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Designing energy efficient roads – Optimising the rolling resistance of roads in the laboratory

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Abstract

In order to reduce energy consumption and CO2-emissions, road agencies encourage the development of energy efficient roads by reducing the rolling resistance and hence reducing the fuel consumption. Although various literature studies indicate that the texture, the evenness, and the stiffness are important, there is no clear design methodology to optimise the rolling resistance of road surfaces in the laboratory. Therefore, the goals of this research are (1) to establish the technical feasibility of an energy-saving asphalt road surface with low rolling resistance, (2) to develop a reliable method for measuring rolling resistance in the laboratory (validated with in-situ measurements), and finally (3) to draft a functional design specification for the construction of an energy-saving asphalt road surface as part of a tender process. In this research, a new laboratory machine has been developed to determine the rolling resistance of roads. This laboratory method has also been validated by means of in-situ measurements using a rolling resistance trailer. Using these laboratory and in-situ measurements, a road surface has been developed with demonstrably improved rolling resistance that also meets all other required road surface properties such as skid resistance, noise reduction and service life. Furthermore, the impact of the optimized road surface with a low rolling resistance on the fuel consumption, the energy savings, and the reduction of CO2-emissions has been determined. Next, the potential on the whole Dutch and European road network has been assessed. This paper provides a practical method to determine the rolling resistance in the laboratory in order to design energy efficient roads. In addition, the results of this research contribute to a deeper understanding regarding the tyre-road rolling resistance with respect to noise, skid resistance and lifespan.

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1. INTRODUCTION

The road transport industry is responsible for approximately 20% of the emission of greenhouse gasses [1]. The reduction of CO_2-emissions in the transportation industry focusses mainly on vehicles and tyres, i.e. hybric and electric cars and low rolling resistance tyres. In addition, road authorities generally focus on the production, construction and maintenance of roads and its impact on the environment, i.e. warm mix asphalt, biobased materials, higher recycling percentages, Euro 6 machinery, etc. However, the longest phase of a road is the usage phase of the road and during this phase, most of the greenhouse gasses are produced by the traffic. The road pavement directly influences vehicle fuel consumption through the rolling losses experienced by a vehicle riding over it. Rolling losses include both energy losses in the suspension system due to an uneven road, and losses at the level of contact between the tyre and the pavement. Various aspects of the quality of the road surface influence rolling losses: evenness, rutting, potholes and deteriorated joints. Other factors, such as pavement characteristics (i.e. texture), can also influence rolling losses. Poor quality or deteriorated pavements contribute to higher rolling losses. Road maintenance will reduce emissions immediately and for the future.
In order to reduce energy consumption and CO_2-emissions of vehicles, road agencies encourage the development of energy efficient roads by reducing the rolling resistance and hence reducing the fuel consumption. Therefore, this research focusses on the road-tyre rolling resistance and its impact on fuel savings and reduction of greenhouse gasses. Fuel savings during this usage phase of the road, for example by a smart design of the road, could have a massive impact on the reduction of greenhouse gasses. An initial study [1] indicate that an upgrade of one third of the entire road network of Europe by 2030 could lead to yearly savings of 14 million tonnes of CO_2. If two thirds of the network were upgraded, this could be 28 million tonnes of CO_2 saved yearly. This is the equivalent of replacing 6 million cars with zero-emission cars. The focus of this research is to design a road surface with a low rolling resistance.
Although various literature studies indicate that the texture, the evenness, and the stiffness of a road are important, there is no clear design methodology to optimise the rolling resistance of road surfaces in the laboratory. In addition there are various in-situ measurement trailers available (i.e. TU Gdansk, Belgium Road Research Centre, BASt), but there is no laboratory test available to design a road surface with a low rolling resistance. To this end, in this research a practical laboratory methodology has been developed to design the rolling resistance of a road surface. This methodology has been validated by means of in-situ measurements using a rolling resistance trailer (TU Gdansk). Using these laboratory and in-situ measurements, a road surface has been developed with demonstrably improved rolling resistance that also meets all other required road surface properties, such as skid resistance, noise reduction and service life. Next, the impact of the road surface with improved rolling resistance on the fuel consumption, the energy savings, and the reduction of CO_2-emissions has been determined. Next, the potential on the whole Dutch and European road network has been assessed.
This paper subsequently describes the goals of this research and research methodology followed (section 2), the results of a literature study (section 3), the designed laboratory methodology (section 4), the validation in-situ (section 5), the impact on CO_2-reduction (section 6), procurement requirements to include rolling resistance in contractual specifications (section 7), and the main conclusions and recommendations of this research (section 8).

