Environmental aspects of the implementation of geogrids for pavement optimisation

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Abstract. Technological developments in highway construction should not only result in durable, safe and cost-effective solutions for roads and pavements but also, and perhaps above all, lead to solutions that minimise the negative impact of construction on the environment. One of the ways to ensure these requirements are met is to apply technology using geosynthetics. This paper discusses the stabilisation of aggregate with hexagonal geogrids and the benefits - from the point of view of reducing the emission of harmful gases to the atmosphere - which can be realised from this approach, compared with traditional approaches. Solutions for the improvement of weak subgrades and optimisation of the entire pavement structure are discussed, along with the presentation of sample calculations of greenhouse gas emissions, carried out with the use of specialized software related to the construction of the structures in various technologies.

1. Introduction

Geosynthetics have been used widely in pavement engineering for several decades, to improve drainage efficiency and as asphalt interlayers, providing three different functions: reinforcement, stress relief (as a stress absorbing membrane interlayer - SAMI) or to act as a water barrier. The stabilising function has been recently identified by ISO as a new, separate function, different to reinforcement. As discussed in this paper, geogrids can also be used for stabilising aggregate placed on firm foundations, which is quite an innovative approach. Furthermore, the positive effect of the stabilisation of unbound aggregate layers within the pavement structure can result in reductions in layer thickness (including asphalt layers), without reducing the design life of the pavement. Verification of theoretical assumptions, made through trafficking tests, provides opportunities for pavement optimisation. This is one of possible ways for sustainable development of roads. When combined with the environmental benefits, this can be seen as a modern approach for designing asphalt pavements.

2. Mechanical stabilisation of unbound aggregate with geogrid

When unbound aggregate is placed and compacted on a layer of stiff geogrid, a geogrid/aggregate composite is created, with aggregate particles interlocked and confined within the geogrid’s stiff apertures. This composite is often referred to as “Mechanically Stabilised Layer” (MSL). In an MSL,
lateral restraint is provided by the geogrid, reducing strain and thereby increasing the stiffness of the layer, compared with a non-stabilised aggregate layer.

Figure 1. Aggregate particles interlocked within a geogrid’s apertures.

Stiff geogrid ribs resist particle movement, also under cyclic loading, preventing layer deformation. One of the effects of stabilisation of an aggregate with a geogrid is an increase in stiffness or modulus of the layer. The modulus of unbound aggregate is a function of the stress state ($\Theta$). Several relationships allowing for the calculation of aggregate modulus exist in literature, one of them is presented in AASHTO Guide for Design of Pavement Structures [1]:

$$E = k_1 \Theta^{k_2}$$  \hspace{1cm} (1)

where:

$\Theta$ - the sum of principal stresses ($\sigma_1 + \sigma_2 + \sigma_3$)

$k_1, k_2$ – constants that depend upon aggregate type.

When a trafficking load is applied to a layer, the stiff ribs of the geogrid react, preventing aggregate particles from moving laterally. This increases the horizontal principal stresses, $\sigma_2$ and $\sigma_3$, and $\Theta$ increases as a result. When $\Theta$ increases, the modulus of a layer increases and so does its bearing capacity.

Many laboratory and in-situ tests have confirmed the stiffness increase of aggregate stabilised with hexagonal geogrid. Kwon et al. [5] used a test combination of AASHTO T307 (Determining the Resilient Modulus of Soils and Aggregates) and NCHRP 598 (Repeated Load Permanent Deformation) to test both stabilised and non-stabilised, poorly graded silty gravel samples. Stabilised samples had a modulus 5% to 20% higher than non-stabilised samples. In-situ resilient modulus tests conducted with Automated Plate Load Tests (APLT) demonstrated a 5% to 30% increase in the modulus of geogrid-stabilised sections [8], [9].

3. Pavement optimisation with geogrid stabilised aggregate base

Increasing the pavement design life or reducing its thickness for a given design life, through the use of geosynthetics in an aggregate base layer is often referred to as a “Pavement optimisation”. Pavement optimisation can be described as obtaining the pavement design objectives at the most economic cost. The design objectives in most cases will be to reach the minimum traffic life requirements but the objective could also be to meet the construction programme or to meet environmental requirements, such as reducing greenhouse gas emissions during construction.

