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Analytical assessment of the impact of material properties on the performance of flexible and composite highway pavements in Flanders

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Abstract

The configuration of pavement material has an important impact on pavement performance. Several different pavement material configurations are used in Flanders. This paper aims to determine which pavement configuration is economically interesting and performs well on two types of pavement damages: fatigue cracking and rutting. This is investigated by creating seven flexible and composite pavement configurations according to SB250. The methodology is based on a damage analysis performed for fatigue cracking and rutting on the pavement configurations using the 3D-Move analysis software. The results of the pavement analysis showed that the composite pavements have the least strain in the x-x and z-z directions, meaning they are the least sensitive to fatigue cracking and rutting. This can be explained by the E-modulus of the materials used in these configurations being higher than those used in flexible pavement configurations. Finally, this research recommends a pavement configuration consisting of an AGT top layer, cement-stabilized crushed stone, or roller-compacted concrete base layer. These configurations perform the best overall economic and pavement performance.

Keywords: 3D-Move Analysis; composite pavement; fatigue cracking; flexible pavement; rutting

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1. Introduction

How flexible and composite pavements are constructed can affect pavement performance differently. In Belgium, many predefined structures are used to build flexible and composite pavements. The top layers can vary, but also the

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base layer varies regularly. In contrast to the subgrade, the properties of these layers are always determined by engineering offices. Subgrade's characteristics depend on the region and are often the same in most parts of Belgium. There are approximately three main types of subgrades. In Flanders, it is almost always sand. It is more rocky in Wallonia, and the border regions are known for their loamy soils. This research focuses on the Flemish Region, except for the border regions. Most people are generally satisfied with the state of the roads in Belgium. One of the reasons could be that most people don't drive often on foreign roads. When crossing the border abroad, people always realize that the state of the roads can improve a lot. Belgium is ranked 53rd out of 141 countries, with a score of 4.4 out of 8, in a world ranking based on road quality (*Road quality report*, 2019). Focusing only on the countries of the European Union, Belgium is ranked 17th out of 27 countries. Differences with neighboring countries like the Netherlands, Luxembourg, France, and Germany, with scores of 6.4, 5.5, 5.4, and 5.3 out of 8, respectively, are too large. This is unusual for a country with a dense road network like Belgium. A study showed that Belgium has the 6th densest road network globally, with 504.5 km/km² (VividMaps, 2011).

1.1. Pavement damages

It can be concluded that this situation is not normal for a country like Belgium, with such an excellent construction culture and a high level of prosperity. This research attempts to find a solution by focusing on two types of damage caused by trucks with dual tires on the highway. These two types of damage are fatigue cracking and rutting. Below, these two terms are clarified. Fatigue cracking is a type of cracking that occurs due to frequent repeated loading and unloading of vehicles from traffic. Fatigue cracking is caused by tensile stresses where the maximum tension occurs, which starts at the bottom of the hot mix asphalt (HMA) layer (Pirdavani, 2023). Over the years, the HMA layer wears out, weakening the pavement and eventually cracking. Rutting is a formation of permanent deformation at a road's surface typically caused by repeated vehicle loads over time. It is a frequent problem in asphalt and other flexible pavements and can result in rough-riding roads. Rutting is caused by the vertical strain on the top of the subgrade (Pirdavani, 2023).

1.2. Pavement types

In this research, seven cases are created for analysis. Each case is a different construction method representing a flexible or composite highway pavement scenario, further clarified in the following sections. In all cases, the type of surface and base layers are different, but the type of subgrade remains the same. Flexible pavement is a type of pavement that uses asphalt material. It is designed to be flexible and adapt to changes in temperature and traffic (*Pavement Types*, 2013; PavementInteractive, 2013). The pavement consists of HMA, a base, a sub-base, and a subgrade layer. This type of pavement is often used for highways, airports, parking lots, or other roads (Pirdavani, 2023). Composite pavement is a type of pavement that combines the advantages of concrete and asphalt. This pavement is designed to provide a solid surface that can withstand heavy loads while being flexible. This type of pavement consists of HMA, a concrete base layer with a higher E-modulus than in flexible pavement, a sub-base, and a subgrade layer (*Composite pavement*, 2014).

