Optimizing vibration parameters of thick single-layer concrete pavements: results of the Belgian Monocrete project

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Abstract

Thick single-layer concrete pavements are increasingly popular in Europe because they help tackle the increasing traffic loads on highways, airport taxiways, or industrial logistic platforms. They require less maintenance than other pavement materials, have a very long service life even under heavy loads, and can withstand static loads without permanent deformation. However, the environmental impact of such pavements is significant, due to the vast quantities of cement and inert materials required for each project. The MONOCRETE research project (March 2021-March 2024), funded by the Walloon GreenWin innovation cluster, brings together industrial partners (Eloy and Holcim) as well as research institutions (BRRC, CRIC-OCCN, and ULiège) with the aim of reducing this environmental impact by incorporating recycled concrete aggregates and an alternative, low-carbon cement. In addition to issues relating to concrete sustainability, the project studies the formulation and execution of thick concrete pavements. Indeed, a greater thickness will accentuate any compaction or vibration problem associated with a poor particle size distribution. The risk of bleeding or segregation is therefore increased. These issues are being studied through a combination of literature review, laboratory testing, and the execution of two test sections, implemented in fall 2022 and spring 2023. The purpose of this paper is to summarize the initial conclusions of this recent project on the vibration of thick concrete pavements.

Introduction

The goal of concrete vibration is to reduce the amount of entrapped air into the fresh concrete to achieve good compaction. However, it has been shown that vibration can also reduce the amount of entrained air, especially when high frequencies are used. Entrained air is a network of air micro-bubbles ($50\ \mu m \leq d \leq 500$) (Groupement Belge du Béton, 2018), which ensures the role of expansion vessels to achieve sufficient freeze-thaw resistance. Stark proved as early as 1986 (Stark, 1986) that freeze-thaw resistance could decrease as the frequency used for vibration increased. Ling and Taylor (2021) have recently shown that the spacing factor increases in parallel.

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Large-scale experiments have also been carried out on concrete placed by slipform pavers in order to evaluate the influence of the vibration on the placed concrete.

A first study was carried out in Iowa in 1999 (Tymkowicz & Steffels, 1999) to investigate the influence of vibration frequency (5,000, 8,000 or locally 12,000 vpm), placement speed (1.5 m/min or 0.75 m/min) and vertical position in the pavement on the air content of hardened concrete. The study showed that air content varied strongly with depth, with air content at the surface generally lower than at the base of the core. The study also confirmed that the highest frequencies (in this case 12,000 vpm) generated a loss of entrained air, the content of which fell below the threshold required to ensure good frost resistance.

Another study (Cable et al., 2000) looked at the influence of the vibration parameters on the entrained air bubble network. On the pilot site, concrete was placed at two frequencies (5,000 or 8,000 vpm) and two speeds (1.22 or 1.88 m/min). Tests revealed that the best bubble network (highest air content and lowest spacing factor) was obtained using a low frequency and speed, while a higher frequency and/or speed sometimes led to a lack of bubbles in the first few centimeters (which are the most important for ensuring the freeze-thaw resistance of the pavement). However, this configuration, combining low frequency and low application speed, was not the one chosen by the application team to optimize the aesthetic appearance of the surface. Instead, the most satisfactory surface finish would be obtained by combining high frequency and high speed. This study therefore suggests that it is probably not optimal for bubble network and freeze-thaw resistance to rely solely on the visual appearance of a concrete pavement to select placement parameters or judge compaction quality.

In several states, these studies have led to recommendations concerning the frequencies and speeds to be used on worksites for placing road concrete. These recommendations include limiting frequency to 5,000 to 8,000 vpm and using an average advance speed of 1 m/min.

In Belgium, as in most other European countries, there are currently no recommendations concerning the parameters for vibrating road concrete. However, it seems that the frequencies used are generally higher than the aforementioned recommendations (> 9,000 vpm). As concrete compositions are quite different from those found in the USA, it was decided to test different vibration parameters on large-scale test beds.