2. GOALS AND RESEARCH METHODLOGY

This research had three main goals:

- To establish the technical feasibility of an energy-saving asphalt road surface with low rolling resistance;
- To develop a reliable method for measuring rolling resistance in the laboratory (validated in practice);
- To determine the impact on fuel consumption and CO_2-reduction and possibly to draft a functional design specification for the construction of an energy-saving asphalt road surface as part of a procurement process.

The intended result of this research was the development of a road surface with demonstrably improved rolling resistance (being a Proof of Concept (PoC) that meets all required road surface properties such as skid resistance, noise reduction and service life) plus a measurement methodology and functional design specification.

The steps in the followed research methodology were:

(1) A literature study to identify the most important parameters for the development of road surfaces with low rolling resistance;
(2) The development and installation of a laboratory setup (modifying existing equipment) to measure the rolling resistance of asphalt surfaces and assess the quality of optimised asphalt mixtures;
(3) The optimisation of existing asphalt mixtures;
(4) The construction of a test road surface in-situ using the best-performing optimised mixture (determined in the laboratory) as validation of the laboratory results.

The result of this research is an asphalt road surface with demonstrably reduced resistance between the vehicle tyre and the road surface (rolling resistance) that hence has a positive effect on the energy and fuel consumption of vehicles. A practical laboratory methodology has also been developed to measure the rolling resistance of road surfaces. This was used to draw up a preliminary functional design specification for energy-saving road surfaces.

3. LITERATURE STUDY

A literature study was conducted to establish which road-surface properties have an influence on rolling resistance and to what extent. Last decade, much research effort has gone into the topic of rolling resistance of road surfaces [1-25]. Also, various European research studies have been conducted on the topic of rolling resistance, i.e. MIRAVEC, MIRIAM, ROSANNE, COOEE, ROSE.
Our literature study focussed on (1) the influence of rolling resistance on fuel consumption, (2) the main properties of a road surface influencing the rolling resistance, and (3) the existing measurement methods to determine the rolling resistance. The literature does not explicitly show that the binder type and binder grade are essential parameters.
First, the fuel consumption of vehicles is determined by a large number of parameters. For example, the aerodynamic force, the mechanical and gravity forces, inertia forces and the vehicle weight and road-tyre rolling resistance. So obviously, the rolling resistance depends on the vehicle type, the speed, the tyre type, etc. Various studies show different percentages how the rolling resistance impact fuel consumption, varying from 15-35% [2], 18-32% [6], and 20% [7]. In this research, we have decided to standardise and simplify this influence on 20%. So, a reduction of rolling resistance of 10% in general leads to a reduction of fuel consumption of 2%.
Second, we focussed on the road parameters influencing the rolling resistance. This resulted in a number of material and surface properties of asphalt roads that can be optimised to change the rolling resistance of a standard asphalt road surface. The study revealed that the texture or Mean Profile Depth (MPD) of the road surface is one of the most important contributors to rolling resistance. Other properties that play a role are the evenness of the surface and, to a smaller extent, the stiffness of the entire road construction. Various studies demonstrate that vehicle fuel consumption and CO_2-emissions increase with an increasing pavement roughness and inadequate surface texture for all types and classes of vehicles [23-25]. Thus, a higher pavement smoothness reduces CO_2 emissions. Another study [23] shows that an increase of surface roughness (measured by using the International Roughness Index - IRI) of 1 m/km leads to an increased fuel consumption for heavy trucks of 1% at normal highway speed (96 km/h) and 2% at lower speed (56 km/h). Surface texture (measured by Mean Profile Depth - MPD) has an influence for heavy trucks too: an increase in MPD of 1 mm will increase fuel consumption by about 1.5% at 88 km/h and by about 2% at 56 km/h. In Denmark, it is shown what happens if the budget for maintenance is not sufficient: fuel consumption could increase by 3% [23,24]. Further, a study at a test track showed that trucks driving on smooth pavements after the rehabilitation of the pavement consume 4.5% less fuel [25].
So, although there is consensus in the literature about the parameters that influence the rolling resistance of the road, the literature reports very big differences on the relative influence. We have summarised this in the Table 1.