It is essential to point out that similar research has been conducted in the past (Abdel-Motableb, 2007; Behiry, 2012). Those studies focused on the same types of damage, namely fatigue cracking, and rutting, but had different objectives. The objective of the research (Abdel-Motableb, 2007) was to determine the ideal values for the thickness and the E-modulus of the different layers to limit both types of damage. In another study (Behiry, 2012), the effects of an increase in axle load and variations in the elasticity of different layers were determined. The results of these two studies help give a first impression of the expected results of this research.

2. Methodology

2.1. Pavement material configuration

According to the SB250 (Agentschap Wegen en Verkeer, 2021), this research created seven typical pavement models, four flexible and three composite pavements. After the configuration of the pavements, the material properties (i.e., E-modulus, Poisson ratio, and density) for each case were determined. Below, the different pavement configurations with the E-modulus for each layer and type of mix are described in Table 1.

Table 1. Description of cases.

Case nr.	Flexible pavement type (cm)	E modulus (MPa)	Base type (cm)	E modulus (MPa)	Subbase type (cm)	E modulus (MPa)
1	AGT (2 cm) with APO-A-underlayment (7 cm) and APO-A underlayment (8 cm)	6500	Unbound crushed stone (40 cm)	500	Type I (28 cm)	100
2	AGT (2 cm) with APO-A-underlayment (7 cm) and APO-A underlayment (8 cm)	6500	Cement-stabilized crushed stone (25 cm)	9000	Type I (38 cm)	100
3	AGT (2 cm) with APO-A-underlayment (7 cm) and APO-A underlayment (8 cm)	6500	Lean concrete (25 cm)	17500	Type I (38 cm)	100
4	AGT (2 cm) with APO-A-underlayment (7 cm) and APO-A underlayment (8 cm)	6500	Roller-compacted concrete (18 cm)	32500	Type I (45 cm)	100
5	AGT (2 cm) with APO-A-underlayment (7 cm) and APO-A underlayment (8 cm)	6500	Lean asphalt (16 cm)	5000	Type I (47 cm)	100
6	SMA-C (5 cm) with APO-A-underlayment (7 cm) and APO-A underlayment (8 cm)	6500	Unbound crushed stone (40 cm)	500	Type I (28 cm)	100
7	ZOA-B (4 cm) with APO-A-underlayment (7 cm) and APO-A underlayment (8 cm)	6500	Unbound crushed stone (40 cm)	500	Type I (28 cm)	100

2.2. Input and output parameters

Once the different pavement configurations were determined, the 3D-Move Analysis software was used to simulate the different cases. The necessary input parameters of the software are briefly explained here. The E-modulus is a material property that represents the stiffness of a material. It is the ratio of stress to strain in a material undergoing elastic deformation. The higher the E-modulus, the stiffer the material, and the less it deforms under stress (*Elasticiteitsmodulus*, 2011). The Poisson's ratio is a material property that describes the relationship between a material's lateral and axial strain. It describes how much a material tends to bulge out or contract in the transverse direction when stretched or compressed in the axial direction (*Poisson's Ratio*, 2017). The density of a material is defined as its mass per unit volume.

Strain is a measure of the deformation of a pavement material under applied loads (Holmes, 2023), such as traffic loads. Fatigue cracking is caused by tensile strain at the bottom of the HMA layer, while rutting is caused by vertical strain at the top of the subgrade (Pirdavani, 2023).

2.3. Response points

This research chose a dual tire configuration. Seven points in the y-direction were chosen for this tire configuration (i.e., two under the centers of tires, four at the edges of the tires, and one between the two tires), where the software should calculate the responses (i.e., strains). These strains were calculated at two depths:

- bottom of the HMA layer for fatigue cracking;
- top of the subgrade for rutting.

2.4. Used software (3D-Move Analysis)

The software used in this research is 3D-Move Analysis version 2.1. This software uses a continuum-based finite layer approach to simulate pavement responses. This approach treats each pavement layer as a continuum and uses the Fourier transform technique (*3D-Move Analysis Software (Version 2.1)*, 2013). The 3D-Move model can account for important pavement response factors such as moving loads, three-dimensional contact stress distributions (normal and shear), and viscoelastic material characterization for the pavement layers. This study conducted a dynamic analysis with a 90 km/h vehicle speed.