Laboratory tests on the concrete mix

The objective of the project is to develop solutions for pavements with a high traffic level. For this reason, we decided to aim at the requirements for highway concrete in the Walloon standard tender specifications, CCT Qualiroutes (Service Public de Wallonie, 2022). The requirements on the concrete composition and performances are listed in Table 1:

Table 1 - Concrete properties for highway concrete in Wallonia (Dmax=20 mm)

Parameter	Value
Cement content	≥ 400 kg/m³
W/C	< 0.45
Cement	CEM III/A 42,5 N LA
WAI	≤ 6.3% (average value for water absorption by immersion)
Average Rc at 90d on cores (h = 10 cm, s = 100 cm²)	≥ 50 MPa (if entrained air is incorporated)
Air content v	3% ≤ v ≤ 6%
Freeze-Thaw resistance in presence of de-icing salts	Losses <5 g/dm² with the ISO/DIS method (ISO, 1984)

For the freeze-thaw resistance evaluation, it was decided to use the Slab Test method (CEN/TS 12390-9) instead of the ISO/DIS procedure. Indeed, it is much more widely used at European level and is likely to replace it in CCT Qualiroutes over the next few years. What's more, the test is more extensively automated, which improves laboratory efficiency. The test is carried out in accordance with Belgian standard NBN B 15-100, with surface cleaning by brush. The surfaces tested are formwork surfaces, which are more representative of the surface condition on site. For highway concrete, the maximal cumulated losses at 28 days are set by Flemish standard tender specifications SB250 (AWV, 2021) at 1,5 kg/m². It has to be noted, however, that the extreme temperature cycle (+20°C/-20°C) of the slab test is questioned within CEN/TC51/WG12 for showing very weak reproducibility.

All the materials were available on the test site for the project. The granular materials were a 0/2 river sand as well as 2/6 and 6/20 porphyry crushed aggregates. To approach the reference curve used for brushed highway concrete 0/20 in Belgium (Ployaert, 2010), their optimal volume proportions were determined to be 36,5% sand, 5.5% 2/6 porphyry and 58% 6/20 porphyry. The resulting curve is presented in Figure 1.

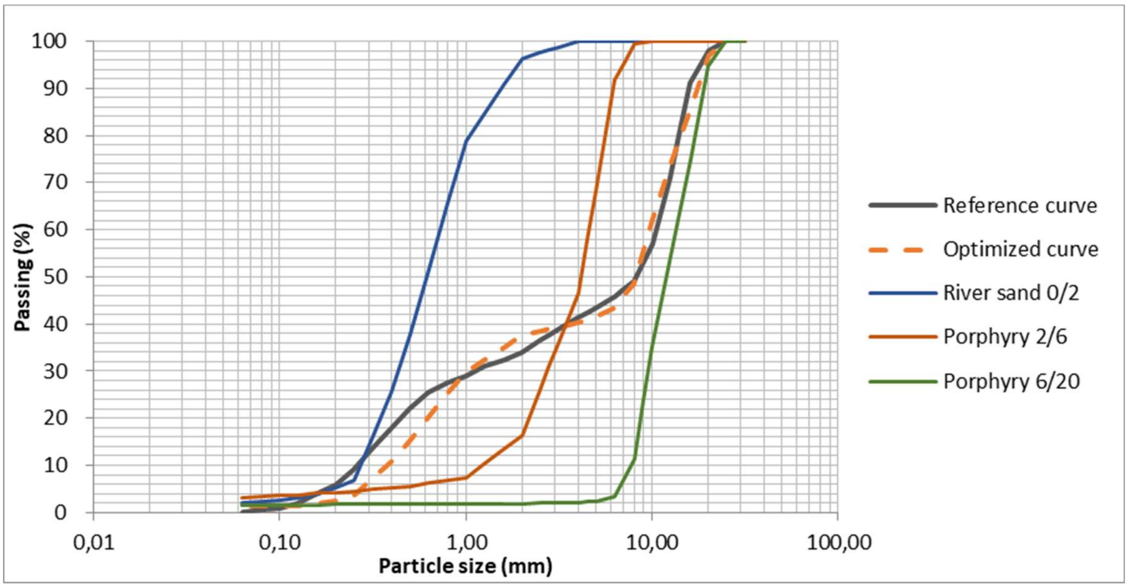

Figure 1 – Particle size distribution of the granular materials

Usually, the cement used for road construction in Belgium is a CEM III A 42,5 N, in which 36 to 65% of the Portland clinker is substituted by blast-furnace slag. The mass proportions of the various concrete constituents are calculated, targeting an air content of 4% and a W/C ratio of 0.41. The quantities of water, plasticizer and air-entraining agent were adjusted in the laboratory to obtain the targeted air content (4%) and slump value (10 -40 mm).