Pavement optimisation has been accepted and used to varying degrees around the world. In the US, the use of geosynthetics for pavement optimisation has been acknowledged and has been in common use for many years, being covered by the AASHTO R50-09 Standard [2]. This states: “Geosynthetics are used in the pavement structure for structural support of traffic loads over the design life of the pavement. The geosynthetic is expected to provide one or both of these benefits: (1) improved or
extended service life of the pavement, or (2) reduced thickness of the structural section”. The
document does not provide detailed design requirements or recommendations instead, it outlines the
procedure that should be undertaken by the geosynthetic manufacturer to incorporate it in a pavement
design.

One of the important requirements stated in [2] is the necessity to perform full-scale pavement
testing for any geosynthetic being considered for pavement optimisation. AASHTO R50-09 states:
“Because the benefits of geosynthetic reinforced pavement structures may not be derived theoretically,
test sections are necessary to obtain benefit quantification.” Different types of geosynthetics, and even
different types and grades of geogrids, can perform differently. Physical characteristics, such as tensile
strength, are not a good indicator of geosynthetic performance in pavements and soft soil
improvement. Strong evidence exists [3], including full scale trafficking tests, that confirms geogrids
with similar tensile strength characteristics can have quite different levels of performance. In some
cases, one type of stiff, monolithic geogrid even outperformed flexible, welded geogrid, despite the
former having twice the tensile strength.

AASHTO R50-09 recognises that design methods based upon performance testing of one type of
geosynthetic may only be applied to the use of that specific geosynthetic: “Design procedures use
experimentally derived input parameters that are often geosynthetic specific. Thus, computed
engineering designs and economic benefits are not easily translated to other geosynthetics.”

4. Trafficking tests
Between 2012 and 2016, a series of trafficking tests were performed to quantify the benefits of using
one type of geogrid in flexible pavements, in line with AASHTO R50-09 requirements. Testing of the
hexagonal triaxial stabilisation geogrid was conducted at the US Army Engineer Research and
Development Centre (ERDC) and consisted of three stages, in which multiple full-scale pavement
sections were constructed and trafficked. Details of the test sections’ arrangement, instrumentation,
trafficking and results are available in reports [4],[6],[7]; the key points are summarised below.

Test sections were constructed using typical construction equipment and technology and consisted
of 2.44m by 15.2m areas. They were built inside a hangar, to eliminate the potential influence of
variable environmental factors. The subgrade consisted of clay of either 3% or 6% CBR. The granular
base layer consisted of either 15cm or 20cm of crushed limestone. Four of the sections had a base
layer stabilised with hexagonal geogrids. Two sections had a double bituminous surface treatment (these sections are not discussed in this paper) and six had surfacing of 5cm, 7.5cm or 10cm of asphalt concrete (AC). The section build-up is shown in Figure 2.

The test sections were trafficked with the Heavy Vehicle Simulator (HVS) (Figure 3), which simulates typical heavy highway traffic for accelerated pavement testing (APT). The set-up consisted of a tandem-axle dual wheel gear loaded 90kN (Figure 4). An environmental chamber surrounded the trafficking gear, maintaining a constant temperature of 25°C ± 5.5°C, to minimise the temperature change influence on the asphalt modulus. Throughout the tests, rut depth measurements were collected. Rutting was the decisive failure mechanism of all the sections tested. Figures 5 and 6 present the results from the trafficking of test sections built on 3% and 6% CBR subgrade, respectively.

All the sections with an aggregate base layer stabilised with hexagonal geogrids outperformed the non-stabilised control section significantly. Stabilised sections with thinner asphalt and/or base layers, also performed better than the non-stabilised sections.

A good reference for analysis of APT results is to compare traffic required to produce a rut depth of 12.5mm (0.5”). 12-12.5mm rut depth is considered a failure point in many Transfer Functions (TF) used in M-EPDM, for example in the Asphalt Institute TF, Nottingham University TF and Shell TF. For sections constructed on 3% CBR subgrade, 100,000 passes of Standard Axle was needed to produce a 12.5mm rut for a section stabilised with hexagonal geogrid, while for non-stabilised sections with the same layer thickness, this rut depth was reached after 6,400 passes or 12,000 passes for a non-stabilised section with a 2.5cm thicker asphalt layer. For sections constructed on 6% CBR subgrade, 12.5mm rut depth was reached after 104,000 Standard Axle passes in the non-stabilised section, while for sections with geogrid-stabilised base layers this rut depth was never reached, even after 800,000 Standard Axle passes.

