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EXPERIMENTAL STUDY ON THE ROLE OF THE VIBRATION DAMPING AND ENERGY ABSORPTION OF FLEXIBLE FUNCTION LAYERS

EKSPERIMENTALNA ŠTUDIJA VLOGE DUŠENJA VIBRACIJ IN ABSORPCIJE ENERGIJE V GIBLJIVIH FUNKCIONALNIH PLASTEH

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In order to solve the pavement-slab breakdowns caused by a poor vibration damping and energy absorption of cement-concrete rigid structures with a lean concrete base, this study proposes an addition of a flexible function layer between the lean concrete base and the concrete pavement slab to form a "rigid+flexible+rigid" structure. The conducted experiments use a dynamic signal-testing and analyzing system to collect the frequency signals from the pavement-structure vibration when a small pavement-slab structure is subjected to a ball-drop impact. The results reveal how much vibration is damped out and how much energy is absorbed by adding a flexible function layer. According to the contrastive tests, the pavement-slab vibration is a declining process under an impact load. The vibration damping is more significant with an increase in the thickness of the function layer, but it becomes slower if the layer reaches a certain thickness. The tests also show that a flexible function layer has a significant role in the vibration damping and energy absorption. Therefore, the cement-concrete pavement structure designed with a flexible function layer can greatly reduce the slab breakdowns caused by the wheel-impact vibrations.

Keywords: cement-concrete pavement, flexible function layer, vibration damping and energy absorption, dynamic response

Da bi rešili problem pokanja plošč pločnikov, ki ga povzroči slabo dušenje vibracij in absorpcija energije betonskih togih konstrukcij z osnovo iz pustega betona, ta študija predlaga dodatek gibljive funkcionalne plasti med podlago iz pustega betona in ploščo pločnika, da se vzpostavi "togo-gibljivo-togo" strukturo. Pri opravljenih preizkusih je bil uporabljen analizni sistem za preizkušanje dinamičnih signalov in za registracijo frekvenčnih signalov iz vibracij pločnika, če je bil ta izpostavljen udarcu pri padcu krogle. Rezultati odkrivajo, koliko vibracij je zadušenih in koliko energije se absorbira z dodatkom gibljive fukcionalne plasti. Na osnovi preizkusov je vibracija pločnika pri udarcu pojemajoč proces. Učinek dušenja vibracij je večji z naraščajočo debelino funkcionalnega sloja in postane manjši pri določeni debelini plasti. Preizkusi so tudi pokazali, da ima gibljivi funkcionalni sloj veliko vlogo pri dušenju vibracij in pri absorpciji energije. Zato se pri strukturi cementnega pločnika z gibljivim funkcionalnim vmesnim slojem lahko močno zmanjša pokanje plošč, ki ga povzročijo udarci pri vibraciji koles.

Ključne besede: pločnik iz cementa, gibljiva funkcionalna plast, dušenje vibracij in absorpcija energije, dinamično odzivanje

1 INTRODUCTION

Many countries have adopted the idea of a rigid base or semi-rigid base for their cement-concrete pavements because this pavement structure has advantages, such as a high degree of rigidness, superior strength and a large load capacity. However, this pavement structure has inferior vibration-damping and energy-absorption capabilities, and thus, the impact of wheel vibrations can easily damage the concrete pavement slab. Therefore, the current study proposes an addition of a flexible vibration-damping function layer between the rigid or semi-rigid base and the concrete pavement slab to form a "rigid+flexible+rigid" pavement structure to solve the problem stated above. The addition of a flexible function layer can significantly reduce the vibration impact of the wheel load on the cement-concrete pavement, improving the working conditions of the pavement and extending the life cycle of a highway.

Some researchers have conducted studies on the flexible function layer of a cement concrete pavement. Ma, Yi, and He (2004)[1] analyzed the influence of the function layer on the surface concrete materials and its mechanical performance. H. Miao (2009)[2] conducted a mixture-accumulative deformation test, an interlayer shear-strength test and a water-damage test for the function layer in an MTS material testing system. Yao et al. (2009)[3] introduced methods for an interlayer shear-strength test, torsion test, and pull-out test by combining the application research of a waxed curing agent and the function layer of a slurry-sealing layer. Wang (2009)[4] analyzed the mixture types of different function layers and the results of the interlayer shear-strength tests under different environment temperatures using different dealing measures for different layers.