Table 1. Summary influence of road parameters

Road parameters	Influence on rolling resistance	Influence on fuel consumption
Texture (MPD, RMS, MTD)	8-84%	1.6-16.8%
Evenness (IRI)	6.5-18%	1.3-3,6%
Stiffness entire construction	0-15%	0-3%

Also, various models have been developed to estimate the rolling resistance [8,14,16,18]. All models use texture parameters for their prediction and some models add evenness and/or stiffness data parameters for the prediction of the rolling resistance.
Third, there are several measurement systems in use today. In Europe there are currently three publicly available measurement devices in use: the trailer of the Gdańsk University of Technology (TU Gdansk), the trailer of Belgian Road Research Centre, and the trailer of BASt (Germany). All systems measure the rolling resistance coefficient (RRC). The RRC is the ratio of horizontal force over vertical force; hence its physical unit is Newton/Newton. For ease of comprehension it is expressed here as kilogramforce/tonforce (kg/t), as is common international practice. Currently, there are no official standards for performing rolling resistance measurements. Therefore, there can be differences in absolute rolling resistance values between measurement systems. In this research, we used the TU Gdansk measurement system for in-situ validation because it has been used since 2014 in the Netherlands. The rolling resistance trailer is a three-wheel trailer. The two front wheels are bearing/support wheels. The rear wheel is the measurement wheel. The measuring wheel is attached to the trailer frame by a swivel arm; the angle of the

swivel arm provides a measure of the rolling resistance force on the measuring wheel. In recent years, improvements have been made to the trailer to further limit the effects of unwanted variations on the measurement result. In the tyre industry, rolling resistance measurements are conducted on a big steel drum, but this cannot be used to determine the rolling resistance of various surfaces (it can only vary the tyre type).
Finally, based on the literature, the most important parameter that influences the rolling resistance is the texture (in terms of Mean Profile Depth). By reducing the MPD from about 2.0 mm to 0.5 mm, a reduction in rolling resistance of 10-40% can be expected, which means a reduction in fuel consumption of 2-8%. These results of the literature study were used as a starting point for the optimisation process. The use of existing and proven materials and asphalt mixtures are used as a starting point, to minimise the risk that the surface fails to meet other road requirements (such as skid resistance, noise reduction and service life).
This study focussed on provincial, secondary roads with a reference mixture of an SMA 11 with an MPD of approximately 1.2 mm, which is now widely used in the Netherlands.

4. LABORATORY METHODOLOGY TO MEASURE ROLLING RESISTANCE

A measurement methodology was developed to optimise rolling resistance at the laboratory scale. The rolling resistance test trailer and measurement principle developed by Gdańsk University of Technology were used as a starting point for this laboratory methodology. This test trailer is the standard for all national rolling resistance measurements in the Netherlands (see Figure 1). Next, the developed measurement machine in the laboratory will be described in paragraph 4.1, followed by the measurement procedure (paragraph 4.2) and finally various asphalt road surfaces are tested and the results are described in paragraph 4.3.

Figure 1: Gdańsk University of Technology test trailer and measurement principle [12]

4.1 Measurement machine in the laboratory

The measurement principle of the TU Gdansk was implemented by modifying the existing SR-ITD® (Skid Resistance & Smart Ravelling & Sophisticated Rolling - Interface Testing Device, see Figure 2). This laboratory machine has been previously developed in a European 7th framework research project (SKIDSAFE). Beside skid resistance and ravelling resistance, this device has been modified with a torque span sensor and can now also test the rolling resistance of a road surface.
The SR-ITD consists of two key components: (1) a moveable turntable or sample holder onto which the asphalt concrete specimen with a diameter of 390 mm is placed and (2) a static loading frame onto which three rubber wheels are installed. Individually each wheel can be placed at variable radii from the centre and at various slip angles. A maximum speed of 85 km/h can be reached when the wheel is placed in the outer position.
For the rolling resistance, the SR-ITD® measures the torque span required to roll a tyre over a plate covered with a certain type of road surface. This is then compared with a number of reference road surfaces. It is a non-destructive measurement method, so the test plate can be used again for skid resistance and/or ravelling resistance. The first step was to achieve the correct ranking of road surfaces that corresponds with in-situ measurements (a relative rolling resistance) rather than an absolute rolling resistance measurement.

