Crack behavior of continuously Reinforced Concrete Pavements (CRCP) in Germany

M. Moharekpour*

Research Assistant, Institute of Highway Engineering, Aachen, Germany

S. Hoeller

Research Engineer, German Federal Highway Research Institute (BASt), Bergisch Gladbach, Germany

M. Oeser

Professor and Head of Institute, Institute of Highway Engineering, Aachen, Germany

ABSTRACT: The traffic volume on German motorways increased steadily and this trend is expected to continue in the future. To guarantee mobility in the future and reduce the national economic consequential costs, road construction with a maximum service life and a minimum of necessary maintenance are needed. Rigid road pavements with continuous reinforced concrete pavement (CRCP) are extremely durable in terms of use and maintenance. The behavior of CRCP is influenced by a number of specific characteristics such as the thickness and the quality of the concrete, the design of the longitudinal and transversal reinforcement, the base layer and the environmental conditions at the time of construction and during service life. These aspects influence the crack pattern crack distance and crack widths. Identified positive crack pattern are one important indicator of positive long-term behavior. In Belgium, the continuously reinforced concrete pavement has been a standard construction for many years. In Germany and Poland CRCP is in the stage of field testing. From 1997 to today, a total of 8 sections with many variations have been built. A detailed comparative study of these sections has so far been lacking. As part of a research project, the RWTH university of Aachen and the German Federal Highway Research Institute (BASt) are investigating these sections with CRCP with and without an asphalt surface course in Germany, and Poland and compare it to the Belgium standard constructions. Load capacity measurements, georadar measurements, visual and automated condition assessments and crack recordings are carried out. The aim is to evaluate the different designs in the sections in terms of their behavior in service, to quantify achievable service lives, necessary maintenance and availability. From this, a preferred variant of the construction is designed, presented in a concept and implemented on a motorway in Germany as part of a trial site. The Project is financed by the German Federal Ministry of Transport and digital Infrastructure (BMVI).

Keywords: continuously reinforced concrete pavements, crack spacing, crack behavior, FWD

1 INTRODUCTION

The two most common materials used for pavement construction are asphalt and concrete. Besides the advantages of asphalt roads like low noise, high skid resistance of a surface layer