Although flexible function layers have been applied in some pavements around the world, the existing research on the flexible function layers added to cement-concrete pavements lacks depth, especially with respect to the vibration-damping and energy-absorption effects of these layers. The current experiment mainly aims to compare the vibration-damping and energy-absorption effects produced under the circumstances of cement-concrete pavements with and without a flexible function layer. This experiment analyzed the declining rule of the vibration response in the pavement structure and explored the vibration-damping and energy-absorption effects of the flexible function layer using a ball-drop impact test and a dynamic signal-test instrument to collect the signal data from the vibration-frequency domain of the pavement structure.

2 TEST METHODS

2.1 Comparison of the structure types of the test models

Figure 1 shows the two test structure models used in the experiment: **Figure 1a** refers to the pavement structure when the concrete slab was placed directly onto a lean concrete base and **Figure 1b** refers to the pavement structure when a flexible vibration-damping function layer was added between the concrete slab and the lean concrete base. The test piece was 62.5 cm long and 50 cm wide. The cement-concrete pavement slab used the C30 asphalt concrete, having a resilience modulus of 31.000 MPa and a thickness of 5 cm. The lean concrete base used the C15 asphalt concrete, having a resilience modulus of 21.000 MPa and a thickness of 4 cm. The flexible vibration-damping function layer used the AC-10 asphalt concrete, having a resilience modulus of 1.400 MPa and the thicknesses of 2 cm and 4 cm. The bottom layer of the pavement structure was a 2 cm thick rubber cushion.

2.2 Material-mixing ratio for the flexible vibration-damping function layer

In line with the *Technical Specifications for Construction of Highway Asphalt Pavements* (JTG F40-2004)[5] relating to the grading scope of the mineral aggregates of a dense-graded asphalt concrete mixture, the experiment used AC-10 as the mixture for the flexible function layer to be tested. The design of the grading is shown in **Table 1**.

The asphalt was the AH-70 matrix asphalt, whose specifications are listed in **Table 2**. The quantity used in the experiment was based on the best amount of the AC-10 asphalt mixture determined with a Marshall test. The Marshall-test piece was prepared in accordance with the *Standard Test Methods of Asphalt and Asphalt Mixtures for Highway Engineering* (JTJ 052-2000)[6]. According to the test, the best amount of the AC-10 asphalt was 5.0 %.

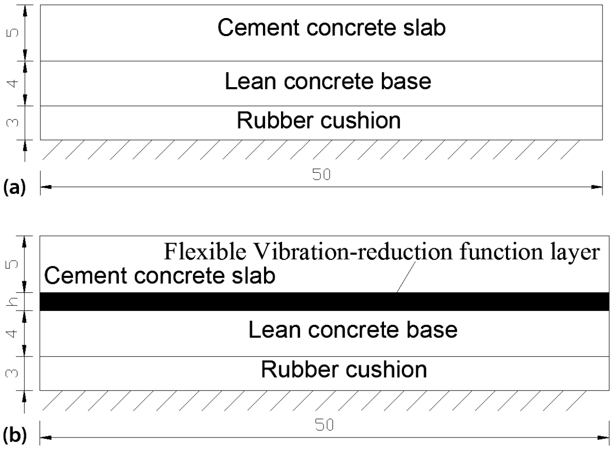

Figure 1: Comparison test model dimensions (cm): a) pavement structure without a flexible vibration-damping function layer, b) pavement structure with a flexible vibration-damping function layer
Slika 1: Primerjava dimenzij preizkusnih modelov (cm): a) struktura pločnika brez gibljivega funkcionalnega sloja za dušenje vibracij, b) struktura pločnika z gibljivim funkcionalnim slojem za dušenje vibracij

Table 2: Asphalt-performance indices
Tabela 2: Značilne lastnosti asfalta

Asphalt test	Test result	Technical requirement
Ductility of 10 °C/mm	300	200
Ductility of 15 °C/mm	837	400
Ductility of 25 °C/mm	1401	–
Penetration at 25 °C/0.1 mm	72.7	60≈80
Softening point (°C)	48.4	45
Flash point (°C)	266	260
Specific gravity (g/cm^3)	1.029	Actual record

3 BALL-DROP VIBRATION TESTS

3.1 Layout of the vibration measuring points

The experiment adopted the ball-impact test[7] proposed by the American Concrete Institute (ACI) to implement a vibration impact to the pavement. A steel ball was used to provide the source of a vibration signal. **Figure 2** shows the stipulated vibration test. The measuring points were located within the pavement slab, speci-

Table 1: Mineral-aggregate gradation of AC-10
Tabela 1: Razporeditev zrnatosti v AC-10