Until now, geogrids have been used typically for construction on weak and very weak soils. The ERDC test results show that this is not the only application for geogrids. A subgrade of 6% CBR (~Ev2 = 60MPa) is a relatively firm subgrade, for which typically, the use of geogrid would not be considered. However, this research demonstrates that the use of hexagonal geogrids to stabilise aggregate base layers can bring benefits to pavements constructed on firm subgrade – a novel application for geogrids. In practice, geogrids can either increase the life of a pavement, without changing its thickness; reduce the thickness of pavement layers, while maintaining required life, or a combination of the two.
Figure 5. Rut depth vs applied ESALs for sections on 3% CBR subgrade.

Figure 6. Rut depth vs applied ESALs for sections on 6% CBR subgrade.

Data gathered during APT tests, as well as data from other tests not described in this paper, has been the basis for modifying pavement design methods to allow for the influence of hexagonal geogrid on pavement life. A series of back calculations and calibrations have been performed to set design parameters in a way that calculated results match results obtained in the tests. Two design methods
have been modified: the AASHTO’93 empirical design method and the Mechanistic-Empirical Design Method.

The influence of geogrid in the AASHTO’93 pavement design method has been taken into account by modifying material factor, a, of an aggregate layer stabilised with hexagonal geogrid. Factor a is increased, however the magnitude of increase is not constant; it depends upon the bearing capacity of the subgrade, the thickness of stabilised layer and the type of hexagonal geogrid. A typical value of a is 0.14 for a crushed aggregate base, which can be increased to between 0.18 and 0.27 by incorporating a geogrid.

The Mechanistic-Empirical Design Method was modified by the addition of two separate factors reflecting the beneficial effects of a geogrid, which are taken into account simultaneously in the design.

First, the modulus of the aggregate layer stabilised with geogrid is increased by multiplying the initial value by a modulus enhancement factor. This is done in the pre-linear elastic analysis stage. Strains in the asphalt layers and the subgrade at critical points and life are then calculated, as in standard M-EPDM procedures. Finally, so-called Life Shift Factors are applied to the calculated life, both for asphalt and subgrade, to determine the final life of pavement being designed.

Special algorithms have been developed for calculating both the aggregate modulus enhancement factor and the Life Shift Factors. These algorithms take into account the thickness of asphalt layer, the stabilised layer thickness, the distance from the geogrid to the bottom of lowest asphalt layer, the distance from the geogrid to the top of subgrade, the subgrade modulus and the type of hexagonal geogrid. Sample stabilised pavement structures described later in this paper have been designed with this modified M-EPDM method.

5. Evaluating the carbon footprint in highway applications of hexagonal geogrids. The Carbon calculator tool

Incorporating geogrid into a pavement can result in the optimisation of its design. Extension of pavement life or reduction of layer thickness, while keeping the same pavement life, can bring significant financial benefits, through the reduced cost of materials, reduced cost of waste and generally more efficient use of resources, compared with traditional solutions using aggregates, concrete or steel. Important environmental benefits resulting from the use of geosynthetics can also be realised when the entire life cycle of a civil engineering project is considered [10]. This paper focuses on the environmental benefits of incorporating geogrid in a pavement structure.

The carbon footprint is the amount of carbon dioxide released into the atmosphere as a result of the activities of a particular individual, organisation or community. In terms of civil engineering, it is a assessed value relating to the amount of CO$_2$ released into the atmosphere as a result of all building processes. Carbon footprint is measured in kilograms kCO$_2$e or tonnes tCO$_2$e of carbon dioxide equivalent [11]. To assess the total carbon footprint for any civil engineering process, e.g. highway construction, it is necessary to take into account the CO$_2$ emissions for every activity relating to the process, i.e:

- Quarrying of natural aggregate fill
- Manufacturing of all materials and products e.g. concrete, steel, chemical binders, asphalt, asphalt mixes and geosynthetics
- Transportation and delivery of above materials from quarries, manufacturing facilities and plants to the project site
- Installing, placing, compacting and assembling all above materials into construction.