*Corresponding author

(M.Asi, 2005), easy maintenance and replacement, asphalt pavement has apparent drawbacks as well, including frequent maintenance, colossal demand for repairing, and short service life (Sungun Kim, 2015). Due to its high stiffness, concrete is able to withstand the stresses from traffic and service over a very long period without permanent deformation. Approximately 9641 km (nearly 73%) out of the 13141 km of Germany's motorways are flexible pavements (asphalt wearing surface). Besides, 3500 km (nearly 26 %) are built in the rigid type (Portland cement concrete pavement with or without a bituminous wearing surface (Infrastruktur, 2020)). According to the traffic forecasts from the German Federal Ministry of Transport and Digital Infrastructure, by 2030, road freight transport in Germany will increase by 17% compared to 2010 (GmbH, 2014). Due to the increase in traffic congestion and the consequent reduction in economic costs, there is a demand for road construction with maximum durability, minimal maintenance, and as few traffic restrictions as possible (Tatiana Petrova, 2018). Continuously reinforced concrete pavement (CRCP) is a representative type of concrete pavement with no transversal joints constructed, and no preventative measures for transverse expansion or contraction joints (Christopher Robinson, 1996) and the role of transverse joints in jointed concrete pavement (JCP) is replaced by suppressing the widening of cracks through longitudinal steel in a concrete slab (Young-Chan Suh, 2020). Therefore, longitudinal bars in CRCP are constructed to limit the crack width and improve the load capacity of transverse cracks (YANG Cheng-cheng, 2020). CRCP offers adequate structural strength throughout the service life because of the ability of concrete to gain strength with time (Sidney Mindess, 1981). CRCP's structural strength is also predicated on its ability to keep cracks tight and thus greatly minimize the development of distress at the cracks (Richter, 1998). The performance of the CRCP is quite satisfactory, with a lower number of distresses than in JCP for pavements with a comparable age .(Pangil Choi S. R., 2014) At the same time, the ride quality of CRCP is consistently better than JCP ((Pangil Choi D.-H. K.-H., 2016). CRCP performs better than JCP or Asphalt pavement and has longer service life and low maintenance cost even under heavy traffic loadings and challenging environmental conditions (Han Jin Oh, 2016). The initial investment cost of CRCP is higher than that of JCP and asphalt pavement, and the repairs of distresses in CRCP are more complicated, expensive, and time-consuming than those in JCP and asphalt pavement (Diependaele, 2018). conducted a life cycle cost (LCC) of CRCP (performance life of 50 years) and asphalt (performance life of 36 years) along a 14.2-km-long carriage way in each direction. Each carriageway consists of a minimum of 4 traffic lanes + 1 emergency lane. The initial cost of CRCP was 150% higher than that of asphalt. In contrast, the estimated maintenance cost and rehabilitation cost of CRCP were estimated to be as low as 9% and 78% those of asphalt, respectively. (Hu, 2015) analysed the LCCs of CRCP and JCP along a 1.6-km-long section of a 2-lane highway in 2012 with a 50-year analysis period.. The total cost of CRCP was 142.3% higher than that of JCP. In contrast, the maintenance cost and rehabilitation cost of CRCP was calculated to be 38.5% and 57.8% less than that of JCP. Major distress found to impact the performance of CRCP were wide transverse and longitudinal cracks, punch-outs, Y-cracking, and spalling (Jeffrey Stempihar, 2020). The American Association of State Highway and Transportation Officials (AASHTO) Design Guide recommends a minimum crack spacing of 107 cm to minimize punch-out or spalling (Blaschke, 1993). The desired crack spacing in Belgium is defined between 0.8 m and 1.3 m based on the technical reports (references).

2 RESEARCH SIGNIFICANCE

Concrete pavements on freeways are constructed in Germany as standardized non-reinforced dowelled slabs on different base and intermediate layers. There are initial indications that this standard construction method will not achieve the planned service life of 30 years. This raises

the question as to which construction methods will be able to meet the requirements of modern infrastructure in the future and ensure the necessary availability of the freeway network. The construction method with a continuously reinforced concrete pavement can be an option. In Germany, this construction method has been used for over 20 years. The developments and applications abroad have been followed with great interest. In Germany, 5 test and trial sections have been installed on federal roads and freeways from 1997 to the present day. Until the introduction as a new standard construction method, these routes will be investigated in detail and compared with Belgian standards. The question is to be answered whether this construction method can guarantee the availability of the highway network under the demands of the future.

3 METHODOLOGY

In this study, three sections with different design parameters on Federal Road B 56 near Dueren, Access Road near Geseke, and Highway A 94 near Munich are investigated, and the performance of CRCP for selected sections are evaluated. Figure 1 shows the location of the considered trial sites in Germany.

Figure 1. Location of trial sites in Germany.

BAST set up the first trial site in CRCP in Germany on the Federal Road B56 near Dueren in a length of 800 m in 1997. The construction consisted of a frost protection layer, an asphalt base layer, and a reinforced concrete surface. The thicknesses of the asphalt base course is 15 cm and CRCP is 22 cm. The bottom layer had a compressive strength of 45 N/mm² and the top layer with aggregates 0/7 mm had a compressive strength of 55 N/mm², and the reinforcement was laid in the middle. In the longitudinal direction, the proportion of reinforcement was 0.61% of cross-section. Four reinforced anchor lugs were built at both ends, which ensured that the concrete slab was saved without shifting. Due to the limited space available, the 7.5 m wide carriageway was installed in strips and anchored together. Figure 2 illustrates the longitudinal section of the three trial sites. The CRCP with a thickness of 22 cm on Geseke and B56 and 24.5 cm on A94 rested on an asphalt base with a thickness of 10 cm, 15 cm, and 10 cm, respectively.