Mesh	Quality percentage (%) with the following mesh size (mm)								
Source	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Specification allowance	100	90≈100	45≈75	30≈58	20≈44	13≈32	9≈23	6≈16	4≈8
Actual value	100	95	60	40	30	25	16	12	6

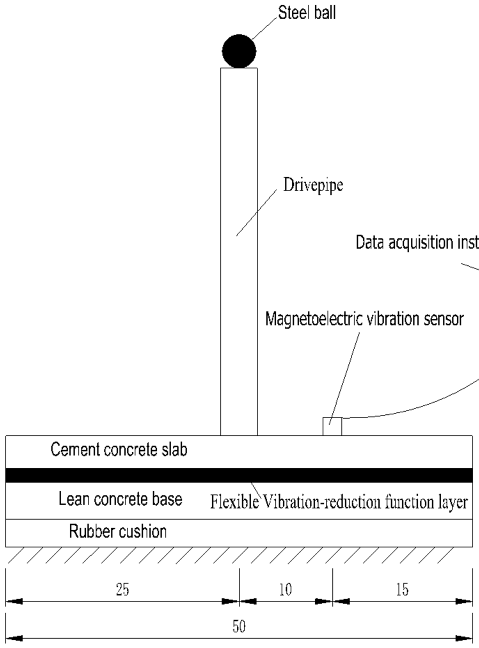

Figure 2: Schematic diagram of data acquisition (cm)
Slika 2: Shematski prikaz zbiranja podatkov (cm)

fically, at the midpoint and corners. A time-domain analysis was conducted on the basis of the vibration signals from the measuring points to investigate the vibration-response rule of the pavement structure. **Figure 3** shows the selection of the measuring points. In this test, the sample frequency was 5.000 Hz, the analyzing frequency was 1.950 Hz and the testing orientation was vertical.

The ball-drop heights of the steel ball in this test were set at (40, 60, 80, 100, 120, and 140) cm to simulate the wheel vibrations and test the load-declining rule of the pavement under different working conditions.

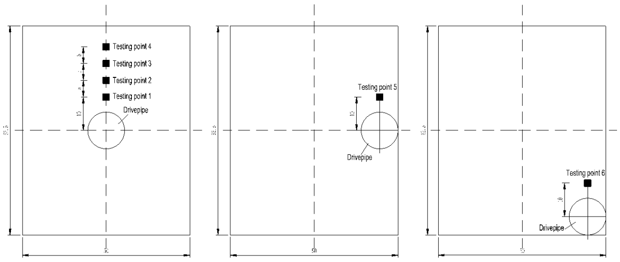

Figure 3: Layout of vibration measuring points (cm)
Slika 3: Razporeditev točk za merjenje vibracij (cm)

3.2 Testing instruments

The main testing instruments included, among others, a dynamic signal-testing instrument, a signal-testing and analyzing system, a magnetic-electric vibration sensor and a steel ball, as shown in **Figures 4** and **5**.

4 ANALYSIS OF THE RESULTS OF THE VIBRATION-DAMPING AND ENERGY-ABSORPTION TESTS OF THE FLEXIBLE FUNCTION LAYER

4.1 Contrastive analysis of the measured vibration-waveform signals

The measured waveforms at various ball-drop heights of the steel ball were the same, except for the occurrence of a significant variation at the peak. In the current study, the data analysis was only applied to the tests, in which the measuring point was within the slab and the ball-drop height was 60 cm. **Figure 6** shows the measured waveform signal from the cement-concrete pavement slab with and without the flexible function layer. **Table 3** shows the comparison results for the measured vibration data from the pavement slab with and without the flexible function layer.

In this study, the declining rate = (maximum peak – attenuation peak)/maximum peak, representing the decline of the pavement slab. A bigger declining rate indicates that the declining effect is more significant. As

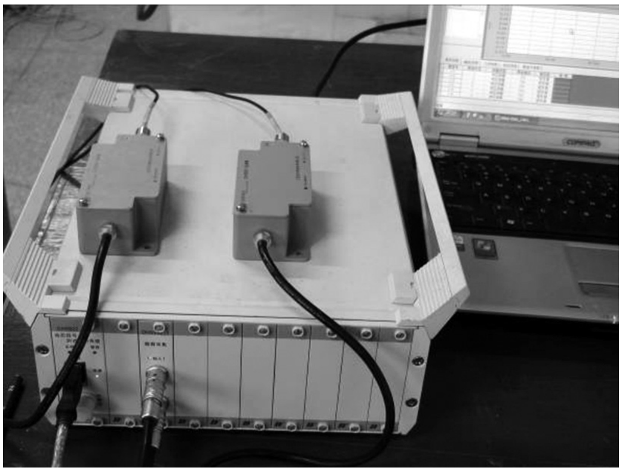

Figure 4: Dynamic signal test instrument
Slika 4: Preizkusna naprava za dinamične signale