Table 2 – Composition and performance of concrete mixes (laboratory)

	Mass (kg) per m^3	**Mass (kg) per m^3**	**Mass (kg) per m^3**
Material	**Compo 1, Lab 1**	**Compo 1, Lab 2**	**Compo 2, Lab 1**
CEM III/A 42,5 N	400	400	400
Round Rhine sand 0/2	635	635	635
Porphyry 2/6	98	98	98
Porphyry 6/20	1035	1035	1035
Effective water	165	165	165
Absorption water	8	8	0
Total water	172	172	165
Plasticizer	1,9	1,9	1,9
Air-entraining agent	1,3	1,3	1,3
Slump (mm)	35	65	8
Air content (%)	4.8	4.4	5
Fresh vol. Massa (kg/m^3)	2333	2307	2300
Rc 7 d	34,5	39,0	37,6
Rc 28 d	51,3	54,0	56,9
Rc 90 d	63,1		
Slab 28 d	3,80	1,52	2,27
Water Absorption 28 d	5,8	5,76	5,35

When looking at the slab test results, indicating the resistance to freeze/thaw cycles, it appears that the losses are high compared to the 1,5 kg/m^2 threshold. From these results, it appears that the 4% air content that was targeted in this study may not be sufficient to insure the frost resistance of the concrete surface.

Test sections

As part of the Monocrete project, experimental concrete pavements were laid in 2022 and 2023 at the concrete plant of Eloy in Bierset, covering a total area of over 3,500 m^2 (Figure 2). These 38 cm-thick roadways were used to assess the influence of vibration parameters on concrete performance and confirm the results obtained in the laboratory pre-studies.

Figure 2 – Test section in Bierset

The first test section of the project, in November 2022, was designed to test the influence of vibration parameters on the concrete pavement. With a length of 75 m and a width of 6.5 m, this section was built with the concrete composition 1 of Table 2 above, except that the total water content was increased to 176 l/m^3 by the concrete plant and that the air entrainer had to be increased to 2 kg/m^3 in order to reach sufficient fresh air content values.

The test section was divided into 6 (3 x 2) zones, in which we varied the vibration parameters:

- needle position (almost horizontal on the left half, or more inclined on the right half);
- vibration frequency (150, 170 or 190 Hz, equal to 9000, 10200 and 11400 vpm);
- machine speed (0.8 or 3.5 m/min).

The vibration frequencies are not specified on the slipform paver but were measured with a frequency sensor. 9000 vpm seems to be the lowest frequency that can be selected with this device. For this reason, it was not possible to test values conforming to the U.S. recommended range of 5000-8000 vpm. The relatively extreme speed conditions enabled us to make different observations.

Firstly, when a slow speed is used in combination with a high frequency, surface irregularities appear, probably corresponding to an over-vibration phenomenon (Figure 3 (a)). Secondly, when high speeds are combined with low vibration frequencies, the surface behind the paver seems to "tear" (Figure 3 (b)).

(a) **(b)**

Figure 3 - Surface irregularities observed when a slow speed is used in combination with a high vibration frequency; (b) Surface "tearing" observed when high speed is combined with low vibration frequency

Finally, at high speeds, several minutes - or tens of minutes - after application of the surface finish (brushing + curing compound), small craters can be observed on the surface, through which water and air bubbles rise (Figure 4). These craters are a symptom of concrete bleeding (gravity tends to expel the air and water still present in the concrete, lighter than the solid particles, towards the surface, which find preferential circulation channels in less consolidated areas). The effect seems more pronounced at higher vibration frequencies, particularly on the left half of the section with almost horizontal needles (Figure 5).

Figure 4 - Bleeding craters appearing on the concrete surface, mostly when high placement speeds are used

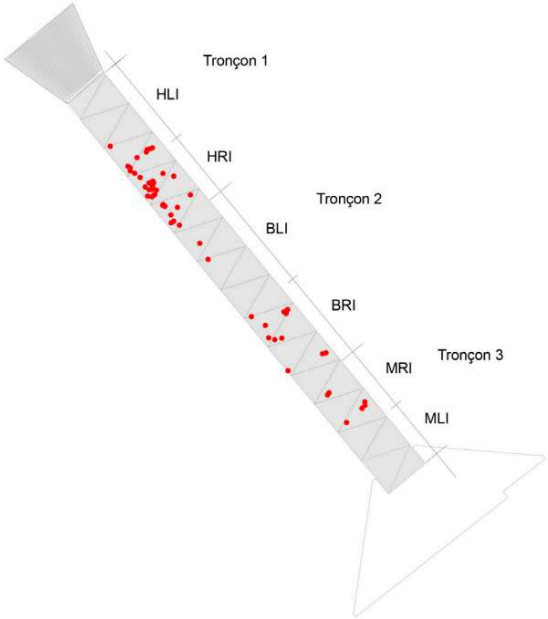

Figure 5 - Position of bleeding craters on the first test section

Table 3 – Craters frequency for each set of vibration parameters

Section	Notation	Frequency	Speed	Surface defects	Craters
1a	HLI	High	Slow	Irregularities	-
1b	HRI	High	Fast		++
2a	BLI	Low	Slow		-
2b	BRI	Low	Fast	Tearing	+
3a	MRI	Medium	Fast		+
3b	MLI	Medium	Slow		- -