Figure 2. Federal Road B56 near Dueren // Highway A94 near Munich // Access Road near Geseke.

In 2009, Heidelberg Cement AG completed an access road between the Milke cement plant and the Elsa quarry south of Geseke in a length of 1.030 m in CRCP. With the new road construction in CRCP, Heidelberg Cement has optimized the transport of raw materials and clinker between the two production sites and, at the same time, relieved the public road network by driving heavy goods vehicles on a separate route. The road is loaded with around 450 heavy trucks of Heidelberg Cement every day. The width of the road, including the shoulder, is 7.50 m. It was built in two construction lanes of 3.5 m and 4.0 m with a slipform paver and connected with tie bars. The concrete (C35/45) was installed on a 10 cm thick asphalt base layer (AC 22 TS). At both ends, four reinforced endanchors were installed to absorb the shear stresses or longitudinal forces from thermal deformations of the construction. The section's reinforcement ratio is 0.75%, whereby longitudinal reinforcement with a diameter of 20 mm was laid on a transverse reinforcement with a diameter of 16 mm at intervals of 17.5 cm. The separately installed lanes were anchored with adhesive tie bars ($\Phi 20$ mm, length of 650 mm) at a distance of 67 cm to prevent the lanes from moving apart in the longitudinal compression joint area. The road surface was then textured with grinding to improve evenness, skid resistance, and drainage. The general information and the average number of vehicles per day, and the number of heavy trucks in these three sections are illustrated in Table 1.

Table 1. General information about considered tracks.

section	unit	Highway A 94 near Munich	Federal Raod B 56 near Dueren	Access road near Geseke
length	m	4000	800	1030
construction date	year	2011	Oct. 1997	2009
ADT	veh/d (in year)	10887 (2018)	3200 (1997)	-
ADT-Truck	veh/d (in year)	2276 (2018)	100 (1997)	450 (2009)

In August 2011, the trial site on Highway A 94 east of Munich was paved in standard road concrete C30/37 in a length of 4 km. It was constructed in one layer with 0/22 aggregates, and longitudinal joints were arranged lane wise. In the end areas, reinforced end anchors were realized. The concrete surface was then covered with a thin overlay of hot mixed asphalt on a sprayed seal some weeks after concrete paving. Two criteria were checked on the surface before paving asphalt: resistance against abrasion $> 1.0 \text{ N/mm}^2$ and residual moisture of concrete $< 3.0 \%$. The C30/37 grade concrete was placed on a 10 cm thick asphalt base layer (AC 22 TS) using a slipform paver. The evaluation of the measured temperatures shows that on

hot summer days the asphalt-covered concrete surface becomes 4°C to 6°C warmer than directly trafficked concrete pavement.

Table 2. Requirements for the reinforcement.

steel grade/section		Highway A 94 near Munich	Federal Raod B 56 near Dueren	Access road near Geseke
longitudinal reinforcement	reinforcement ratio	0.75 %	0.61 %	0.75 %
	diameter	20 mm	16 mm	20 mm
	axle spacing	17.5 cm	15 cm	17.5 cm
	Concrete cover	central	9 cm	9 cm
transverse reinforcement	reinforcement ratio	0.12 %	0.09 %	0.15 %
	diameter	16 mm	12 mm	16 mm
	axle spacing	70 cm	60 cm	60 cm
	angle to the longitudinal reinforcement	60°	65°	60°

In CRCP, longitudinal steel bars installed inside the concrete pavement are primarily intended to restrain a significant volume change in the concrete due to temperature variations and traffic load. The longitudinal-reinforcement ratio of the Highway A94 near Munich and the Access Road near Geseke are 0.75% and Federal Road B 56 near Dueren 0.61%, respectively.

