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Life cycle cost analysis of continuously reinforced concrete pavements (CRCP)

– a comparative study

Institut für Stahlbetonbewehrung e.V.

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CONTENT

1 INTRODUCTION

Continuously reinforced concrete pavements (CRCP) have already proved their value in many circumstances. In several countries, such as Belgium, the United States and South-Korea, CRCP is the main structure for highly trafficked highways. A major factor in selecting the type of pavement is cost. Often, this cost is limited to the initial construction cost. However, the longevity of concrete pavements and in particular of continuously reinforced concrete pavement as well as their low maintenance needs, result in an overall lower cost. In order to account for the initial and future cost, a life cycle cost analysis (LCCA) is performed on different types of pavement structures.

The LCCA considers the initial construction cost, the maintenance cost, and the rehabilitation cost. In addition, the social and environmental cost can be calculated. Traffic congestion during construction and maintenance of the pavement leads to negative impacts on the transport system, such as traffic delay, excessive fuel consumption and higher vehicle emissions. Enumerating these impacts in their monetary terms allows to evaluate the social impact of the type of pavement. As this impact is strongly dependent on the actual situation of the pavement, i.e. capacity of the highway, period of maintenance, duration of maintenance, ..., only a systematic approach is presented in this LCCA.

The environmental impact does not only describe the impact of the materials and construction on the environment, but also the emissions during lifetime due to the rolling resistance of the pavements. Several research projects have been conducted to describe these impacts during the user phase of the pavement. This will not be elaborated in this LCCA.

This document first presents the principle of continuously reinforced concrete pavements. Additionally, the principles of the LCCA performed are described, with specifications of the different parameters considered. In a following chapter, the results are presented and finally the conclusions are drawn.

2 CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS – CRCP

2.1. THE PRINCIPLE OF CRCP

Continuously Reinforced Concrete Pavement (CRCP) is a concrete pavement with a continuous longitudinal reinforcement to eliminate transverse contraction joints. The concrete is allowed to crack, but these transverse cracks are closed by the presence of the longitudinal reinforcement, so no water infiltration takes place. To do so, the rate of reinforcement steel needs to be sufficiently high (0,7 to 0,8 %) in order to allow the concrete to crack with a regular crack pattern, with crack distances ideally between 0,5 and 2,4 m.

The technique of continuously reinforced concrete pavements has been applied since the 1960s and in a larger amount since 1970 in Belgium with very positive results, leading to highways of around 50 years old, still in good condition and with low maintenance costs. The standard design underwent several changes addressing longitudinal reinforcement rate, depth of the reinforcement layer, presence of an asphalt interlayer, pavement thickness, concrete mix, surface finishing and lane width. Following concept is applied since the mid-90s:

- 0.75 % longitudinal reinforcement
- 80 to 100 mm concrete covering above the reinforcement
- asphalt interlayer
- thickness 230 to 250 mm (with air entrained concrete) for construction class B1 (corresponding to the highest traffic loading)
- concrete with air entrainer and fine exposed aggregate surface
- width of the slow lane 3.75 m
- base layer in lean concrete

This has provided significant satisfaction considering no large and generalised cases of damage were established on CRCP sections constructed with this concept. On the other hand, clusters of closely spaced cracks, the spalling of crack edges and Y-cracking are observed, that may cause damage in the longer term. In addition, large distances between the first cracks were present, which led in some cases to the appearance of horizontal cracking at the height of the reinforcement. To avoid the cluster formation as well as the large crack distances, from 2012 on, crack initiation is applied in Belgium. This is done by sawing as soon as possible a tread of 40 cm long, 4 cm deep with an interdistance of 1,2 m at one side of the paved concrete.

Figure 1: Regular crack pattern with the application of the saw cut as crack initiation (E34 – Kaprijke)

2.2 THE EVOLUTION OF THE STANDARD STRUCTURE IN CRCP IN BELGIUM

CRCP has already been used on a large scale in Belgium for more than fifty years. The standard design underwent several changes addressing longitudinal reinforcement rate, depth of the reinforcement layer, presence of an asphalt interlayer, pavement thickness, concrete mix, surface finishing and lane width (position of the longitudinal joint). Four different concepts were applied over the years, summarised in Table 1.

	Concept 1	Concept 2	Concept 3	Concept 4
Principle	1 layered CRCP with brushed or grooved surface	1 layered CRCP with brushed or grooved surface	1 layered CRCP with exposed aggregate surface	1 or 2 layered CRCP with exposed aggregate surface
Period	1965 – 1980	1980 – 1990	1990 – 2012	2012 – now
Thickness concrete pavement	20 – 23 cm	20 – 23 cm	23 cm	25 cm
Longitudinal reinforcement rate	0,85 %	0,67 %	0,76 %	0,75 %
Concrete cover (middle reinforcement)	7 +/- 1 cm	9 +/- 1 cm	8 +/- 1 cm	9 +/- 1 cm (two-lift)
Surface treatment	Brushed or grooved	Brushed or grooved	Exposed aggregate	Exposed aggregate
Asphalt interlayer	6 cm	None	5 cm	5 cm
Base layer in lean concrete	20 cm	20 cm	20 cm	25 cm
Subbase	20 cm	20 cm	20 cm	20cm
Type of concrete – Dmax	40 mm	31,5 mm	20 mm	20 mm for 1-lift CRCP 6,3 mm for top layer and 31,5 mm for bottom layer of 2-lift CRCP
Type of concrete – air entrainer	No	No	Yes	Yes (in 1-lift concrete and in top layer of 2-lift concrete)
Crack initiation	No	No	No	Yes

Table 1: Evolution in concepts of CRCP in Belgium

In Germany, the experience with CRCP is limited to test sections, as is reported in H DBB (Hinweise für durchgehend bewehrte Betondecke, H-DBB, FGSV-Arbeitskreis 8.3.4). Two major types of structures have been built: CRCP on an asphalt base layer or CRCP on a lean concrete base layer, with a geotextile between both layers. The thickness of the CRCP is between 22 cm and 25 cm. For highly trafficked roads, 25 cm is taken. A recent study of the test tracks in Germany (A5 in Bruchsal, A5 in Darmstadt, privat access road in Geseke, A94 in Frostinning, B56 in Düren and A11 in Bernau) in the project FE08.0248 'Asphaltdeckschicht auf durchgehend bewehrter Betondecke; wissenschaftliche Begleitung der Versuchsstrecken während der Betriebsphase', BAST, indicate a good behaviour of all test tracks, with a slight preference for the asphalt base layer or asphalt interlayer on a lean concrete base layer. As it is not clear yet what structure will be taken as the standard structure, the different structures are presented in Table 2.

	Structure G1	Structure G2	Structure G3
CRCP (0,75 % longitudinal reinforcement)	250 mm	250 mm	250 mm
Interlayer		geotextile	50 mm Asphalt interlayer
Base layer	150 mm asphalt base layer	150 mm lean concrete (HGT)	150 mm lean concrete (HGT)
Sub base	Frost protection layer	Frost protection layer	Frost protection layer

Table 2: Standard structures as applied in Germany

3 LIFE CYCLE COST ANALYSIS

3.1. PRINCIPLE

The goal of this life cycle cost analysis is to evaluate the long-term impact of the CRCP. For this, the CRCP-structures are compared to two alternative structures, namely the jointed plain concrete pavement (JPCP) and the bituminous pavement.