These initial observations seem to confirm that bleeding craters can be induced by an excessive slipform paver speed, even if the combination with a high frequency allows the surface finish just behind the paver to have an acceptable aspect. The best parameter combinations, according to the field observations, would be a slow speed with a low or medium frequency. More detailed analyses of the properties of the hardened concrete will be carried out to confirm and refine these results.

During the concrete placement, tests were made on the fresh concrete to control the water content, the consistency and the air content, and cubes were cast for later controls on hardened concrete. Cores were then drilled from the pavement to measure its performances after 28 and 90 days. A summary of the most significant results is presented in Table 4.

Table 4 – Extract of results from the first test section: tests on fresh concrete, on the drilled cores and on cubes cast on site

Information			**Tests on fresh concrete**			**Tests on drilled cores**			**Tests on cubes**		
Section	Freq	Speed	% Water	Slump (mm)	Air (%)	Rc 90+d (MPa)	Slab 28 d (kg/m²)	WAI 90 d (%)	Rc 28 d (MPa)	WAI 28 d (%)	Slab 28 d (kg/m²)
						Top		Top			
1	High	Slow	7.9	25	3.3				64.01		
			7.73	15	3.4	60.3	2.44	5.57			
		Fast				57.3	1.70	5.55			
2	Low	Slow	7.48	15	4	54.2	1.44	5.53	60.85	5.57	2.31
		Fast				51.9	2.05	5.40			
3	Average	Fast	8	50	4.2	53.2	2.18	5.53	60.19	5.7	0.71

Even though only one composition was used and tests on fresh concrete were performed just after mixing, we observed variations in the fresh and hardened concrete performances (measured on cubes). Those variations have to be taken into account when analyzing the results measured on cores, from which we would like to isolate the influence of the vibration parameters.

For the compression tests at 28 and 90 days, each core was sawn into three 10 cm high specimens. Figure 6 compares the strengths measured at the base, middle and top of the pavement.

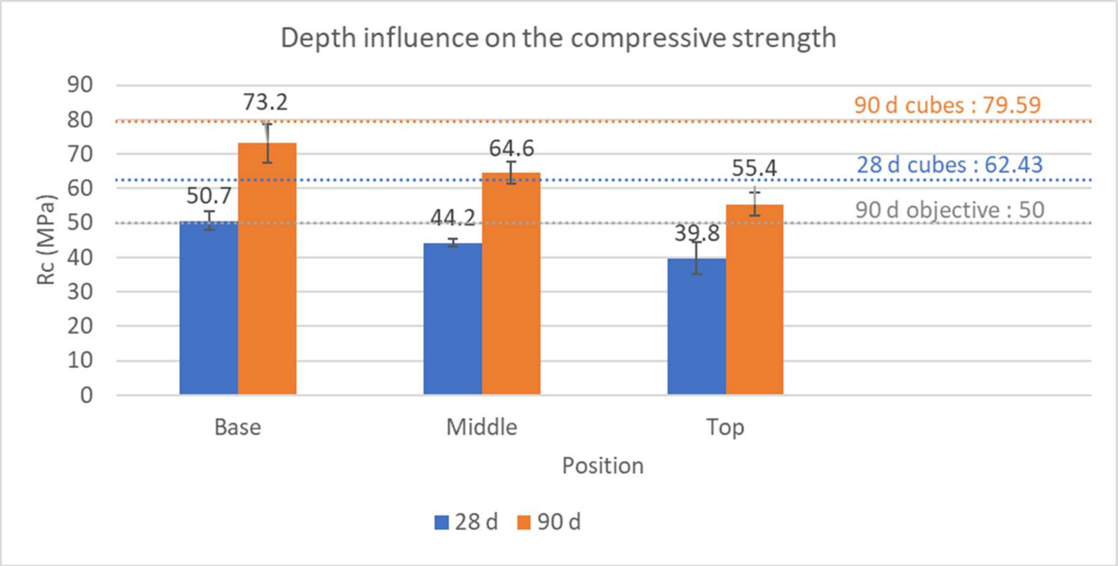

Figure 6 – Influence of the vertical position of the core samples on their compressive strengths and comparison with the strength measured on cubes stored in the laboratory