Table 3: Measured vibration-data comparison table of the pavement slabs with and without a flexible function layer
Tabela 3: Primerjalna tabela izmerjenih vibracij na plošči pločnika z gibljivim funkcionalnim slojem in brez njega

Structure type of the pavement slab	Max peak (mm)	Min peak (mm)	Attenuation peak (mm)	Attenuation time (s)	Difference between the max and min peaks (mm)	Declining rate
Without a flexible function layer	0.227	–0.664	0.141	0.268	0.941	37.89 %
With a flexible function layer	0.140	–0.373	0.082	0.287	0.513	41.43 %

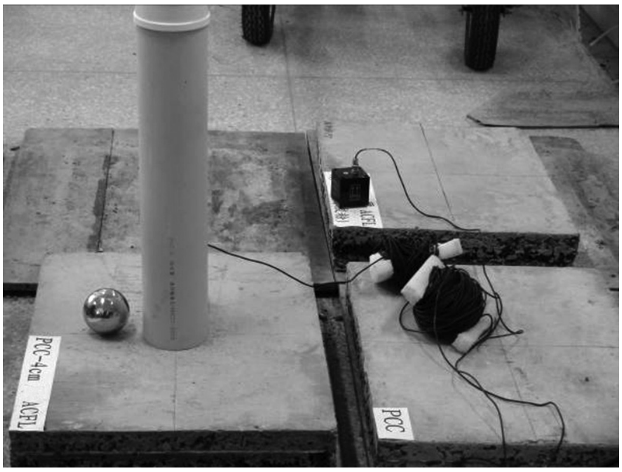

Figure 5: Steel ball and sleeve
Slika 5: Jeklena krogla in vodilo

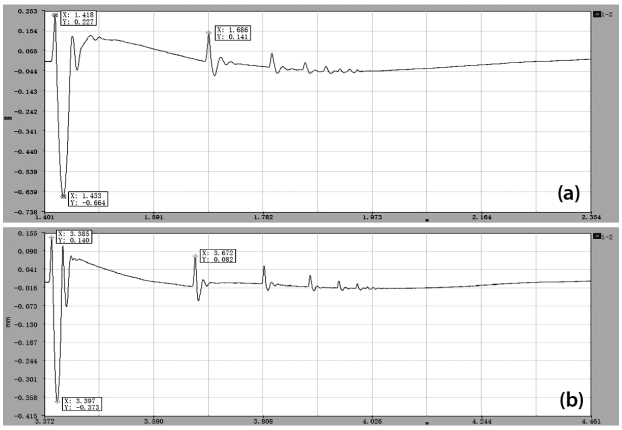

Figure 6: Time-domain waveform comparison diagram of the pavement slab with and without a flexible function layer: a) pavement structure without a flexible vibration-damping function layer, b) pavement structure with a flexible vibration-damping function layer
Slika 6: Primerjava časovnega poteka vala v plošči z gibljivim funkcionalnim slojem in brez njega: a) struktura pločnika brez gibljivega funkcionalnega sloja za dušenje vibracij, b) struktura pločnika z gibljivim funkcionalnim slojem za dušenje vibracij

can be seen in **Figure 6**, the time-domain curve of the vibration signal of the pavement slab under the load impact fluctuated in the following way: the vibration signal first achieved its maximum peak as the impact occurred, then decreased to its minimum value and eventually came close to zero through a declining process with several fluctuation cycles. The fluctuation showed that the vibration of a pavement slab under the load impact was a declining process.