The LCCA is calculated using the deterministic approach, introducing a standard cost for construction and maintenance actions. The investment alternatives are compared on the basis of the Net Present Value (NPV). To do so, the future costs and benefits are transformed into present costs, taking the discount rate into account, according to the formula

$$\text{NPV} = \text{IC} + \sum_{k=1}^{Q} \text{FC}_k * \left(\frac{1}{(1+r)^{y_k}}\right) - \text{RV} * \left(\frac{1}{(1+r)^{p}}\right)$$

with
- NPV = net present value
- IC = initial cost of construction
- FC_k = future cost of activity k
- RV = residual value of the pavement (benefit)
- r = real discount rate
- y_k = year in the future in which the cash flow of activity k occurs
- Q = total number of activities
- p = number of years in analysis period

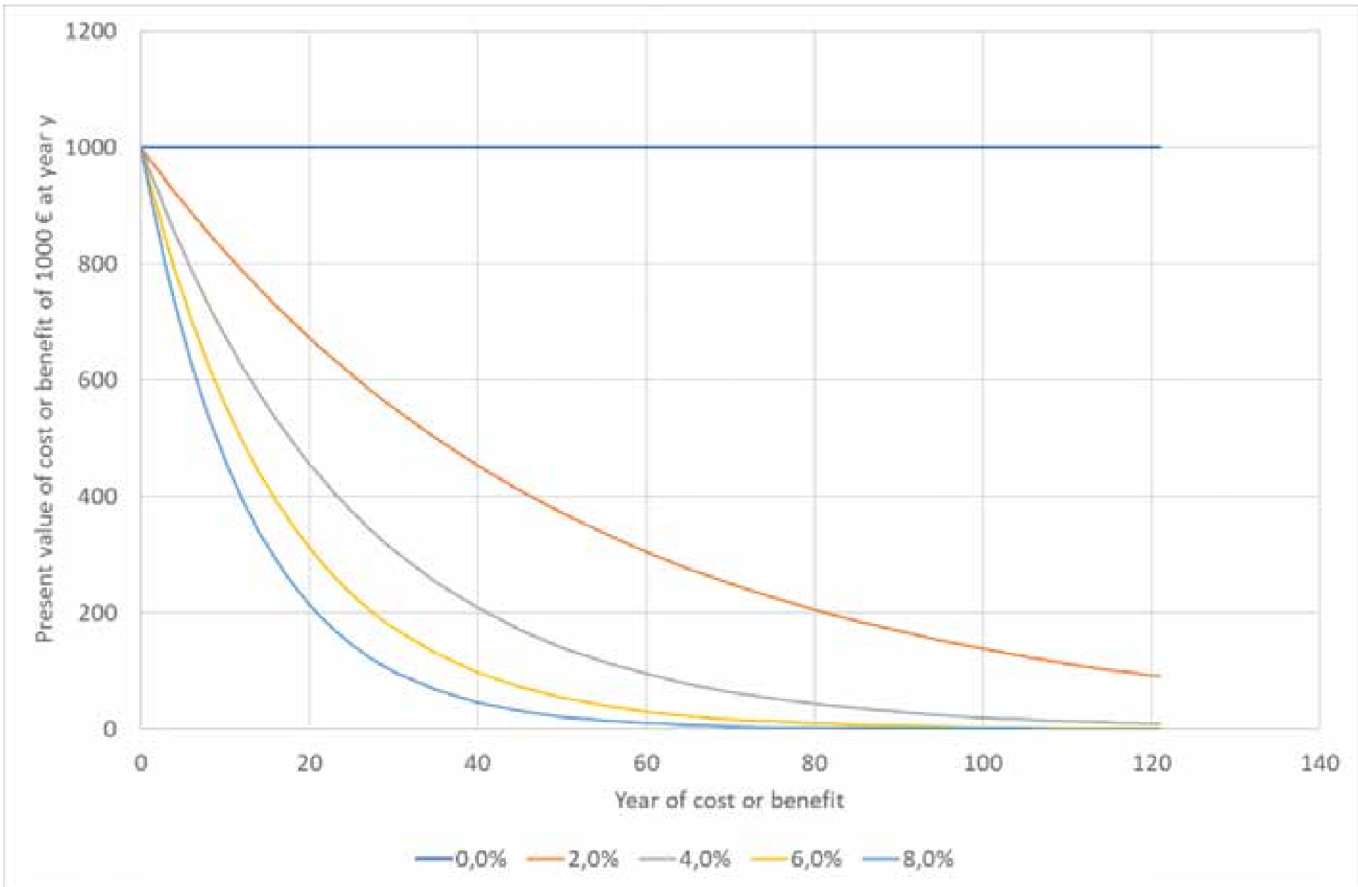

Figure 2: Influence of the discount rate on the present value of a cost or benefit made in year y

High real discount rates favour alternatives that have low initial costs and high future costs, while low real discount rates favour alternatives with higher initial costs and lower future costs.

The LCCA compares different solutions over a certain period. If the end of the performance period of the evaluated pavement does not coincide with the evaluation period, the pavement has a residual life through remaining services. However, these are difficult to estimate. To avoid this, the NPV can be determined over an 'infinite horizon' [1]. In that case, the construction is evaluated taking a typical cycle of activities into account, i.e. maintenance, demolition and rehabilitation/reconstruction. The net present value over an infinite horizon is determined following the equations below.

$$\mathrm{NPV}_L = \sum_{k=1}^{Q} \mathrm{FC}_k * \left(\frac{1}{(1+r)^{y_k}}\right) - \mathrm{RV} * \left(\frac{1}{(1+r)^L}\right)$$

$$F_{\infty H_L} = \frac{(1+r)^L}{(1+r)^L - 1}$$

$$NPV_{\infty H} = IC + NPV_L * F_{\infty H_L}$$

with IC = Initial Cost of
FC_k = future cost of activity k
RV = residual value of the pavement through recycling
r = real discount rate
y_k = year in the future in which the cash flow of activity k occurs
Q = total number of activities
L = number of years of performance life between initial construction and reconstruction

The higher the discount rate, the faster the NPV at infinite will equal the NPV calculated over that certain period. For example, the NPV at infinite differs with 1 % from the NPV calculated over 120 years of service life, when 8 % discount rate is considered. At a discount rate of 2 %, the difference between both is still 27 %. So, at 2 %, a residual value should be taken into account, which is not the case at 6 % or higher. To eliminate the influence of the residual lifetime, the calculation is made with the NPV at infinite.

3.2 PAVEMENT STRUCTURES TO BE EVALUATED

Three different types of pavement structures are included in the life cycle cost analysis:

– structure 1 – CRCP: continuously reinforced concrete pavement
– structure 2 – JPCP: jointed plain concrete pavement
– structure 3 – Bituminous pavement

The analysis is done for a highly trafficked highway. The selected length of the section to be evaluated is 10 km. The cost of the CRCP takes into account protection of the fresh concrete, anchor lugs, applying of the crack initiation, sawing and sealing of the longitudinal joints and all works needed to put the concrete in place. The selected highway has 3 lanes of 3,50 m, a redirecting lane of 0,75 m and an emergency lane of 3,75 m, with a total width of 15,6 m, as is given in Figure 3. The thickness of the total structure is taken 80 cm.