4 RESULTS AND SHORT DISCUSSION

In Belgium, the best long-term behavior was found for sections with free cracks at intervals of 0.8 m to 1.3 m. In the USA, a crack spacing of 1.07 m is aimed for. Based on these two experiences, the following classification was made for further investigations. In order to better evaluate crack spacing in all sections, the following classification was made. Crack spacing smaller than 0.3 m, which is shown in red, and these are the critical crack spacing as there is a risk of punch-out. Crack spacing between 0.3 m and 0.7 m are shown in yellow. There is no direct danger of punch-out, but danger could arise if a further division takes place here due to an additional crack. The third class is shown in light blue, which belongs to the crack spacing between 0.7 m and 1.4 m. The fourth class, shown in blue, includes all crack spacing between 1.4 m and 2.5 m. In dark blue are the crack distances larger than 2.50 m. These are less critical but more significant than the desired crack spacing. The third and fourth classes also still belong to the desired crack spacing. Figure 3 illustrates the classification of crack spacing, which were carried out in 2019 and 2020 for all three considered sections in the number of cracks per 100 meters.

On Federal Road B56 near Dueren during the crack survey on 02/11/2008, 93.6 cracks per 100 m were determined in both directions. This results in an average crack spacing of 1.08 m. Approx. 43 cracks have been added from 2001 to 2008. The last crack survey was carried out on November 2019, and 125 cracks per 100 m and an average crack spacing of 0.80 m were recorded. Approx. 20% of all recorded cracks in the driving direction (N) were Y-cracks. 80 cracks per 100 m (63%) belong to the first and second classes, and only 43 cracks per 100 m (35%) are assigned to the desired classes. On A94 near Munich, 79 days after the concrete construction and before asphalt overlaying on 07/05/2011, a manual crack survey recording the location and opening widths was carried out. During this time, 38 cracks per 100 m and an average crack spacing of 2.6 m have formed. On 06/2014, 72 cracks per 100 m and an average crack spacing of 1.40 m were recorded. The current Monitoring was

Figure 3. Classification of crack spacing in number of cracks per 100 m, a) Access Road near Geseke, b) Ferdal Road B56 near Dueren, c) Highway A94 near Munich.

carried out on 08/2020, and 78 cracks per 100 m and an average crack spacing of 1.3 m were recorded. 2.4 cracks per 100 m (3%) are the critical cracks, which have a crack risk of punch-out. 54 cracks per 100 m (69%) are assigned to the desired classes. Figure 4 illustrates the classification of crack spacing in percent. The current survey on the B56 was carried out in two different days due to a construction site in one part of the route.

Figure 4. Classification of crack spacing in percent: a) Access Road near Geseke, b) Ferdal Road B56 near Dueren, c) Highway A94 near Munich.

4.7 cracks per 100 m (6%) belong to the fifth class with a crack spacing ≥ 2.5 m. All tracks visual condition in the last survey was good, and no sections exhibited punch-outs and other damages. Evaluating the structural condition of pavement sections is a complex task.

One of the more feasible means for structural condition evaluations is the use of falling weight deflectometer (FWD) (Pangil Choi D.-H. K.-H., 2016) with three drops per point and a minimum impulse of 50 kN. The load capacity of the sections was measured using FWD to

evaluate the mechanical response of the field pavement, estimate the load capacity, to provide better pavement maintenance (Huang, 2020) and future performance of the road surface. The results in the load center were shown in Figure 5.

Figure 5. Load capacity resulting from FWD-values: a) Geseke, b) B56 Dueren, c) A94 Munich.