The strength after 90 days is sufficient for all samples (>50 MPa for a network I pavement with air-entraining agent). The influence of specimen position is quite clear, with compressive strength 20% lower at the top than at the base of the pavement. This difference can probably be explained by a certain segregation of the material during vibration. Another influencing factor could be the lower temperature at the surface than at the bottom. The low temperatures observed on site between placement and the cores sampling may also explain the relatively low absolute value of the compressive strengths. Indeed, the values are well below the average compressive strengths measured on cubes made with fresh concrete taken during the worksite, and stored at 20°C, which stand at 62 MPa at 28 days and 80 MPa at 90 days.

As for the compressive tests, the water absorption measurements were also performed on samples sawn from the top, the middle, and the bottom of cores. The results are presented in Figure 7.

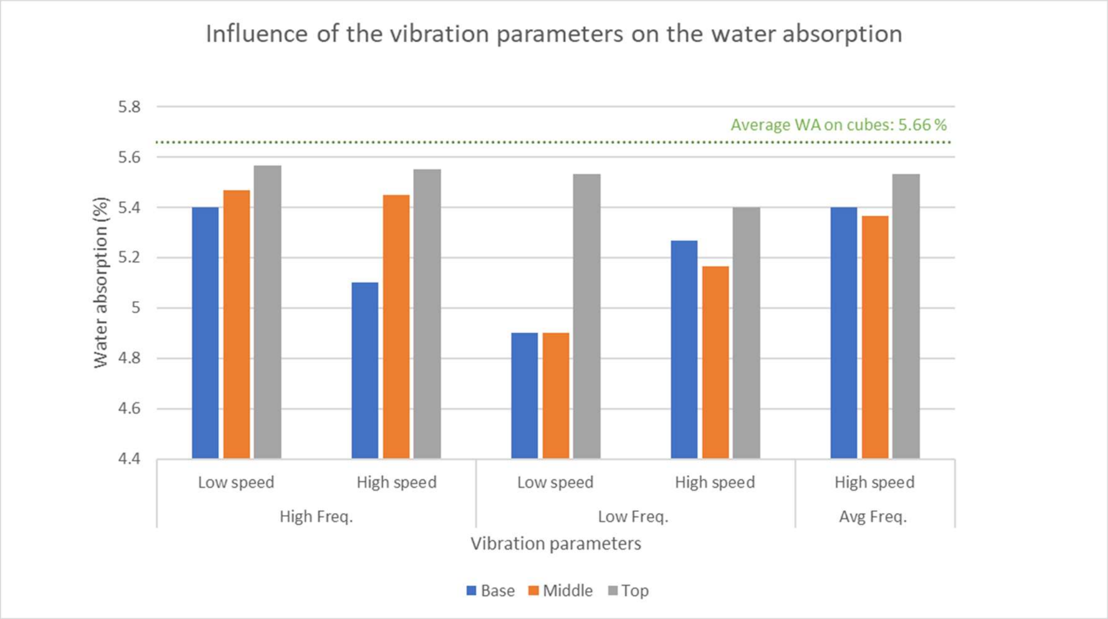

Figure 7 - Influence of the vibration parameters on the water absorption

In every sample, the water absorption is higher at the surface than deeper in the pavement, but it remains inferior to the values measured on cube samples. The limit set by CCT Qualiroutes (maximum average of 6.3%) is also respected. The combination of low speed and low frequency seems to enhance the internal properties of the pavement without improving the surface conditions.

The slab test results, presented in Table 4, are too high, confirming the laboratory preliminary test results indicating that air contents up to 5-6% were required to obtain slab test losses at 28 days inferior to the threshold of 1.5 kg/m². Only the mix with 4% air and a low water content is compliant. From these results, we also observe large variations between slab test results on cores and slab test results on cubes.

The vibrating cores were placed with different inclinations on either side of the pavement to investigate the effect of their position on the concrete properties. The influence on compressive strength was measured on cores extracted side by side at two different locations: in zone 2b, 3 cores (on each side) were taken after 28 days and in zone 1a, 1 core was extracted after 90 days and 2 after 400 days. The average strength for each zone and each depth is shown in Figure 8.