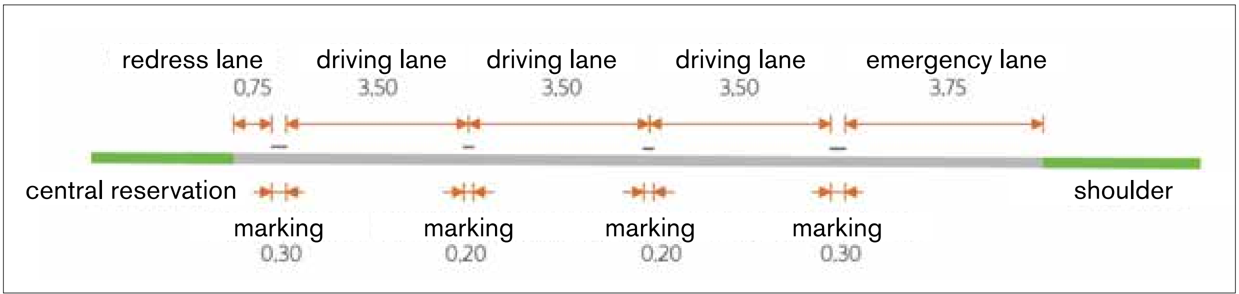

Figure 3: cross section of the highway as is used for the calculations

Four different structures of CRCP from Belgium and two from Germany are evaluated:

structure 1.1 – CRCP, two-lift pavement, exposed aggregate surface (concept 4):

– 5 cm concrete 0/6,3 with air entrainer, placed wet-in-wet
– 20 cm concrete 0/32 without air entrainer as under layer, reinforcement rate of 0,76 %
– 5 cm asphalt interlayer ABT-B
– 25 cm lean concrete
– 25 cm subbase layer

structure 1.2 – CRCP, one-lift pavement, exposed aggregate surface:

– 25 cm concrete 0/20 with air entrainer, reinforcement rate of 0,76 %
– 5 cm asphalt interlayer ABT-B
– 25 cm lean concrete
– 25 cm subbase layer

structure 1.3 – CRCP, composite pavement:

– 3 cm SMA-D (Splitt mastic asphalt with aggregates 0 to 6,3 mm)
– 25 cm concrete 0/32, reinforcement rate of 0,76 %
– 5 cm asphalt interlayer ABT-B
– 25 cm lean concrete
– 22 cm subbase layer

structure 1.4 – CRCP, old concept:

– 23 cm concrete 0/32 without air entrainer, reinforcement rate of 0,85 %
– 4 cm asphalt interlayer ABT-B
– 23 cm lean concrete
– 30 cm subbase layer

structure 1.5 – CRCP, German structure with asphalt base layer

– 25 cm concrete 0/20 with air entrainer, reinforcement rate of 0,76 %
– 15 cm asphalt base layer
– 40 cm frost protection layer

structure 1.6 – CRCP, German structure with geotextile and lean concrete base layer

- 25 cm concrete 0/20 with air entrainer, reinforcement rate of 0,76 %
- 0,5 cm geotextile
- 25 cm lean concrete
- 9,5 cm frost protection layer

The structure 2 in JPCP has following layers:

structure 2.1 – JPCP, Belgian concept

- 27 cm jointed plain concrete pavement with slab lengths of max. 5,0 m, doweled in the transverse joints and with tie-bars in the longitudinal joints
- 5 cm asphalt interlayer
- 25 cm lean concrete base layer
- 23 cm subbase layer

structure 2.2 – JPCP, German concept for a BK100

- 27 cm jointed plain concrete pavement with slab lengths of max. 5,0 m, doweled in the transverse joints and with tie-bars in the longitudinal joints
- 0,5 cm geotextile
- 15 cm HGT (cement stabilised base)
- 37,5 cm frost protection layer (Frostschutzschicht)

The structure 3, the bituminous pavement, consists of 3 asphalt layers on a stabilised aggregate layer:

structure 3 – bituminous pavement

- 3 cm SMA-D
- 10 cm AVS-A (asphalt with a bitumen with increased elasticity modulus with aggregates 0 to 20 mm)
- 10 cm AVS-A
- 30 cm stabilised aggregate base layer
- 27 cm subbase layer

An overview of the different structures is given in Figure 4.

