nawierzchnie bitumiczne czy betonowe (ryc. 6b). Alternatywą dla tych rozwiązań są technologie wykorzystujące betonowe elementy prefabrykowane (ryc. 5, 6c, 6d, 6e, 7) czy też oprysk emulsjami asfaltowymi (ryc. 6f).

Jednym z większych problemów związanych z eksploatacją dróg leśnych w Polsce jest ich niewystarczająca nośność. Wyniki badań zarówno płytą statyczną, jak i lekką płytą dynamiczną wskazują, że najniższymi wartościami parametrów nośności charakteryzują się nawierzchnie z gruntów naturalnych (ryc. 8, 9). Z kolei największą nośność wykazano dla nawierzchni wykonanych z optymalnych mieszanek kruszyw naturalnych. Na uwagę zasługują również wyraźnie lepsze parametry nośności uzyskiwane dla klasycznych nawierzchni tłuczniowych budowanych w technologii nawierzchni macadamowej w porównaniu do pozostałych nawierzchni z kruszyw. Relatywnie mała efektywność geosyntetyków jest skutkiem używania ich na wybitnie nienośnych podłożach drogowych (ryc. 8, 9). Warto w tym miejscu nadmienić, że niewłaściwe wykorzystywanie materiałów geosyntetycznych jest niekiedy przyczyną problemów eksploatacyjnych (ryc. 10).

Szeroki zakres realizowanych inwestycji drogowych wymaga wsparcia ze strony szybkich i miarodajnych metod oceny jakości robót budowlanych. Duże nadzieje w tym względzie wiąże się z wypracowaniem standardów nawierzchni drogowych oraz użyciem lekkiej płyty dynamicznej. Problemem wymagającym rozwiązania w najbliższej przyszłości jest opracowanie efektywnych i szybkich technik inwentaryzacji stanu technicznego sieci drogowych oraz empirycznych modeli liniowych, pozwalających na wykorzystanie wyników badań lekką płytą dynamiczną do oceny wartości wtórnego modułu odkształcenia (ryc. 12).