2.5. Comparison of performance

The mechanistic-empirical technique provides two different equations to calculate the allowable number of traffic (N) based on the critical strain values for both distress types, fatigue cracking, and rutting (Pirdavani, 2023). For fatigue cracking, formula 1 was used to calculate the allowable number of traffic.

$$N_{HMA} = \left[\frac{0.005889}{Tensile\ strain}\right]^{5} \tag{1}$$

For fatigue cracking, formula 2 was used to calculate the allowable number of traffic.

$$N_{subgrade} = \left[\frac{0.003900}{Vertical\ strain}\right]^{7.1} \tag{2}$$

2.6. Comparison of material cost

The labor and transportation costs are not included in this comparison. The following formula calculates the material cost:

$$P = p * \rho * t \tag{3}$$

Where, P is price per m², p is price per ton material (BesixInfra, 2023), ρ is density and t is thickness of each layer.

3. Results

After the software had run different simulations, it was clear that the tensile strains in the X-X direction were most determinative for fatigue cracking. Therefore, strains in the Y-Y direction are not considered.

This analysis compares the strain results in the pavements for fatigue cracking and rutting for different cases. This section is divided into two main parts:

- analysis results for fatigue cracking;
- analysis results for rutting.

3.1. Analysis results for fatigue cracking

First, this section compares the strain results in the X-X direction for all the created cases. After this, there is zoomed in on the three cases of composite pavement because the differences in those results are not visible on the graph with all seven cases due to marginal differences in the obtained strains.

Fig. 1 shows the strains in the X-X direction for all cases. The horizontal axis shows the coordinates of the measuring points in the transverse direction of the road. Each measuring point presents the most critical strain in the function of the time that the truck passes. The larger the strain, the more sensitive the pavement is to fatigue cracking. The positive strain is compressive, while the negative strain is tensile.

What can be seen in Fig. 1 is the difference between flexible pavements (cases 1, 5, 6, 7) and composite pavements (cases 2, 3, 4). The strain for composite pavements is positive and nearly the same, in contrast to that of flexible pavements. These strains are negative and multiple times larger than the strain for composite pavements.

Noticeable in this figure is the general pattern of the flexible pavement cases. They have the same curve, and the values for cases 1, 6, and 7 are close (all having similar base types), except for case 5. This case has the same curve, but that strain is 3 to 4 times smaller than the other flexible pavement cases. The response points with the most considerable strain are the same in all the cases and are located below the center of the tires. The response points with the least strain are similar and located at the tires' outer edges.

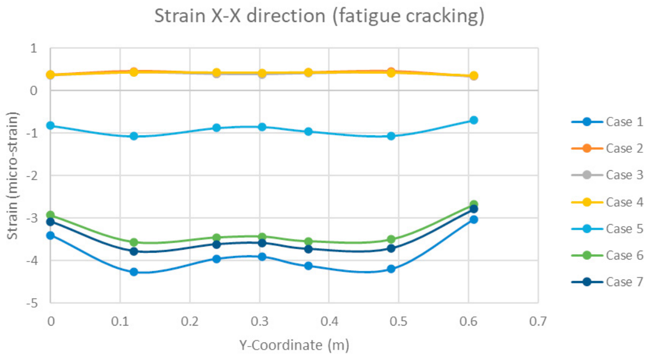

Fig. 1. Strain X-X direction (fatigue cracking, all pavement types).

The average strain for flexible pavements is -3.128 micro-strain and is 618% more than the average strain of composite pavement, which is 0.436 micro-strain. If the flexible pavement cases with different top layers and the same base layer are compared (i.e., cases 1, 6, 7), it can be concluded that case 1 has the largest strain, while case 6 has the smallest strain. The largest strain in case 1 (4.26 micro-strain) was 27% higher compared to the strain in case 6 (3.56 micro-strain) and 18% higher compared to the strain in case 7 (3.77 micro-strain). The largest strain in case 7 was 8% higher than in case 6.

When the two flexible cases with the same top layer and different base layers are compared (i.e., cases 1 and 5), it can be concluded that case 1 has the largest strain. This strain (4.25 micro-strain) is 297% higher than the strain in case 5 (1.07 micro-strain).

Due to the minor differences in the strain in composite pavements, these cases are further analyzed in detail. Fig. 2 shows the strain of these cases. All these cases have a similar top layer but a different base layer.