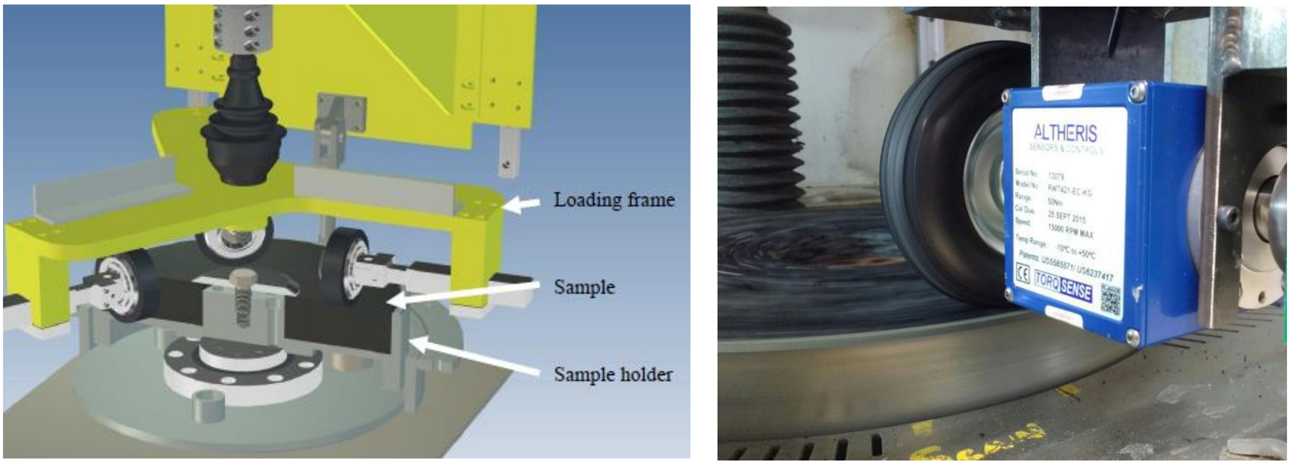

Figure 2: Measuring rolling resistance on an asphalt surface in the laboratory

4.2 Test procedure

The test procedure for determining the relative rolling resistance using the SR-ITD® (Skid Resistance & Smart Ravelling & Sophisticated Rolling - Interface Testing Device) is:

1. Producing road surface specimen:
   - Road surface specimen with minimum dimensions of 500 x 500 x 60 mm (compacted according to NEN-EN 12697-33);
   - 3 specimen per material type.
2. SR-ITD test procedure:
   - Determine the MPD (Mean Profile Depth) of the plate.
   - Determine the rolling resistance (torque span) of the road surface:
     - type of tyre rubber: Blickle soft – VW 125/15R;
     - 100 revolutions per minute;
     - test duration of one minute;
     - load of 20 kg;
     - 3 independent measurements per specimen.
3. Report the following parameters:
   - Average torque span per measurement;
   - Average MPD per measurement;
   - Relative rolling resistance in comparison to the reference (SMA 11).

The next section describes the results of the tests that we have conducted in the laboratory on various asphalt road surfaces.

4.3 Test results in the laboratory on asphalt road surfaces

Various existing asphalt surfaces were tested in the laboratory for rolling resistance by means of repetitive testing, namely a SMA 11 (reference), a AC 16 surf, a surfacing 5, a PA 5, and a SMA 8. Next, based on these results two asphalt road surfaces were designed and optimised on rolling resistance, namely a thin surface 5 (optimisation #1) and another thin surface 5 (optimisation #2, named Novachip 5). The main asphalt mix characteristics are summarised in Table 2. The results of the rolling resistance and texture measurements are shown in Table 3 and visualised in Figure 3.

These laboratory results show that rolling resistance in the laboratory can be reduced by approximately 20-25% in comparison with the reference SMA 11. Also, the results show that the MPD is a good indicator for the rolling resistance, however it also depends on the mixture type and aggregate used.