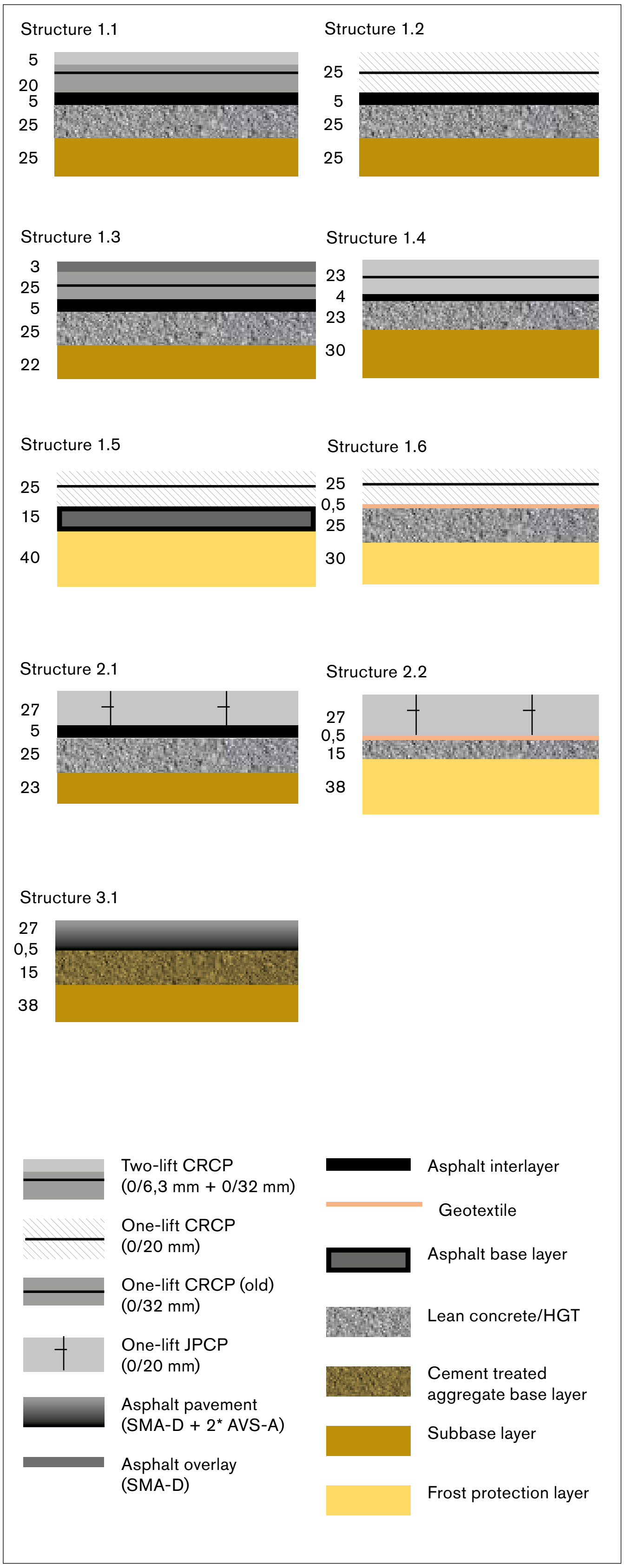

Figure 4: Overview of the different structures

3.3 STRUCTURAL BEHAVIOUR

The structural behaviour of the different structures is evaluated by VENCON 2.0 (@CROW, the Netherlands) for the concrete structures (structure 1.1 to 1.6, 2.1 and 2.2). For the bituminous structure, a calculation with DIMMET (@SPRW, BRRC and FEBELCEM, Belgium) is made. VENCON 2.0 is a software developed to calculate concrete road structures. The result is a certain thickness of the concrete pavement in relation with the structure beneath and the type and intensity of the traffic. DIMMET is developed to calculate rigid as well as flexible pavements. It gives as result a chance of rupture at the theoretical design lifetime and calculates the maximum number of heavy vehicles allowed on the structure before rupture.

The calculation of the concrete pavements is done for a pavement geometry, as indicated in Figure 3. The longitudinal joint between the emergency lane and the first lane is a bending joint, with in the case of CRCP transverse reinforcement as connection. A load transfer of 70% is presumed in this case (standard by VENCON). The longitudinal joint between the first and the second lane is a construction joint, with tie-bars between both lanes. A load transfer of 50% is presumed in this case. The load transfer in the longitudinal direction at transverse cracks is 90% in the case of CRCP and 70% in the case of a doweled JPCP. The necessary thickness at the most critical point is presented in Table 3.

Temperature gradient, traffic intensity and type of traffic is taken equal in all cases. Calculations are made for a highly trafficked highway.

The influence of the soil is limited, considered the presence of the subbase layer of minimum 220 mm up to 380 mm.

VENCON calculates a thickness for the concrete pavement together with an over-thickness, related to the evenness of the base layer. In the case of a bituminous interlayer of base layer, 10 mm tolerance is added. In the case of a cement bound base layer, 15 mm needs to be added as tolerance for execution.

The results are presented in Table 3. Structure 1.1, 1.2 and 1.3, variations on CRCP, will behave in a similar way as there is no difference presumed in bending strength between the one-lift and two-lift concrete and the thin overlay will not influence the structural behaviour.

	Construction thickness (design thickness + tolerances)	Design thickness	Most critical point
Structure 1.1/1.2/1.3	244 mm	234 mm	Longitudinal construction joint of first lane (heavy traffic)
Structure 1.4	244 mm	234 mm	Longitudinal construction joint of first lane (heavy traffic)
Structure 1.5	255 mm	240 mm	Longitudinal construction joint of first lane (heavy traffic)
Structure 1.6	249 mm	234 mm	Longitudinal construction joint of first lane (heavy traffic)
Structure 2.1	254 mm	244 mm	Longitudinal construction joint of first lane (heavy traffic)
Structure 2.2	265 mm	250 mm	Longitudinal construction joint of first lane (heavy traffic)

Table 3: Theoretical calculation of the thickness of the concrete pavement for the different structure in the case of a heavy trafficked highway

The results indicate that there is little difference in the theoretical behaviour of the structure if an asphalt interlayer is applied or not. This is since no adhesion is considered in the calculation. Moreover, the structural calculation does not take into account the possible deterioration of the surface of the base layer due to erosion. By placing an asphalt interlayer, the risk of erosion and therefore the risk of punch-out is lower.

The results also indicate the influence of the longitudinal reinforcement: as the load transfer at the transverse crack or joint in the case of CRCP is much higher, due to the presence of the longitudinal reinforcement, the theoretical thickness could be reduced significantly by 11 to 12 % based on the calculation at the transverse crack.

Also, an increase of reinforcement in the longitudinal construction joint will theoretically increase the lifetime or decrease the theoretical thickness.

However, caution needs to take as these calculations only reveal the structural behaviour and are theoretical calculations. They do not consider any aspects of erosion or scaling or settlements.

Moreover, a change in type of traffic, lane width, wandering and occupancy of the different lanes can lead to different conclusions.

Calculation with DIMMET indicates that also the bituminous structure can resist the heavy traffic. At the design lifetime of 36 years for the bituminous structure, a theoretical chance of rupture is 8,3 % and the allowed number of axes is $1{,}05 \times 10^{10}$. Rutting will occur in all layers with a total theoretical depth of 14,1 mm after 36 years. If the same calculation is done for the CRCP-structure 1.1, with a theoretical lifetime of 40 years, the chance of rupture of 0,2 % and the total amount of axes is $3{,}26 \times 10^{11}$, so more than 30 times more vehicles than the asphalt structure. The residual lifetime of the concrete structures will therefore be higher in the case of CRCP than of the bituminous structure.

These verifications indicate that all structure theoretically will resist the traffic and the environmental impact during the presumed lifetime for the cost calculation.

3.4. CONSTRUCTION COST

In the calculation of the construction cost, only the structure itself is considered. All aspects, which are comparable to all types of structures, such as marking, barriers, ground works,… are not taken into account, except if due to e.g. the replacement of the top layer, an additional replacement of the markings is needed.

The calculation of the construction cost is done based on in Belgian prevailing prices in 2019/2020 for performing works on motorways. The social costs, such as lane availability, user cost, environmental impact,… were considered qualitatively but not budgeted for quantitatively. There is a slight difference between construction cost and reconstruction cost, as it is presumed that in the case of a rigid pavement, the subbase is designed for two lifetimes of the pavement. This is supported by the fact that in the case of the CRCP applied on the E40, the subbase layer is still in very good conditions, even after 50 years in service.

Figure 5: View on a core taken from the E40, Belgium, near Heverlee in September 2020 after almost 50 years in service. A limited degradation of the lean concrete and the asphalt interlayer is visible.

The construction and reconstruction costs of the different structures are presented in Figure 6. The reconstruction of the pavement is limited to the pavement and the base. The reconstruction cost does also incorporate the demolition cost of the pavement and base layer.