On the Y-axis, the average deflection was shown, and the zero value was at the top. The deflections run downwards. With a drop weight of 50 kN, the deformations were determined at regular intervals of 20 m. All values were between 30 μm and 100 μm . The evaluation of the FWD measurements shows an average FWD-value of 48 μm (mean temp: 24.4°C), 53 μm (mean temp: 26.5°C), and 78 μm (mean temp: 17.6°C) for the A94, Geseke, and Dueren, respectively. Thus all deflections were low, which means good load capacity (Pangil Choi D.-H. K.-H., 2015). Meanwhile, the best load-bearing section is A94 near Munich due to a 24.5 cm CRCP and reinforcement ratio. The concrete slab's interface bonding strength and concrete compressive strength were determined on drill cores and are represented in Figure 6.

Figure 6. The results of tests on drilling cores: left: compressive strength on drill cores, right: Leutner shear test.

The results of the compressive strength test on drill cores show better results on access road Geseke compared to other sections. The section on Highway A94 near Munich was overlaid with a thin hot mix asphalt on a sprayed seal, and the shear test, which developed in Germany in the late 1970s, was carried out to measure the bond strength of the interface between asphalt and concrete layer. During the shear test at the standard loading rate of 50 mm/min, a constant rate of shear displacement was applied across the interface, and the resulting shear force was monitored (Asphalt, 1999). From the measured data in Figure 6, $\tau_{\max}$ is the peak shear stress of the interface, and $\delta_{\max}$ is the displacement at peak shear stress. The shear stress of the interface between concrete and asphalt shows a good result. According to Additional technical contract conditions and guidelines for the construction of asphalt pavements Asphaltbauweisen, 2013, the peak shear stress of the interface between the surface layer and binder layer should be higher than 15 kN (Asphalt Z., 2007). In order to investigate and evaluate the development of crack characteristics in concrete pavements, the crack width changes along the drill cores were recorded with laser scanners from LMI Technologies with a resolution of 150 μm (x-y) and 19 μm (z). The device scans the crack path on the drill core surface and visualizes the measuring object in 3D. The results were imported and evaluated in MATLAB.

Figure 7. Evaluation of crack paths on drill cores; left: laser scanner, right: recorded images.

A crack length of 3 cm is measured for drill core No. 21. The mean crack width is 0.737 mm and is clearly above the maximum width of 0.5 mm. The crack width at the pavement surface is 0.958 mm, which is below the limit of 1.0 mm. Drill core No. 22 shows two wider cracks along the drill core depth, forming a continuous crack. The first crack has a length of 5 cm and extends in depth into the bottom concrete. The average crack width is 0.527 mm and thus slightly exceeds the maximum crack width. In the lower part of the drill core, the second crack has a length of 2.5 cm and a significantly higher mean crack width of 0.951 mm. Overall, the crack length extends along the drill core length with different crack widths. The crack becomes clearly narrower in the transition area from crack no. 2 to no. 1. While the crack width at drill core 21 increases up to the maximum crack width and then decreases again, crack No.2 at drill core 22 has a funnel-shaped opening. The following table lists the relevant measured values for crack path on two cores of the B56.

The highly loaded access road near Geseke shows many short cracks. Due to the minimal crack lengths, most of the cracks are surface cracks. Remarkable are the slight spalling at the crack widths, which are clearly visible on most drill core surfaces. There are different crack widths in drill core depth on ten drill cores. Table 4 shows the mean crack widths resulting from the measured crack widths. For the investigation of the crack widths, drill cores with a crack length of at least 3 cm are considered. At the drill cores G7, G10-1 and E2-1 the crack widths decrease from the crack mouth to the crack root. While crack no. 2 at drill core G13 runs with a funnel-shaped crack opening, crack no. 1 has developed narrower over the maximum crack width to the end of the crack. A similar crack path as for crack no. 1 can be seen on drill core G11.