Table 2. Asphalt mix characteristics

Asphalt mix characteristics	SMA 11	AC 16 surf	Surfacing 5	PA 5	SMA 8	Optimisation 1: Thin surface 5	Optimisation 2: Novachip 5
% sieve 16.0 mm	100.0	97.9	100.0	100.0	100.0	100.0	100.0
% sieve 11.2 mm	93.5	85.0	100.0	100.0	100.0	100.0	100.0
% sieve 8.0 mm	55.6	75.0	100.0	100.0	96.2	100.0	100.0
% sieve 5.6 mm	26.8	65.0	96.6	97.3	60.0	89.0	96.8
% sieve 2.0 mm	21.0	60.0	31.0	18.0	33.0	16.5	35.0
% sieve 63 µm	8.4	6.8	5.1	5.0	4.1	7.5	5.0
Binder type	Pen 70/100	Pen 40/60	PmB 3% SBS	PmB 3% SBS	PmB 3% SBS	PmB 5% SBS	PmB 5% SBS
Binder content	6.5%	5.7%	6.6%	5.8%	5.9%	6.5%	6.2%
Air void content	5.0%	3.5%	13.9%	19.0%	6.0%	12.5%	13.5%

Table 3. Asphalt road surfaces and their relative rolling resistance

Asphalt road surface	**Relative rolling resistance (SR-ITD®)**	**Texture (MPD in mm)**
SMA 11	100% (reference surface)	1.26 (100%)
AC 16 surf	90%	0.76 (60%)
Surfacing 5	90%	0.82 (65%)
PA 5	84%	1.03 (82%)
SMA 8	80%	0.65 (52%)
Optimisation #1: Thin surface 5	78%	0.84 (67%)
Optimisation #2: Thin surface 5 (Novachip 5)	73% → Validation in practice	0.71 (56%)

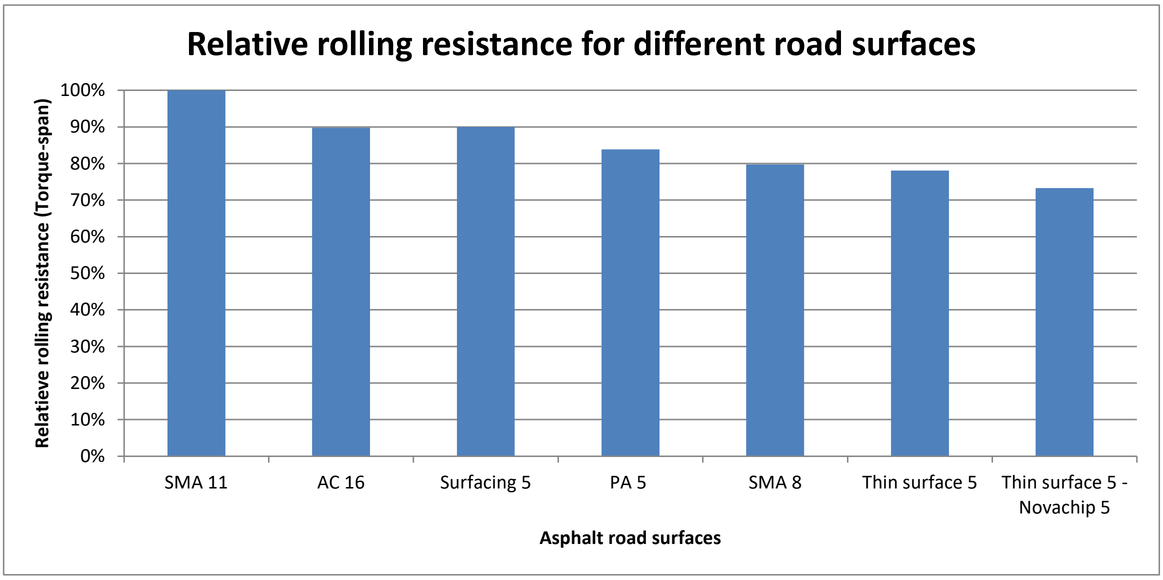

Figure 3: Rolling resistance measurements for different asphalt road surfaces

Also, we have determined the repeatability (r), the variation in measurements on the same asphalt slab using the same equipment, and the reproducibility (R), the variation in measurements for different slabs of the same asphalt mixture using the same equipment. For the rolling resistance measurements, the variation coefficient of the repeatability was 3.4% and the variation coefficient of the reproducibility was 4.5%. This is similar, or even better, than other mechanical tests, like the Indirect Tensile Strength test, triaxial test or four-point-bending test.

5. VALIDATION OF THE LABORATORY RESULTS IN PRACTICE

After the road surfaces had been optimised using the laboratory methodology, the best-performing surface mixture, optimisation #2: Thin Surface 5 (Novachip 5) and the reference mixture (SMA 11), were both constructed in practice to validate the laboratory results in the field (as a Proof of Concept). In Hoorn (the Netherlands), a test section was constructed of approximately 500 metres for each road surface (see Figure 4). The Novachip 5 was constructed in a layer thickness of 25 mm and the SMA 11 was constructed in a layer thickness of 35 mm. The test sections were constructed using standard road construction machinery. The asphalt temperature and number of roller passes were monitored using intelligent compaction technology in order to monitor there was no significant difference in construction and compaction.