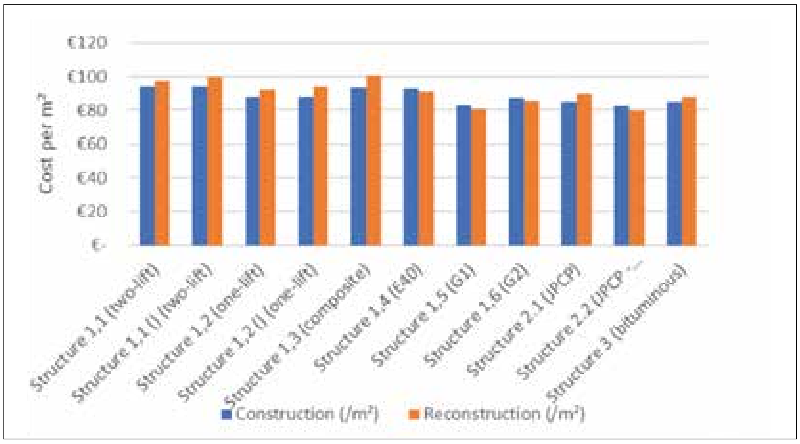

Figure 6: Construction and reconstruction cost of the different pavement structures

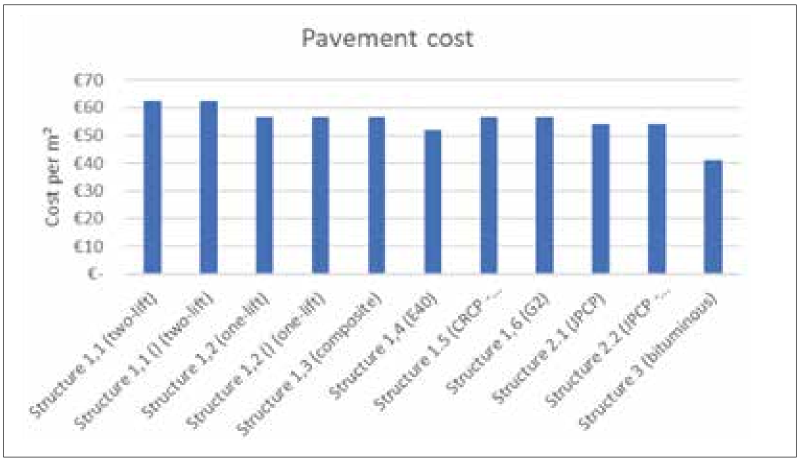

Figure 7: Results, specific for structures applied in Germany

The cost of the pavement itself is presented in Figure 8.

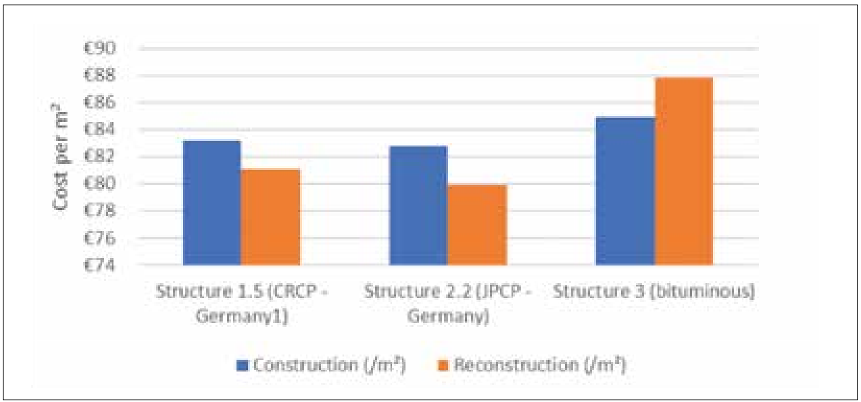

Figure 8: Cost of the pavement

The lifetime of the CRCP is taken to be 40 years, with a prolongation of 20 years if it overlaid with a dense asphalt layer (SMA) to prohibit water to enter the CRCP. The lifetime of the JPCP is taken to be 36 years, similar to the bituminous pavement structure. The joint maintenance interval is longer in the case of CRCP, compared to JPCP as the movement of the longitudinal joint is much less than the movement of the transverse joints due to the presence of the transverse reinforcement or tie bars.

The lifetime of the different structures is presented in Table 4.

		Theoretical lifetime
Structure 1.1	Two-lift CRCP	40 years
Structure 1.1*	Two-lift CRCP with asphalt overlay after 40 years	60 years
Structure 1.2	One-lift CRCP	40 years
Structure 1.2*	One-lift CRCP with an overlay after 40 years	60 years
Structure 1.3	Composite CRCP	60 years
Structure 1.4	CRCP from E40 Heverlee, overlayed after 40 years	60 years
Structure 1.5	CRCP – Germany with asphalt base layer	40 years
Structure 1.6	CRCP – Germany with geotextile and lean concrete base layer	40 years
Structure 2.1	JPCP – Belgium	36 years
Structure 2.2	JPCP – Germany	36 years
Structure 3	Asphalt pavement	36 years

Table 4: Theoretical lifetime of the different structures

3.5. MAINTENANCE STRATEGY

The continuously reinforced concrete structures follow more or less the same maintenance strategy, as is revealed in Table 5. The maintenance for the JPCP is higher as the transverse joints need to be replaced more frequently.

In the case of an asphalt overlay, the lifetime of the markings needs to be considered. In the SB 250 (technical specifications of the Flemish Road Authorities), a minimum durability of 6 years is asked in case of longitudinal structured markings (between the right lane and the emergency lane), a minimum of 3 years is asked for in the case of non-structured markings. This means that the replacement frequency of the top layer is by preference a multiple of 3 or 6 years.

The durability of the top layer alters as it is placed on CRCP, JPCP or as a part of a bituminous pavement. In the case of CRCP, the deformation of the top layer is very limited as there are no transverse joints. Visual inspection of the overlay on the E40 in Heverlee showed no reflective cracking after 10 years in service. This results in a longer lifetime than is the case of an overlay on a JPCP. In the case of a bituminous pavement, the top layer and the total structure will be more exposed to rutting.

Taking this into account, the lifetime of the overlay on CRCP is taken to be 12 years, for an overlay of JPCP or a top layer of a bituminous pavement, the lifetime is 9 years. This will minimise the cost of the replacement of the marking. The lifetime of an overlay on a JPCP is taken shorter than that on a CRCP as the movement of the joints and cracks and the faulting of the slabs will be more important in the case of a JPCP than of a CRCP.

Structure	1.1/1.5/1.6	1.2	1.3	1.4	2
Type	CRCP, one-lift	CRCP, two-lift	CRCP, composite	CRCP, old concept	JPCP
Resealing joints	Every 12 years, longitudinal joints	Every 12 years, longitudinal joints	Every 12 years, longitudinal joints	Every 12 years, longitudinal joints	Every 10 years, longitudinal and transfer joints
Local repair of punch-outs (1.000 €/piece)	Every 6 years, starting at year 12 – rate: 0,1/km/ year	Every 6 years, starting at year 12 – rate: 0,1/km/ year	Every 12 years, starting at year 12 – rate: 0,05/km/ years	Every 6 years, starting at year 12 – rate: 0,05/km/years	
Replacement of the top layer, two right lanes			Every 12 years	Every 12 years, starting at year 48	
Replacement of the top layer, all lanes			Every 36 years		
Slab replacement (2.465 €/piece)					Every 5 years, starting after year 10 – rate: 1/km/1 year
Reconstruction	At 40 years / 60 years with additional overlay after 36 years	At 40 years / 60 years with additional overlay after 36 years	At 60 years	At 60 years	At 36 years

Table 5: Maintenance strategy for the concrete pavements

In the case of JPCP, the transverse as well as the longitudinal joints need to be maintained. In the case of CRCP, only longitudinal joints are present. The movement of a longitudinal joint is much more limited as rebars are present over this joint. In the case of CRCP, the transverse reinforcement is holding the lanes together over a longitudinal bending joint.

The maintenance strategy, presented in Table 6 is taken into account for the bituminous structure.