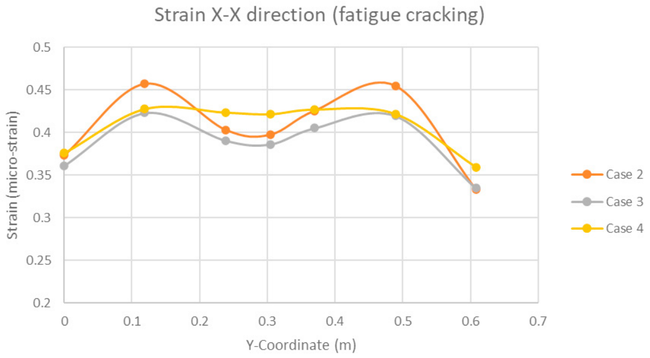

Fig. 2. Strain X-X direction (fatigue cracking, composite pavements).

Noticeable in Fig. 2 is the general pattern of composite pavement cases. Case 2 has the most significant strain in the X-X direction, while case 3 has the slightest strain. The response points with the maximum strains are the same in all cases and are located under the center of the tires. The largest strain in case 2 (0.455 micro-strain) is 8% higher than the largest strain in case 3 (0.420 micro-strain) and 6% higher than the largest strain in case 4 (0.427 micro-strain). The largest strain in case 4 is 2% higher than in case 3.

3.2. Analysis results for rutting

The strain in the Z-Z direction is determinative for rutting. This section compares all cases' strain results in the Z-Z direction (see Fig. 3). Data points are determined similarly for the graphs of the fatigue cracking with a different depth.

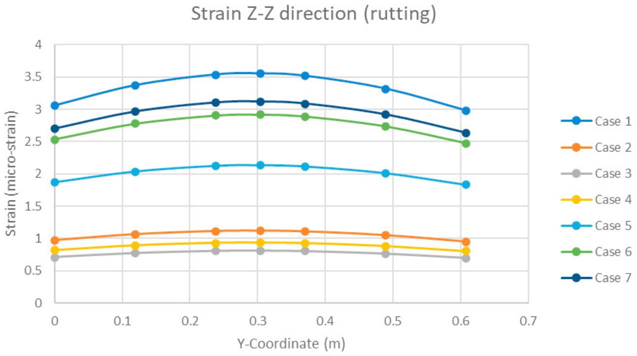

Fig. 3. Strain Z-Z direction (rutting, all pavement types).

It is evident in Fig. 3 that the strains are positive and that all curves follow the same pattern. There is a clear difference between flexible (cases 1, 5, 6, 7) and composite pavements (cases 2, 3, 4). The strains in the composite pavement are significantly smaller than the flexible pavement. The response points where the most significant strains occur are the same for all cases and are between the two tires.

The average strain for the flexible pavement is 2.929 micro-strain and is 207% more than the average strain of composite pavement with 0.953 micro-strain.

If different flexible pavement cases are compared, it can be concluded that case 1 has the largest and case 5 has the smallest compressive strains. The largest strain in case 1 (3.55 micro-strain) was 67% higher than in case 5 (2.13 micro-strain).

Comparing composite pavement cases shows that case 2 has the maximum compressive strain, while case 3 has the smallest. The maximum compressive strain in case 2 (1.116 micro-strain) is 38% higher than in case 3 (0.810 micro-strain) and 20% higher than in case 4 (0.932 micro-strain). The maximum compressive strain in case 4 is 15% higher than in case 3.

3.3. Comparison of performance and material cost

This section compares the different cases in terms of performance and material cost in Tables 2 and 3. The ratio columns give the ratios between each case and the lowest-performing case, or the price of each case compared to the most expensive one. By doing so, the ratio of each case represents how much better it performed compared to other cases.

3.3.1. Comparison of performance

Table 2 ranks the different cases based on performance against rutting (and fatigue cracking only for flexible pavements). The higher the allowable number of traffic, the higher the place in the ranking. The pavement configuration of case 3 has the best fatigue cracking and rutting performance. The pavement configuration of case 1 performs worst of all cases.

3.3.2. Comparison of material cost

Table 3 is a ranking of the different cases based on material cost (BesixInfra, 2023). The lower the material cost, the higher the place in the ranking. Table 3 shows that the pavement configuration of case 1 has the lowest material cost. The pavement configuration of case 6 has the highest material cost of all cases.

By looking into Tables 2 and 3, it can be concluded that pavement configuration 3 is extensively better in terms of performance and cost. Among flexible pavements, case 5 is the best option; however, it still underperforms significantly compared to composite pavement cases.