One geogrid manufacturer has developed software for calculating carbon emissions, the “Carbon calculator”, which uses methodology provided in PAS 2050:2011, Specification for the assessment of the life cycle greenhouse gas emissions of goods and services [12]. An independent consultant [13] was commissioned by the hexagonal geogrid manufacturer to develop this tool, which evaluates the carbon emissions savings to quantify the environmental benefits of using a MSL.
The carbon calculator estimates the carbon savings gained by using a MSL incorporating hexagonal geogrids for ground stabilisation, compared with the construction of a non-stabilised granular layer of equivalent performance. Savings are the result of a reduction in aggregate layer thickness, through the use of an MSL.

The carbon saving calculation considers an MSL and an associated non-stabilised layer for a given set of input parameters. The evaluation process can be split into three sections, as follows:

1. Determine the embodied carbon within the materials used in the construction of both highway structures at their respective “factory gates”.
   - In case of the geogrid, the polypropylene is delivered to geogrid manufacturing facility by a combination of sea and road transport (depending on the supplier’s location). The geogrid manufacturing process uses electricity and natural gas to power machinery. Embodied carbon and energy are assessed and calculated in accordance with [18] and [19] and expressed in equivalent kgCO2e/km (polypropylene transportation) and in accordance with [18] and expressed in a value of kgCO2/m2 (energy use).
   - For the aggregate component of the MSL, the calculation is based on emissions related to quarrying of the aggregate. The embodied carbon of natural aggregate is calculated based on [16] and is expressed in kgCO2/kg.

2. Assess the carbon emissions from delivering materials to site, based on the distance from the manufacturing facility (geogrid) and from the quarry (aggregate) to the project site.

3. Assess the carbon emissions for construction of the highway structures (stabilised and non-stabilised):
   - Installation of the geogrid is a manual operation and so no embodied carbon can be measured
   - The aggregate component of an MSL is typically placed and compacted using mechanical plant and these operations generate their own carbon footprint, which are taken into account in the final assessment. This is calculated in accordance with [19] and expressed in kgCO2/m2.

There are also some assumptions which the carbon calculator is based, the most important of which are:

1. The user has to be given a stabilisation scheme, providing the MSL thickness, the number of layers of geogrid required and the strength of the subgrade
2. Carbon emissions data is based on available grades of hexagonal geogrids
3. The equivalent non-stabilised thickness is calculated based on the input data
4. The calculator assumes that deformation due to construction traffic is limited to 40mm in accordance with [14].
5. Carbon emissions for the construction of both stabilised and non-stabilised layers are calculated separately and the percentage difference is presented to the user
6. Geogrid is delivered from the factory in the UK or China to the site, as chosen by the user – outward distance only
7. Aggregate is delivered to the site from quarry at a distance specified by the user – outward and return distance
8. Aggregate is compacted in accordance with [15]
9. Embodied carbon in aggregate is calculated in accordance with [16]
10. Embodied carbon in the geogrid is calculated in accordance with [12], including embodied carbon of polypropylene in accordance with [17]
11. Embodied carbon and conversion factors for fuel consumption and efficiencies are in accordance with [18]
12. Embodied carbon for container ship transportation and aggregate properties are in accordance with [19].
Table 1. Inventory of Carbon and Energy main summary [16].

| Lp. | Material                                                                 | EE - Embodied Energy [MJ/kg] | EC - Embodied Carbon [kgCO₂/kg] |
|-----|--------------------------------------------------------------------------|------------------------------|---------------------------------|
| 1   | Aggregate (gravel or crushed stone)                                      | 0.083                        | 0.0048                          |
| 2   | Bitumen, general                                                        | 51.0                         | 0.38-0.43                       |
| 3   | Asphalt, 4% (bitumen) binder content (by mass)                          | 2.86                         | 0.059                           |
| 4   | Asphalt, 8% (bitumen) binder content (by mass)                          | 5.00                         | 0.076                           |
| 5   | Polypropylene                                                           | 95.40                        | 4.98                            |
| 6   | Cement stabilised soil layer 5%                                         | 0.68                         | 0.06                            |
| 7   | Concrete 25/30MPa                                                       | 0.78                         | 0.106                           |
| 8   | Concrete blocks – 8MPa compressive strength                             | 0.59                         | 0.059                           |
| 9   | Glass fibre                                                             | 100.00                       | 8.10                            |
| 10  | Sand                                                                    | 0.081                        | 0.0048                          |
| 11  | Granite aggregate                                                       | 11.00                        | 0.64                            |
| 12  | Lime aggregate                                                          | 1.50                         | 0.087                           |