Structure	3	Rate
Type	Bituminous structure	
Crack and joint treatment	Every 3 years, starting at year 4 after replacement of top layer	5/km/year
Pothole, patching and surface defects repair	Every year, starting at year 4 after replacement of top layer	5/km/year
Replacement of the top layer, two right lanes	At year 9	Only 2 right lane: 3,5 m width
Replacement of the top layer, all lanes	At year 18	All lanes
Reconstruction	At year 36	Pavement and base layer

Table 6: Maintenance strategy for the bituminous pavements

3.6 MAINTENANCE COST

The maintenance cost is calculated, taking into account the cost for the removal of the existing material, the cost for the placement of the new material as well as the cost for the lane closure. The social cost is not considered.

In the case of an asphalt overlay of a CRCP, the cost for repair is taken 10 % higher to include the extra cost for the overlay and the extra cost for the slightly longer lane closer.

The repair of a punch-out considers following phases:

- removal of the asphalt layer over a surface of 2,30*2,30 m^2 (15 cm more than the concrete itself)
- sawing over full depth and removal of the concrete pavement over a surface of 2,0*2,0 m^2
- placement of the longitudinal reinforcement
- replacement of the concrete
- replacement of the asphalt overlay (if this is the case)
- signalisation of the lane - closure over 2 lanes

As the main cost is the signalisation of the lane closure, the difference between the repair of the composite pavement and the CRCP without asphalt overlayer is only 5 %. The frequency of appearance of the damage however will be higher if no asphalt overlayer is applied.

For the repair of asphalt, no lane closure is taken into account but only a lane disruption, secured by safety cars is taken into account. For the repair of CRCP and JCPC, a lane closure is considered. The repair of one punch-out varies between 1.029 € and 1.106 €, depending on the thickness of the pavement and the presence of an asphalt overlay. The repair of a slab costs approximately 2650 €/slab and the repair of a crack and pothole in a bituminous pavement costs 32,4 and 85€ respectively.

3.7 SOCIAL COST

To determine the social cost of the type of pavement, one must consider the impact on the traffic due to the construction of the pavement and due to the periodic maintenance on the traffic flow. To forecast the availability of the road, an estimation of the time of obstruction of the lanes is made in relation to the maintenance and repair to be done.

Although the time of construction of a highway is only limited influenced by the construction time of the pavement itself, the type of pavement may influence the critical path of the total highway. Therefore, the obstruction time during construction is considered as is presented in Table 7. As unit, the section of 10 km is taken.

	CRCP	Composite CRCP	JPCP	Bituminous pavement
Construction time	55 days	60 days	55 days	50 days
Joint maintenance 6 hours for longitudinal joints per joint	50%	50%	50%	50%
24 hours for transverse joints per lane				
Slab replacement 24 hours			50%	
Slab injection and stabilisation 24 hours			50%	
Repair of cracks, pits,… of the top layer 6 hours				Local repair with collision trucks, 75%
Punchout repair 24 hours	50%	50%		
Replacement of bituminous top layer of the right lane 24 hours	50%	50%		50%
Replacement of bituminous top layer over total width 48 hours	0%	0%		0%
Demolishing of the pavement	5 days	5 days	5 days	3 days

Table 7: Summary of the obstruction time and availability for the different structures during construction and maintenance

Unavailability of (a part of) the highway will result in traffic congestion leading to a longer travel time, higher fuel consumption and more important emissions.

Traffic congestion results in larger travel times, which is immediately perceived by the traveller and causes direct or indirect economic losses. The value of travel time is the monetary value that a person will be ready to pay for a unit travel time reduction and depends on many factors such as the income of the traveller, intention of the trip, the condition and time of travel and the mode of travel [2]. The delay cost is calculated taking into account the difference of the actual travel time with the average travel time at free flow conditions, the type of vehicle and the amount of vehicles.

The increase in fuel cost due to congestion is influenced by the type and number of vehicles, the type of fuel used and the fuel consumption rate.

Traffic congestion will also lead to an increase of the air pollution due to a higher emission due to stop and go conditions during congested periods. This may change drastically due to the electrification of the vehicles and due to the more efficient engines.

As the LCCA is calculated for a typical highway without further specifications, the calculation of the social cost is limited to the calculation of the lane disruption time. This lane disruption time can then be used to calculate the social cost for a specific highway, where traffic flows are known and the influence of the disruption on the fluidity of the traffic can be simulated.

4. RESULTS AND DISCUSSION

4.1. LIFE CYCLE COST ANALYSIS

The overall result of the calculation is presented in Figure 9 and in Table 8. The results clearly indicate there are three important parameters: the initial cost, the discount rate and the lifetime of the initial construction.