On these two test sections, the following measurements were conducted:

- Rolling resistance measurements using the Gdańsk University of Technology trailer;
- Wet skid resistance (friction coefficient) according to the Dutch national test standard;
- Noise reduction using CPX measurements;
- Mechanical properties: Cracking toughness (ITS), water resistance (ITSR) and rutting resistance (fc).

Figure 4: Road sections for field validation

5.1 Rolling resistance

In-situ rolling resistance measurements were performed using the TU Gdansk measurement trailer on the SMA 11 and the Novachip 5 directly after construction (2016) and two years later (2018). Table 4 summarises the results of these measurements.
From these results, it can be concluded that the rolling resistance of the Novachip 5 is 12% lower than the rolling resistance of the SMA 11 (6.5 kg/ton vs. 7.4 kg/ton). Further, the rolling resistance is only slightly lower (3%) after two years.

Table 4. Results in-situ validation using the rolling resistance TU Gdansk trailer

Road surface	Rolling resistance (2016)	Rolling resistance (2018)
SMA 11	7.4 kg/ton (80 km/hr)	7.6 kg/ton (80 km/hr)
Optimisation #2: Thin surface 5 (Novachip 5)	6.5 kg/ton (80 km/hr)	6.7 kg/ton (80 km/hr)

Furthermore, older road sections with the other road surfaces tested in the laboratory were monitored using the TU Gdansk rolling resistance measurement trailer and shown in Table 5. The rankings produced by the rolling resistance measurements in the field were largely the same as those recorded in the laboratory. For one surface (the PA 5), the texture produced in the laboratory was different to that in the field, which explains the alternative ranking for this surface). This sufficiently validates the predictive capacity of the laboratory methodology for relative rolling resistance measurements. An exact prediction of an absolute rolling resistance in the laboratory is much more complex due to many influencing factors (i.e. frequency of the screed, the direction of paving, etc.) and the very small resistance to measure.

Table 5. Results other older road sections using the rolling resistance TU Gdansk trailer

Road surface	Rolling resistance (2016)
Surfacing 5	8.4 (80 km/hr)
PA 5	6,9 (80 km/hr)
SMA 8	7.8 (80 km/hr)
Thin surface 5	6.6 (80 km/hr)
SMA 11 (various older surfaces in the province Zuid-Holland)	8.4 (80 km/hr) 7.6 (80 km/hr) 8.0 (80 km/hr) 8.5 (80 km/hr)

5.2 Other functional properties: Skid resistance, noise reduction

In addition to the rolling resistance, also other important functional properties were monitored on the two validation sections (SMA 11 and Novachip 5): the skid resistance and noise reduction.

The skid resistance measurements were conducted according to the national standard. This measurement system consist of a towing vehicle, containing a controller and data acquisition system and a water supply system, coupled to a measurement trailer according to CEN/TS 15901-9:2009 or equivalent. This trailer contains a measurement wheel, the axis of which is parallel to the road surface and perpendicular to the driving direction. The measurement wheel is connected to one of the bearing wheels of the trailer through a single-gear box. The measurement wheel is subjected to 86% slip ratio, meaning that the circumferential velocity of the measurement wheel is 14% of that of the freely rotating bearing wheels (of the same circumference as the measurement wheel). The measurements should be executed in the right wheel path, i.e. with the centre of the measurement wheel at a distance of 0.6 m to the left of the inside of the right lane marking. The friction measurement for acceptance testing of a road surface should be executed either before 24 hours after opening to traffic, or between 6 and 20 weeks after opening to traffic. The measurements are executed at a speed of 70 ± 3.5 km/h.
The results of the skid resistance measurements are shown in Table 6. These results show that the optimised asphalt mixture (Novachip 5) also scored much better than the reference mixture (SMA 11) for skid resistance. The optimised mixture (Novachip 5) has a skid resistance which is approximately 25-30% better than the reference mixture (SMA 11).