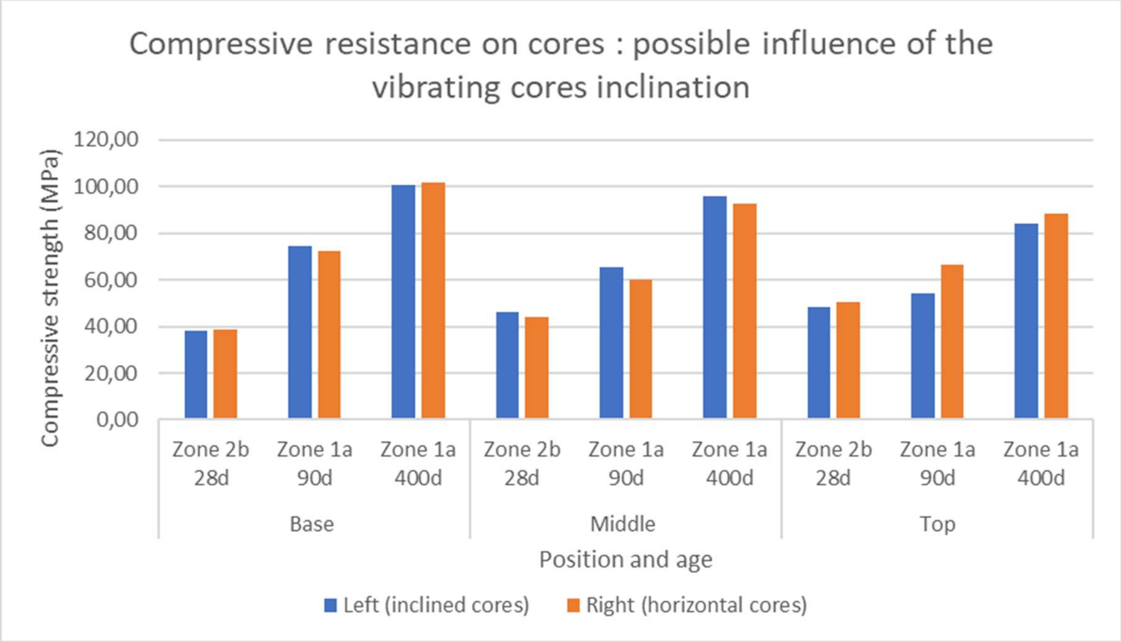

Figure 8 - Influence of the vibrating cores inclination on the compressive strength

From Figure 8, it can be seen that the average strength at the top of the pavement always appears to be higher for horizontal cores than for inclined cores. The opposite is observed at mid depth. This observation has been made at three locations, but on a very limited number of specimens so it should be confirmed by further investigation. It is also interesting to note that the concrete strength in zone 1a increases significantly (+ 45%) between 90 days and 400 days.

In the spring of 2023, another test section of almost 500 m long was built, using cements and aggregates from the circular economy to reduce the ecological footprint of the pavement. The results related to this specific topic will be presented in a separate paper.

Preliminary conclusions

Thick single-layer concrete pavements offer a good solution to today's mobility challenges, but they need to be placed with great care. The MONOCRETE project aims to optimize their vibration parameters while reducing their environmental impact by incorporating materials from the circular economy.

This paper presents the first results of the project concerning the influence of vibration parameters on concrete. A conventional Belgian road concrete mix was placed on a test section with variable vibration frequencies, speeds and vibrators inclinations. It was found that surface defects, including the appearance of bleeding craters, could occur as a result of poor parameters choices. The best parameter combinations, based on field observations, would be a slow speed with a low or medium frequency. Depth-dependent tests on cores showed that the concrete properties (compressive strength, water absorption, etc.) can vary significantly with the vertical position in the pavement. It is likely that the position of the vibrating cores influences this evolution.

As theses parameters seem to have a significant influence on the concrete, it would be good to have European guidelines to help each contractor to select the best vibration parameters for each project, or at least to avoid problematic combinations. The results of the MONOCRETE project will help us to write a first draft of such guidelines, but further studies will be needed to develop a methodology for the selection of ideal parameters, which will probably depend on the paving machine but also on the concrete mix properties.

In addition to the influence of vibration parameters, the MONOCRETE project also aimed to investigate the possibility of incorporating recycled materials (cement and aggregates) into the concrete mixes. This was achieved in the framework of a second test section, the results of which will be presented in another paper. The environmental impact of the proposed solutions will also be assessed through a comprehensive life cycle analysis study.

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