6. The carbon footprint of an entire pavement. An example of using the carbon calculator for an optimised pavement

The incorporating an MSL in a pavement design can provide environmental and economic benefits. The information gathered to determine embodied energy for materials, delivery, placement and compaction can be used to estimate the carbon footprint of an MSL when used as a part of whole pavement assessment. The data related to embodied carbon for the aggregate and bitumen components of asphalt is presented in [16] (some of the example building materials are presented in Table 1). Information included in [18] allows compaction operations to be included in the resulting evaluation of carbon footprint for asphalt layers of manufactured and installed asphalt layers (in kgCO₂/kg).

The results of sample analysis performed with the carbon calculator are presented below. The analysed pavement was designed for heavy traffic (KR7 - according to [20]). The following assumptions were made:

- Heavy traffic: KR7, pavement life > 52M 100kN axles/lane
- Subgrade strength: E2=25 MPa (G4 - according to [11])
- Length of road section: 1km
- Width at road level: 20m
- Maximum excavation for the non-stabilised and non-optimised pavement structure: 1.25m
- Maximum excavation due to stabilised (MSL) and optimised (PO) pavement structure: 0.94m
- Width at deepest applicable formation level: 25m
- Width at deepest applicable formation level due to both MSL and PO reduction: 23.7m
- The pavement is designed below the existing ground level (in the cut)
- Site: Bialystok, Podlaskie voivodeship, Poland
- Distances: between quarry and site: 25km; between the asphalt plant and site: 10km; between the site and disposal site of unacceptable soils: 10km.

The primary pavement structure with a non-stabilised granular layer (according to [20]) and a structure with an (1) MSL incorporating hexagonal geogrid (for ground stabilisation) and with (2) asphalt and aggregate base course layers incorporating hexagonal geogrid (for PO) are presented in Table 2. Both pavements were designed with an equivalent performance, to reach the same level of required life.
Table 2. Comparison of both structures - primary according to [20] and optimised with hexagonal geogrids.

| Structure layers                                      | Thickness of primary pavement structure [11] (cm) | Thickness of optimised pavement structure (cm) |
|-------------------------------------------------------|--------------------------------------------------|-----------------------------------------------|
| Wearing course, asphaltic concrete                    | 4                                                | 4                                             |
| Binder course, asphaltic concrete                      | 8                                                | 7                                             |
| Asphalt base course, asphaltic concrete               | 18                                               | 16                                            |
| Aggregate base course, C90/3                          | 20                                               | 17                                            |
| Hexagonal geogrid to stabilise aggregate base course layer, Type 1 (PO) | -                                                | X                                             |
| Sub-base aggregate course                             |                                                  |                                               |
| CBR>=60%                                              | E2=120MPa                                        | E2=120MPa                                     |
| Aggregate capping layer for existing soil improvement, CBR>=20% | 40                                               | 25                                            |
| Hexagonal geogrid to stabilise aggregate capping layer, Type 2 (MSL) | -                                                | X                                             |
| Non-woven geotextile for separation and filtration    |                                                  |                                               |
| Existing sub-soil, (G4)                              | E2=50MPa                                         | E2=50MPa                                      |
| Total thickness                                       | 125                                              | 94                                            |
| Thickness reduction                                   |                                                  | 31                                            |

Analysis using the carbon calculator obtained the following costs, plus the amount of embodied carbon, for both construction approaches (Table 3).

Table 3. Calculation results – costs and carbon emissions.

| Parameter                                      | Primary pavement structure [11] | Optimised pavement structure |
|------------------------------------------------|---------------------------------|-------------------------------|
| Cost of executing construction (million PLN)   | 6,383                           | 5,500                         |
| Carbon emissions during construction (million kgCO₂e) | 4,977                           | 3,822                         |

The use of an MSL and pavement optimisation resulted in construction cost savings of 13.8% and carbon emission savings of 23.3%.

7. Conclusion
The use of hexagonal geogrid for pavement optimisation can bring significant economic savings and environmental benefits to projects. In the opinion of the authors, the environmental aspects, particularly the calculation of the reduction of CO₂, should become a standard check procedure at the design stage for any kind of road. The example calculations shown in the paper confirm the potential benefits of pavement optimisation in terms of protecting the environment.