Table 3. Evaluated crack development on the drill cores of the B56 near Düren.

core no.:		21	22-1	22-2
Crack length [cm]		3,0	2,5	5,0
	start	0,958	0,619	0,654
Crack path [mm]	max. crack width	1,143	1,459	0,654
	end	0,398	1,459	0,502
Position of the max. crack width [cm]		0,670	17,84	0,170
Average crack width [mm]		0,737	0,951	0,527

Table 4. Evaluated crack development on the drill cores of the Geseke.

core no.:		G7	G10-1	G10-2	G11	G13-1	G13-2	G15	E2-1	E2-2
Crack length [cm]		6	4	3	3	3,5	3	2,5	3	2
	start	1,676	1,861	2,059	1,054	0,766	1,347	1,081	1,022	0,645
Crack path [mm]	max. crack width	1,676	1,861	2,059	1,325	0,926	1,347	1,144	1,022	0,645
	end	0,591	0,336	0,565	0,099	0,393	0,904	1,144	0,320	0,276
Position of the max. crack width [cm]		0,22	1,33	0,72	2,01	2,88	0,49	12,68	0,21	0,32
Average crack width [mm]		1,140	0,777	0,749	0,651	0,631	0,686	1,013	0,616	0,449

5 DISCUSSION

All sections considered in this study were executed with longitudinal and transverse steel reinforcement. This construction method has shown positive behavior. The tests did not indicate that the yield point of the material was exceeded or that corrosion of the reinforcement occurred. Nevertheless, it should be considered which alternatives to steel reinforcement are available. One option is the use of profiled glass fiber or carbon rods. In 2019, a short test section was set up in Poland with a concrete ceiling with continuous glass fiber bar reinforcement. The investigation and evaluation of both standard and innovative construction methods must consider the entire life cycle. This also includes dismantling and recycling. The processes for recycling concrete pavements that exist in Germany can in principle also be applied to continuously reinforced concrete road surfaces. However, this can be made more economical. One option here is the Resonant machine. Here, the concrete slab is crushed with a high-frequency pressure stamp. Steel and concrete can then be separated with little effort.

6 CONCLUSIONS

In order to guarantee the necessary transport of goods on motorways and especially with heavy loads, the previous standard construction methods in asphalt and concrete may no longer be sufficient. A construction with a continuously reinforced concrete pavement with an optional thin asphalt surface layer could be an alternative. In Germany, 8 trial and test sections have been built using this construction method from 1997 to the present. In the context of this study, three sections with a continuously reinforced concrete paving slab on B56 near Düren, access road near Geseke, and A94 near Munich, which were built in 1997, 2009, and 2011 are analyzed. The visual condition in the three sections is acceptable. There are no concrete punch-outs or slab displacements. Free transverse cracks have appeared, which, on the basis of the Belgian experience, are predominantly positive. Load capacity measurements with the FWD showed small deflections in all sections. The shear strength and adhesive tensile strength between asphalt and concrete were tested on drill cores. All results met the required

values. Comparing the considered section show that section A94 with 1.5 cm paving thin overlay hot onto a sprayed seal on 24.5 cm CRCP with a 0.75% reinforcement ratio gives the best performance. In this section, most cracks belong to the desired crack spacing between 0.7 m and 2.4 m. The load capacity is much better than other sections, the bond strength of the interface between asphalt and concrete layer is higher than the suggested value, and the compressive strength of concrete is acceptable. The research project aims to find out whether the construction with a continuously reinforced concrete pavement and optionally with a thin surface layer of asphalt or alternative building material can be a new standard construction method for highly loaded motorways with loads of the future. The results of investigations to date are positive, and potential is evident.

ACKNOWLEDGEMENTS

This study was sponsored under the research project “FE 08.0248/2016/CGB “Asphalt surface course on continuously reinforced concrete pavement; scientific monitoring of the test sections in composite construction during the operating phase”, these are being investigated by the RWTH Aachen University together with the German Federal Highway Research Institute (BAST). The authors would like to thank the German Federal Ministry of Transport and Digital Infrastructure (BMVI) for supporting this research.