Table 2. Comparison of performances in different cases.

Case nr.	Type	N (fatigue cracking)	Ratio	N (rutting)	Ratio
3	AGT + Lean concrete	/	/	1.40E+26	36176
4	AGT + Roller-compacted concrete	/	/	5.18E+25	13385
2	AGT + Cement-stabilized crushed stone	/	/	1.44E+25	3721
5	AGT + Lean asphalt	4.99E+18	984	1.46E+23	38
6	SMA-C + Unbound crushed stone	1.24E+16	2.5	1.57E+22	4
7	ZOA-B + Unbound crushed stone	9.27E+15	1.8	9.82E+21	2.5
1	AGT + Unbound crushed stone	5.07E+15	1	3.87E+21	1

Table 3. Comparison of prices in different cases.

Case nr.	Type	Price (€/m²)	Ratio
3	AGT + Lean concrete	25.39	1.00
4	AGT + Roller-compacted concrete	25.85	1.02
2	AGT + Cement-stabilized crushed stone	26.21	1.03
5	AGT + Lean asphalt	27.37	1.08
6	SMA-C + Unbound crushed stone	29.72	1.17
7	ZOA-B + Unbound crushed stone	30.07	1.18
1	AGT + Unbound crushed stone	33.52	1.32

4. Discussion

The analysis of the results makes it possible to draw three crucial conclusions. Each finding is then interpreted and discussed separately. The main conclusions are:

- the critical points for fatigue cracking are consistently below the center of the tires;
- the critical points for rutting are always in between the two tires;
- a larger E-modulus leads to smaller strains.

For flexible pavements, the strains at the critical points are negative, which means tension causes fatigue cracks or bottom-top cracking. For composite pavements, however, the strains are positive, meaning that compression results in top-bottom cracking (Pirdavani, 2023). The reason for the cracking difference is the base layers' E-modulus. A top layer with an E-modulus higher than the E-modulus of the base layer causes tension, while a top layer with an E-modulus lower than the E-modulus of the base layer causes compression. The result is that no fatigue cracks occur in composite pavement cases. Hence, these cases will not be further interpreted regarding fatigue cracking.

For flexible pavement cases, the critical points are below the center of the tires because this is where most of the truck's weight is transferred to the ground. The strains decrease proportionally to zero in the positive and negative x-directions from these points. This makes sense because the effect of weight decreases further from the contact points. It is also important to realize that the deformations in the space between the two tires do not decrease to zero and that the slope of the graph is lower in this area. The reason for this is that both tires also influence each other. Therefore, tensions caused by the outer tire overlap with those caused by the inner tire. If the distance between the tires on the axle is greater, the influence of one tire on the other is negligible.

Critical points for rutting are points with the maximum vertical positive compressive stresses and strains. The critical points are always in between the two tires because the deformation zone of each tire widens laterally in proportion to the depth, so from a certain depth, the strain zone of one tire overlaps with the one of the other tire. This overlap results in a maximum strain between the two tires.

In this research, only the E-modulus and Poisson's ratio vary for each material. The E-modulus varies from 500,000 to 32,500,000, and the Poisson's ratio varies from 0.15 to 0.35. It is clear that the E-modulus has the most significant influence on the strain, and because the modulus of elasticity is in the denominator, a higher denominator translates into a lower strain.

5. Conclusion

The most important conclusions that can be drawn from the research are:

1. the critical points for fatigue cracking are consistently below the center of the tires;
2. the critical points for rutting are always in between the two tires;
3. a larger E-modulus leads to smaller strains;
4. the pavement configuration with an AGT top layer and a lean concrete base layer is the best in terms of performance;
5. the pavement configuration with an AGT top layer and an unbound crushed stone base layer is the best in terms of material cost;
6. the pavement configurations with an AGT top layer and a roller-compacted concrete base layer or a cement-stabilized crushed stone base layer are the best in terms of performance and material cost.

This research focuses on highways. Research focusing on more minor roads could also be interesting. Research on other axle configurations could also be interesting. The results may only be considered indicative and should be interpreted cautiously, since changes in the properties of the pavement structure may change the strain values significantly. This implies that the direction of the changes in performance measures will remain intact, meaning that the performance ranking stays similar. However, the magnitude of the differences could be different if other study designs were implemented (e.g., other axle configurations or geometric properties of the pavement structure).

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