Table 6. Results in-situ skid resistance measurements

Road surface	Wet skid resistance	Dry skid resistance
SMA 11	0.37 (-)	4.8 m/s^2
Optimisation #2: Thin surface 5 (Novachip 5)	0.48 (-)	6.0 m/s^2

Next, Close-Proximity (CPX) noise measurements were conducted according to ISO/DIS 11819-2. The noise measurements were performed at 50 km/h for light motor vehicles, in accordance to the procedures for a single road surface. Also, together with the noise measurements, texture measurements were performed. The results of the noise and texture measurements are shown in Table 7. These results show that the in-situ texture has been decreased from 1.35 mm to 0.70 mm and the noise level has been reduced from 70.2 dB(A) to 64.6 dB(A). Due to the logarithmic scale of noise, this difference of 5.6 dB(A) is an enormous improvement in terms of noise reduction. So, besides an improvement on rolling resistance and skid resistance, also the noise reduction has been improved.

Table 7. Results in-situ skid resistance measurements

Road surface	Noise level	Mean Profile Depth
SMA 11	70.2 dB(A)	1.35 mm
Optimisation #2: Thin surface 5 (Novachip 5)	64.6 dB(A)	0.70 mm

5.3 Lifespan and costs

The lifespan is of course dependant on the asphalt and binder properties. The mixture information of the SMA 11 and the Novachip 5 are summarised in Table 8.

Table 8. Asphalt mixture information

Parameter	SMA 11	Novachip 5
Aggregate	Bestone 75.6%	Bestone 63.9%
Sand	10.7%	25.2%
Filler	7.1%	4.7%
Binder	6.6% 70/100	6.2% Sealoflex SFB 5-90 (HS)
Bulk density	2438 kg/m^3	2434 kg/m^3
Mixture density	2319 kg/m^3	2120 kg/m^3
Air void content	4.9%	12.8%

The characteristics of the binder Sealoflex SFB 5-90 (HS) are:

- Penetration at 25 °C (0.1 mm): 70-100;
- Softening point (°C): ≥ 85;
- Force-ductility, energy to failure (J/cm2): 10,0;
- Fraass breaking point (°C): ≤ -18;
- Elastic recovery at 25 °C (%): ≥ 90;
- Viscosity at 135 °C (mPa.s): 1500-2500;
- Viscosity at 185 °C (mPa.s): 200-350.

For the CE-marking of both mixtures, water sensitivity in terms of Indirect Tensile Strength Ratio (ITSR) were determined according to NEN-EN 12697-12 and 12697-23. Further, the rutting resistance (fc) has been determined for the Novachip 5 according to NEN-EN 12697-25. This has only been determined for the Novachip 5 due to the reduced layer thickness and the possible risk for rutting. The resulting mechanical properties and the costs are summarised in Table 9.

Table 9. Results in-situ validation using the rolling resistance TU Gdansk trailer

Parameter	SMA 11	Novachip 5
ITSR	> 80%	> 80%
Rutting resistance (fc)	-	0.10 µm/m/puls
Material costs per ton	ca. € 60 per ton	ca. € 80 per ton
Material costs per m^2	ca. € 5 per m^2	ca. € 5 per m^2

The expected lifespan of both asphalt mixtures is approximately 12 years. The reduced layer thickness of the Novachip 5 (of 25 mm) has been compensated by the highly SBS-modified binder. Using this highly polymer modified binder (PmB) result in a better resistance against stripping, cracking and rutting. Also, the Novachip 5 is constructed with the special Novachip-machine whereby the tack layer and the asphalt layer are constructed in one procedure resulting in a very good bonding (adhesion) with the underlying layer. Also, the Novachip 5 can be constructed with 10-15 m/min resulting in less hindrance for road users and local residents.

In terms of costs the material costs per asphalt ton, the Novachip 5 is more expensive due to the PmB (app. €20 per ton more expensive). However, there is less material needed (due to the reduced layer thickness and density), resulting in similar material costs per square meter (app. €5 per m^2).

In conclusion, the Novachip 5 has a lower rolling resistance of 12%, has a 25-30% better skid resistance, produces 5.6 dB(A) less noise and has the same expected lifespan for similar costs per square meter. The next section hones in the impact of the reduced rolling resistance on the reduction of greenhouse gasses.

6. IMPACT OF THE RESULTS ON CO_2-REDUCTION

A reduction in rolling resistance directly reduces fuel consumption. The amount of the reduction depends on the nature and speed of the traffic. As discussed in the literature section, the assumed ratio between rolling resistance reduction and fuel savings is approximately 5:1 for the type of traffic and speeds typical of a provincial road. In other words, every percentage point of rolling resistance reduction results in 0.2% fuel savings. So, the rolling resistance reduction of 12% measured in the field validation results in 2.4% fuel savings in comparison with a newly laid SMA 11 reference road surface.