REFERENCES

- Asphalt, A. z. (1999). *Teil 4: Prüfung des Schichtenverbundes nach Leutner*. Cologne: FGSV.
- Asphaltbauweisen, A. (2013). *Zusätzliche Technische Vertragsbedingungen und Richtlinien für den Bau von Verkehrsflächenbefestigungen aus Asphalt*. Cologne: FGSV.
- Blaschke, B. C. (1993). *Aashto Guide for Design of Pavement Structures*. Washington D.C.: The American Association of state highway and transportation officials.
- Christopher Robinson, M. A. (1996). Distress as function of age in continuously reinforced concrete pavements: models developed for Texas pavement management information system. *Transportation Research Record*, pp. 145–151.
- Diependaele, M. (2018). *A guide on the basic principles of Life-Cycle Cost Analysis (LCCA) of pavements*. Brussels: European Concrete Paving Association.
- GmbH, I. C. (2014). *Verkehrsverflechtungsprognose 2030*. Berlin: Federal Ministry of Transport and Digital Infrastructure.
- Han Jin Oh, Y. K.-M. (2016, July 01). Experimental evaluation of longitudinal behavior of continuously reinforced concrete pavement depending on base type. *Construction and Building Materials*, pp. 374–382.
- Hu, J. e. (2015). Optimizing concrete pavement type selection based on life cycle cost analysis. *International Concrete Sustainability Conference*. Miami: NRMCA.
- Huang, Y. Z. (2020, April 16). A method for evaluating CRCP performance based on edgeloading FWD test. *Materials and Structures*, pp. 53–46.
- Infrastruktur, D. B. (2020, Januar). *BMVI*. Retrieved from <https://www.bmvi.de/SharedDocs/DE/Artikel/G/infrastruktur-statistik.html>
- Jeffrey Stempihar, N. W. (2020, July 24). Assessment of California’s Continuously Reinforced Concrete Pavement Practice and Performance. *Transportation Research Record*, pp. 832–842.
- M. Li, W. K. (2014, May 30). “Investigation on material properties and surface characteristics related to tyre-road noise for thin layer surfacings. *Construction and Building Materials*, pp. 62–71.
- M.Asi, I. (2005, september 25). Evaluating skid resistance of different asphalt concrete mixes. *Building and Environment*, pp. 325–329.
- Pangil Choi, D.-H. K.-H. (2015, November 6). Evaluation of structural responses of continuously reinforced concrete pavement (CRCP) using falling weight deflectometer. *Canadian Journal of Civil Engineering*, pp. 28–39.
- Pangil Choi, D.-H. K.-H. (2016, 02 02). Evaluation of structural responses of continuously reinforced concrete pavement (CRCP) using falling weight deflectometer. *NRC Research Press*, pp. 28–39.
- Pangil Choi, S. R. (2014). *Project Level Performance Database for Rigid Pavements in Texas, II*. Texas: Texas Department of Transportation.
- Richter, C. (1998). *What makes portland cement concrete pavements rough?* Washington D.C.: FHWA.

- Sidney Mindess, J. F. (1981). *Concrete*. Englewood Cliffs, N.J.: Prentice-Hall.
- Sungun Kim, S. H. (2015, August 05). Estimation of service-life reduction of asphalt pavement due to short-term ageing measured by GPC from asphalt mixture. *Road Materials and Pavement Design*, pp. 153–167.
- Tatiana Petrova, E. C. (2018, December 31). Methods of road surface durability improvement. *Transportation Research Procedia*, pp. 586–590.
- YANG Cheng-cheng, W. X.-f.-h.-j. (2020, March 01). Study on the Load Transfer of Transverse Cracks of Continuously Reinforced Concrete Pavements. *Journal of Highway and Transportation Research and Development*, pp. 10–17.
- Young-Chan Suh, D.-H. J.-W. (2020, January 12). Comparison of CRCP and JCP based on a 30-year performance history. *International Journal of Pavement Engineering*, pp. 1–8.