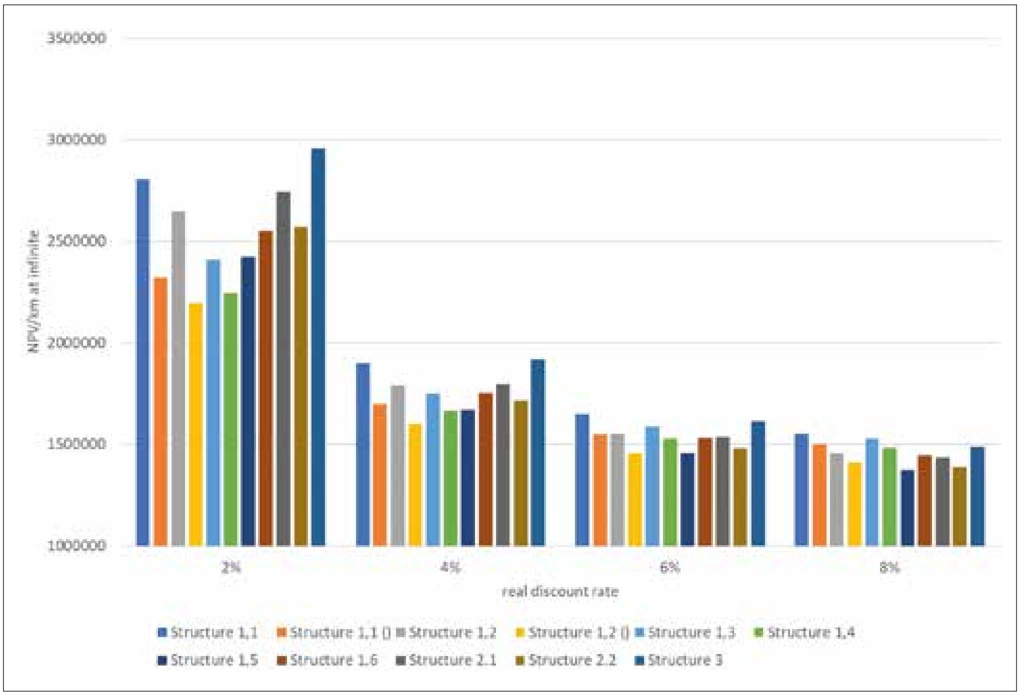

Figure 9: Overall results for the different structures

	construction cost	2 %	4 %	6 %	8 %
structure 1,1	€ 1 462 820	€ 2 806 572	€ 1 901 190	€ 1649 453	€ 1 551 480
structure 1,1()	€ 1 462 820	€ 2 323 017	€ 1 698 570	€ 1 549 659	€ 1 500 999
structure 1,2	€ 1 374 438	€ 2 645 029	€ 1 789 556	€ 1 551 553	€ 1 458 834
structure 1,2()	€ 1 374 438	€ 2 195 907	€1 600 910	€ 1 458 517	€ 1 411 737
structure 1,3	€ 1 460 020	€ 2 410 591	€ 1 753 111	€ 1 588 955	€ 1 530 122
structure 1,4	€ 1 446 077	€ 2 246 028	€ 1 667 409	€ 1 528 632	€ 1 482 892
structure 1,5	€ 1 298 276	€ 2 426 366	€ 1 668 104	€ 1 456 852	€ 1 374 365
structure 1,6	€ 1 366 526	€ 2 551 113	€ 1 754 310	€ 1 532 452	€ 1 445 909
structure 2.1	€ 1 329 925	€ 2 744 506	€ 1 796 383	€ 1 535 555	€ 1 433 756
structure 2.2	€ 1 292 735	€ 2 570 565	€ 1 716 113	€ 1 480 431	€ 1 388 063
structure 3	€ 1 325 314	€ 2 960 001	€ 1 921 328	€ 1 615 677	€ 1 486 658

Table 8: Construction cost and final cost of the different structures per km

The initial cost has a direct influence on the NPV. As an initial cost, it cannot be discounted. Here, the influence of the structure is important. Not only the pavement is important, but also the base layer and even the subbase layer can play an important part. This can be seen, comparing the Belgian design and the German design. In the German design, an asphalt base layer on a frost resisting layer is used. This results in a cheaper structure. In this research, it is presumed that this structure will have the same performance lifetime as the Belgian structure. First results of the test sections of CRCP put in place in Germany support this presumption. If, however the structure has a shorter lifetime, a higher total cost will be the result as reconstruction will need to be done earlier, which means that it can be less discounted in the NPV.

The lifetime of the initial construction is also an important parameter as it determines the moment of required reconstruction. The later this is, the more it will be discounted and the lower the NPV will be. Similar conclusions can be drawn concerning maintenance: the later maintenance needs to take place and the lower the maintenance cost will be, the lower the NPV is. This is shown by comparing structure 1.1 and 1.1 () of structure 1.2 and 1.2 (). By increasing the lifetime with 20 years, from 40 to 60 years, the NPV is between 17 % and 6 % lower if the discount rate varies between 2 and 6 %. If the asphalt overlay is placed directly, the initial cost will be higher, but the maintenance cost will be lower. As the maintenance is very limited, this will result in a slightly higher total cost than the cost for a CRCP overlayed at 40 years.

The discount rate is as well a very important parameter as it indicates how the costs of the future can be discounted for in the present. As is shown in for the different structures, the total cost is composed by the initial cost, the repair and maintenance cost and the reconstruction cost. The higher the discount rate, the more the initial cost determines the total cost. Comparison between CRCP, JPCP and the bituminous pavement structure also indicate the influence of a higher maintenance cost. In the case of a bituminous pavement, the maintenance is more important and takes a higher part in the total cost.

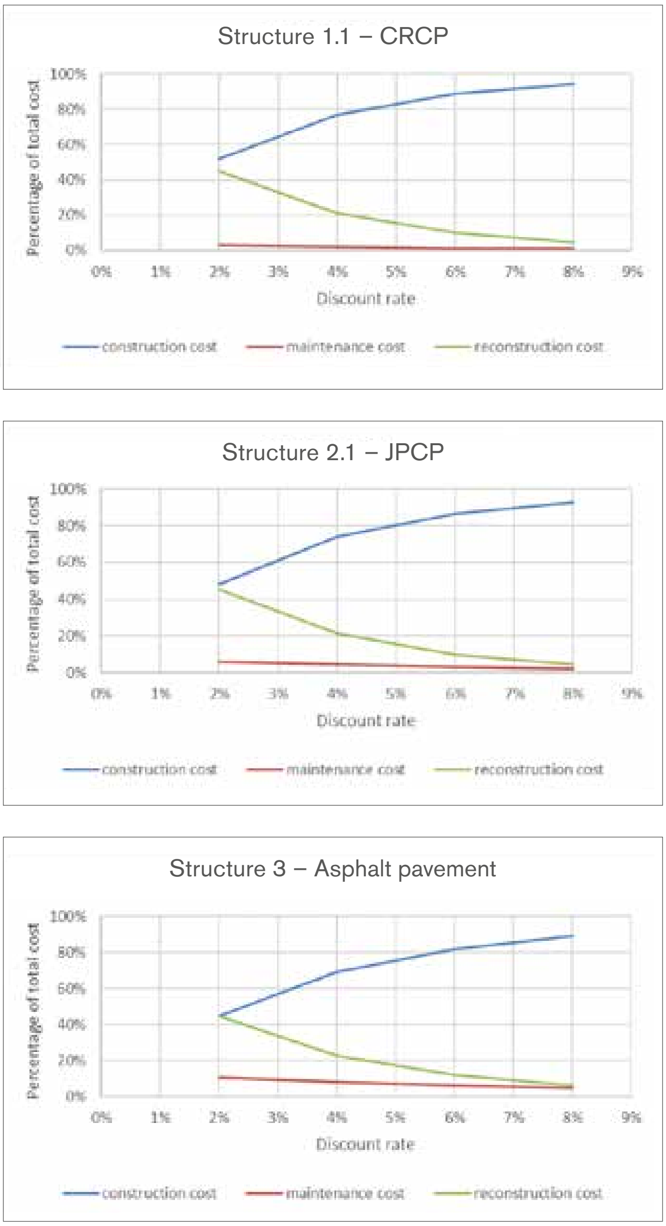

Figure 10: Influence of the discount rate on the cost division in the NPV at infinite

4.2. SOCIAL COST

The results of the calculation of the unavailability of the highway are summarized in Figure 11, representing the number of days that the road is not available for traffic due to construction and maintenance. This is a general approach, taking into account the time of the interference and the lane availability on the considered tracks of 10 km. In most cases, full closure of the highway is not necessary, and works can be carried out during a low traffic period.