The impact of the improved road surface on energy consumption and the environment has been estimated (1) for a provincial road in the Netherlands, (2) for the primary and secondary roads in the Netherlands, and (3) for the primary (highway) roads in Europe.
This first example calculates the impact for 1 km provincial road in the Netherlands. With an average fuel consumption of 15 km per liter and a traffic intensity of 30.000 vehicles per day, there will be app. 730.000 litres of fuel used on 1 km provincial road per year. When 2.4% fuel can be saved by a low rolling resistance road surface per year per km app. 17.500 litres of fuel can be saved. With an average CO_2-emission per litre of fuel of 2.5 kg CO_2 this means a CO_2-reduction of 43.750 kg (44 ton of CO_2) per km provincial road per year. In this way, the CO_2-emissions caused by production and construction of a new road surface (materials, production, transportation and construction) are compensated within 1 to 2 years.
The second example is for the roads in the Netherlands. In total, there are app. 123.000 km of roads in the Netherlands from which 13.000 km are primary and secondary roads. Following the logic and procedure above for only the primary and secondary roads (with an average traffic intensity of 50.000 vehicles per day), approximately 380 million litres of fuel and app. 950.000 tonnes of CO_2 can be reduced.
The third example is for the roads in Europa. In total, there are app. 6.9 million km of roads in Europa from which 100.000 km are primary, highway roads. Following the logic and procedure above for only the primary, highway roads in Europe (with an average traffic intensity of 20.000 vehicles per day), approximately 1.15 billion litres of fuel and app. 2.9 million tonnes of CO_2 can be reduced.

7. INCLUDING ROLLING RESISTANCE IN PROCUREMENT

The topic of rolling resistance still is in its academic and practical infancy. There is currently insufficient experience, both in the laboratory and in-situ, to include absolute limit values for rolling resistance in procurement documents or design specifications. However, to encourage rolling resistance reductions today, we recommend including the following indirect specifications for new asphalt mixtures to reduce fuel consumption and CO_2-emissions:

- A maximum Mean Profile Depth (MPD) of 1.0 mm;
- Smaller grain sizes (< 11 mm), specifically in porous asphalt mixtures

Also, we recommend to encourage the road construction industry further professionalisation of the topic of rolling resistance by:

- Determine the rolling resistance in the laboratory using the SR-ITD on more asphalt mixtures;
- Measure the in-situ rolling resistance using the Gdańsk University of Technology's measurement principle and test trailer on more road surfaces.
- Measure the texture (MPD) both in the laboratory and in-situ.

In doing so, more data and information derives on the topic of rolling resistance in order to establish limit values in design specifications or future procurements.

8. CONCLUSIONS AND RECOMMENDATIONS

This paper provides a practical method to determine the rolling resistance in the laboratory in order to design energy efficient roads with a low rolling resistance. This resulted in a Proof of Concept (PoC) for an asphalt road surface with demonstrably reduced rolling resistance, both in the laboratory and in-situ.
The optimised mixture (PoC) demonstrably leads to a substantial reduction of the rolling resistance of 12% and with that achieves a reduction in fuel consumption of ca. 2.4%. This results in enormous energy savings and reduction of CO_2-emissions. Further research effort should be put into distinguishing between the rolling resistance of passenger cars and heavy-duty vehicles (in terms of loads and tyres).
In addition, the optimised asphalt mixture has a 25-30% better skid resistance, produces 5.6 dB(A) less noise and has the same expected lifespan for similar costs per square meter. So, further benefits include a better air quality (since emissions other than CO_2 will also be reduced proportionally), better liveability due to its noise reduction, and safer roads due to a better skid resistance. More research effort should still be put into determining the ravelling resistance of the asphalt mixture.

The market to apply this asphalt mixture are provincial and municipal roads where rolling resistance (service life and fuel consumption) and noise reduction are important factors. Also, the asphalt mixture is suitable as overlay for highways.
Also, this improvement in rolling resistance still is relevant with the ongoing electrification of the transportation sector. After all, if less electrical energy is required due to reduced rolling resistance, the practical range of electric cars also improve.
Together, the results of this research contribute to a deeper understanding regarding the tyre-road rolling resistance with respect to noise, skid resistance and lifespan.

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