References:
[1] American Association of State Highway and Transportation Officials 1993 *AASHTO Guide for Design of Pavement Structures*, Washington, USA
[2] American Association of State Highway and Transportation Officials 2009 *Standard Practice for Geosynthetic Reinforcement of the Aggregate Base Course of Flexible Pavement*
Structures AASHTO R 50-09, Washington, USA

[3] Jenner C G, Watts G R A and Blackman D I 2002 Trafficking of Reinforced, Unpaved Subbases Over a Controlled Subgrade, Proceedings of 7th International Conference on Geosynthetics, Nice, France

[4] Jersey S R, Tingle J S, Norwood G J, Kwon J and Wayne M 2012 Full-Scale Evaluation of Geogrid-Reinforced Thin Flexible Pavements. Transportation Research Record, Journal of the Transportation Research Board, No. 2310, TRB of the National Academies, Washington, USA

[5] Kwon J, Wayne M, Norwood G J and Tingle J S 2012 The Implementation of Findings From Accelerated Pavement Testing in Pavement Design and Construction Practice, Advances in Pavement Design through Full-scale Accelerated Pavement Testing – Jones, Harvey, Mateos & Al-Quadi (Eds.), Taylor&Francis Group, London, UK

[6] Norwood G J and Tingle J S 2014 Performance of Geogrid-Stabilized Flexible Pavements. Final Report. EDRC/GSL TR-14-28. U.S. Army ERDC, USA

[7] Robinson W J, Tingle J S and Norwood G J 2017 Full-Scale Accelerated Testing of Multi-Axial Geogrid Stabilized Flexible Pavements. Draft Final Report. EDRC/GSL TR-17-X. U.S. Army ERDC, USA

[8] White J D 2014 In Situ Performance Verification of Geogrid-Stabilized Aggregate Layers: Dewitt County, Cuero, Texas – Schlinke Rd., Geomatters Technologies Inc., Ames, USA

[9] White J D 2014 Preliminary APLT Comparison of Ev Strain Modulus and In-situ Resilient Modulus/Permanent Deformation, Geomatters Technologies Inc., Ames, USA

[10] Jones R and Dixon N 2011 Sustainable development using geosynthetics: European perspectives. Geosynthetics (Vol. 29, No. 3)

[11] The Cut Costs and Carbon Calculator, https://www.carbontrust.com/resources/tools/cut-costs-and-carbon-calculator-catering/, accessed 25 February 2018

[12] Publically Available Specification PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services http://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf accessed 25 February 2018

[13] Coffey Geotechnics Ltd. Tensar Carbon Calculator Assumptions – based on International Carbon Calculator V4.0, 701.2AB_M_001B_Assumptions for Carbon CalculatorV4.0

[14] Powell W D, Potter J F, Mayhew H C and Nunn M E 1984 The structural design of bituminous roads (No. LR 1132 Monograph)

[15] Manual of Contract Documents for Highway Works 2016 Vol. Specification for Highway Works Series 600 Earthworks, Amendment – February 2016; Table 6/1 and Table 6/4. http://www.standardsforhighways.co.uk/ha/standards/mchv/vol1/pdfs/600.pdf

[16] Hammond G and Jones C 2011 Inventory of Carbon & Energy (ICE) Version 2.0 Sustainable Energy Research Team, Dept. of Mechanical Engineering, University of Bath, www.bath.ac.uk/mch-eng/sert/embodied

[17] Plastics Europe Eco-profiles http://www.plastics-europe.org/application/files/7415/1747/5136/eco-profile_methodology_version2-0_April2011.pdf accessed 25 February 2018

[18] DEFRA Conversion Factors (UK Government Department for Environment, Food and Rural Affairs https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2017

[19] Waste and Resources Action Programme (WRAP) CO2 Emission Estimator Tool http://www.wrap.org.uk/search/gss/co2%20emission%20estimator%20%20 accessed 25 February 2018

[20] Pavement Design catalogue Katalog Typowych Konstrukcji Nawierzchni Podatnych i Półsztywnych 2014 Załącznik do zarządzenia nr 31 GDDKiA z dn. 16.06.2014r. https://www.gddki.gov.pl/userfiles/articles/2/zarzadzenia-generalnegodyrektor_13901/zarzadzenie%2031%20zalacznik.pdf