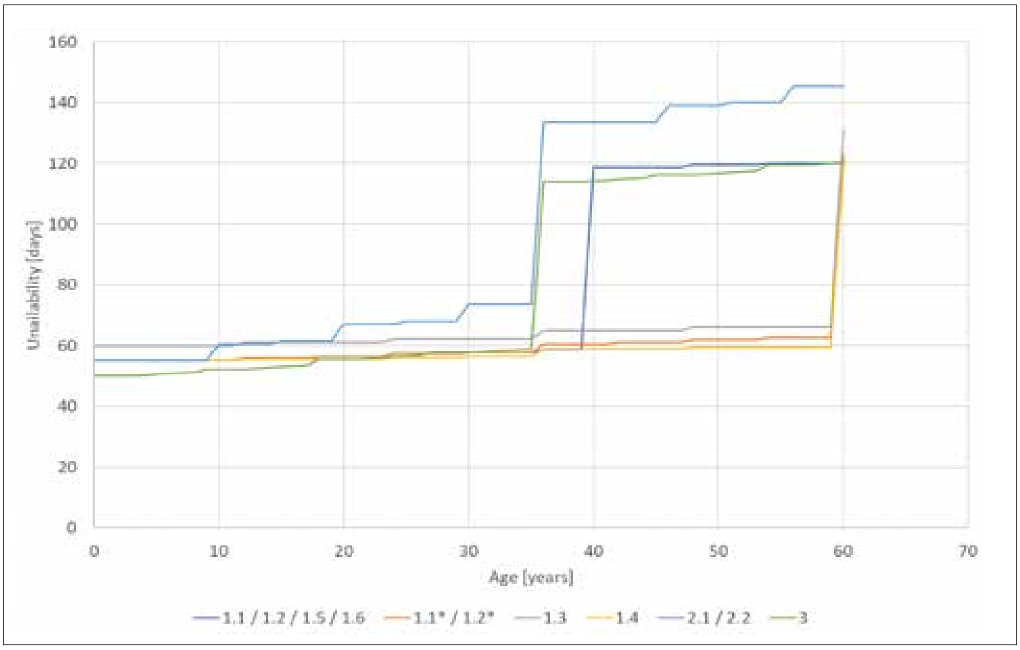

Figure 11: Unavailability (obstruction) of the highway during construction and maintenance over the whole lifetime

The social cost related to the lane disruption will increase only if the construction or maintenance activities will lead to extra congestion on the highway. Congestion adversely affects the economy and social well-being of the road users by wastage of time, deterioration of the health, travel time delay, inability to forecast travel time, increased fuel consumption which causes air pollution and gas emission, wear and tear on vehicles, noise pollution and reduction in road safety [2].

Therefore, extra social cost can be mitigated if maintenance works are planned during low trafficked times and good deviation facilities are foreseen during construction times. Figure 12 indicates the lane disruption due to maintenance.

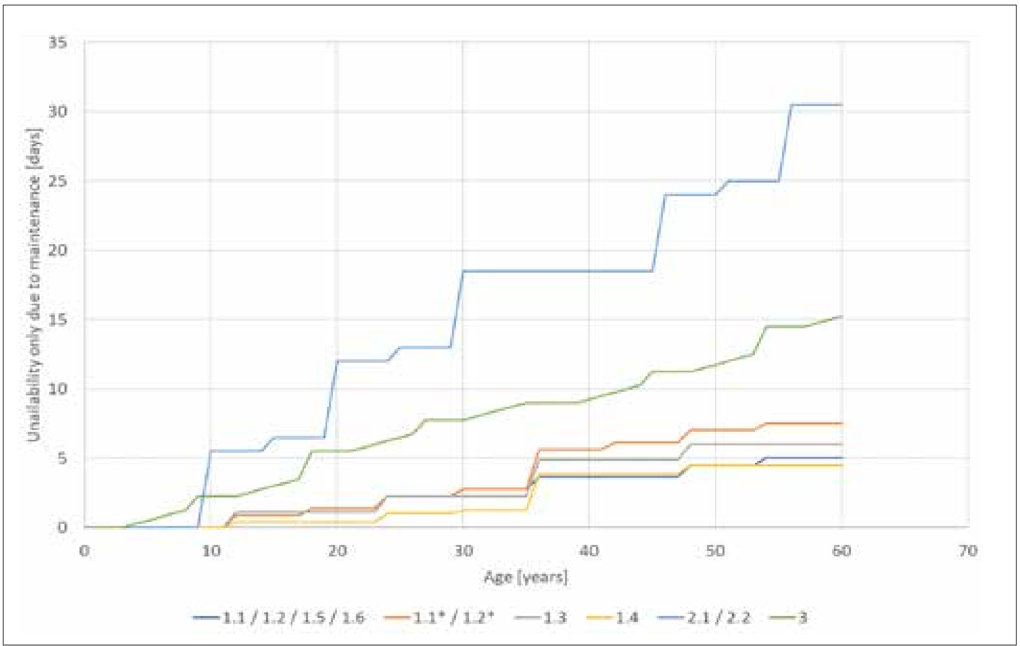

Figure 12: Unavailability due to maintenance of the highway

The analysis of the results indicate that longevity of the pavement has a major influence on the lane availability. The longer the pavement can stay in service, with limited maintenance, the better. Therefore, CRCP with a lifetime of more than 40 years will always result in a higher lane availability than a bituminous pavement or a JPCP. If construction time is not considered, as a good deviation plan can lower disruption time due to reconstruction to a large extent, the advantage of CRCP becomes obvious. Although the composite structure has a slightly higher lane disruption, the difference with a regular CRCP is limited.

5. CONCLUSIONS

The life cycle cost analysis of a continuously reinforced concrete pavement reveals that CRCP is competitive with JPCP and bituminous pavements and even results to be more economical than the two other types of pavements. This is due to the low maintenance cost, taking place at a later stage in the lifetime. This does not only decrease the overall cost of the pavement structure, but also increases the lane availability, with a positive effect on the social cost of the pavement.

Comparison of the structures for CRCP, JPCP and bituminous pavements according to RStO-12 indicate a higher construction cost and rehabilitation cost for the asphalt pavements compared to the cementitious pavements due to the increase in cost for the base layer. By increasing the stiffness of the pavement, the base layer thickness can be reduced and the total cost for the structure will decrease.

Comparison of the different CRCP-structures looked at in this LCCA indicates that the best result is obtained by the structure with the lowest initial cost. However, if the lifetime can be prolonged, more optimal results can be obtained. Economically, it is more appropriate to prolong the lifetime by interventions at a later point after installation. E.g. the structures with an asphalt overlay after 40 years have a prolongation of the lifetime of 20 years. These structures score better than the composite structure, where the asphalt overlay is directly placed at the start. Of course, this statement does not take into account any other aspects like the environmental impact.

The higher initial cost is dominant in the net present value, calculated at infinite, independent of the discount rate. However, if the discount rate increases, the initial cost will be more important for the NPV at infinite. On the other hand, at lower discount rates, the reconstruction cost becomes more important. The later this reconstruction can be done, the lower the NPV will be.

The results indicate that up to a discount rate of 6 %, the choice for CRCP is economically more favourable. At 8 % both structures become economically equal.

In this calculation, the social costs due to lane closure are not directly considered as they depend to a large extent on the congestion due to construction or maintenance of the pavement. While during construction, an optimal deviation plan can be foreseen, the construction time does not necessarily result in a higher social cost. The influence of the maintenance can be reduced by optimising the period of intervention. The calculation of the lane disruption time for the different types of pavements indicates the important unavailability of the JPCP, the doweled slab concrete pavement. The difference between bituminous pavements and CRCP is limited if the longevity of the CRCP is not considered. However, if the lifetime of the CRCP can be extended up to 50 or 60 years by an asphalt overlay, a significant gain in lane availability is achieved over the lifetime with CRCP. The advantage of CRCP is also visible if only maintenance is considered. The disruption time of a continuously reinforced concrete pavement is half of that of a bituminous pavement and one fourth of a JPCP.

The considerations and assumptions made in this LCCA are, off course, only valid if the foreseen construction quality is obtained and the foreseen lifetimes will be achieved.

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