As can be seen in **Table 3**, the addition of a flexible function layer decreased the maximum value of the vertical vibration response, the minimum absolute value of the vertical vibration response and the attenuation peak from (0.227, 0.664 and 0.141) mm to (0.140, 0.373

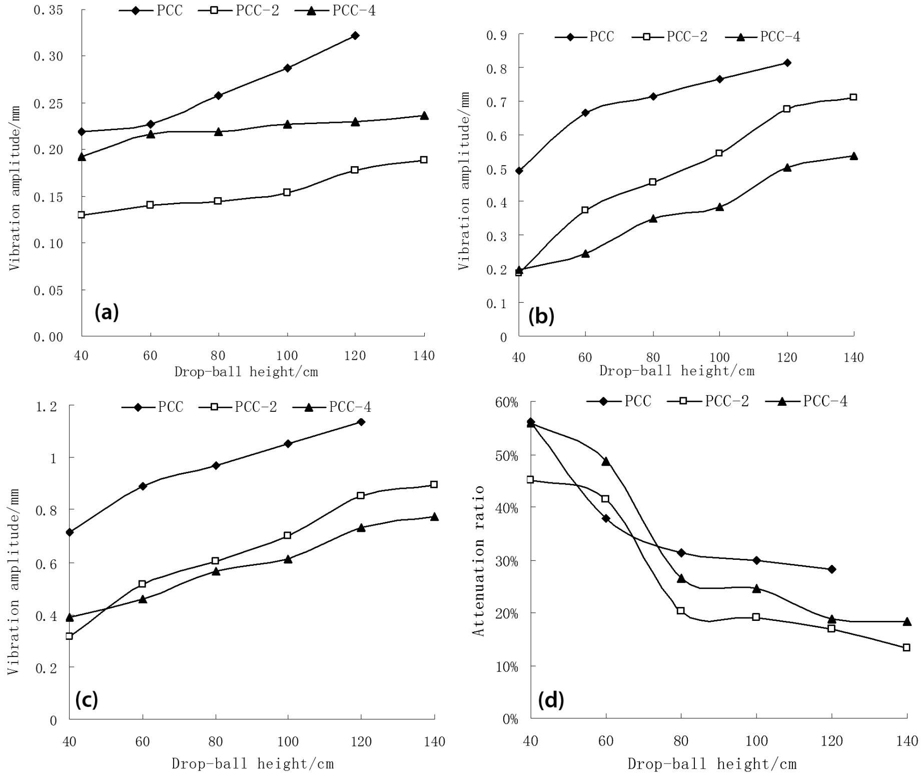

Figure 7: Vibration response variation diagram with changes in the thickness of the flexible function layer: a) the maximum peak, b) the absolute value of the minimum peak, c) the difference between the maximum and minimum peaks, d) attenuation value
Slika 7: Spreminjanje odziva na vibracije s spreminjanjem debeline gibljivega funkcionalnega sloja: a) maksimalne vrednosti, b) absolutne vrednosti minimuma, c) razlika med maksimalno in minimalno vrednostjo, d) vrednost dušenja

and 0.082) mm, respectively. Moreover, their amplitude reductions were 62.1 %, 78.0 % and 72.0 %, respectively. The difference between the maximum and minimum peaks of the pavement structure was reduced from 0.941 mm to 0.513 mm. Therefore, the addition of a flexible function layer in the cement-concrete pavement can efficiently reduce the vibration response of the pavement slab.

4.2 The variation rule of the vibration response with respect to the thickness of the flexible function layer

First, the magnetic-electric vibration sensor was placed onto the slab and then the pavement structure (PCC) was impacted from the ball-drop heights of (40, 60, 80, 100, 120 and 140) cm. We designed one pavement structure with a 2 cm flexible function layer (PCC-2) and another pavement structure with a 4 cm flexible function layer (PCC-4) to examine the effecting rule of the pavement-vibration responses of the flexible function layers with different thicknesses.

Figure 7 shows the images of the variation rule of the maximum peak, the absolute value of the minimum peak as well as the attenuation peak, the attenuation time, the difference between the maximum peak and the minimum peak and the declining rate of the vibration responses of the flexible function layers with different thicknesses. Since the pavement structure without a flexible function layer (PCC) was already broken under the ball drop from the height of 140 cm, only five data points were collected for the PCC curves on **Figures 7a** to **d**.

Figure 7a shows the variation diagram of the maximum peak of the pavement vibration response with respect to the changes in the thickness of the flexible function layer. As can be seen, the maximum peak of the vibration response increased when the ball-drop height was higher. Moreover, initially the maximum peak of the vibration response significantly decreased and later the decrease became slower as the thickness of the flexible function layer increased.

The absolute value of the minimum peak of the vibration response increased with the increasing ball-drop height, but declined with the increase in the thickness of the flexible function layer, as shown in **Figure 7b**. Taking the 80 cm ball-drop height as an example, the absolute values of the vibration responses for PCC, PCC-2 and PCC-4 were (0.712, 0.457 and 0.348) mm, respectively. Compared with PCC, PCC-2 displayed a reduction of 35.8 %, and compared with PCC-2, PCC-4 displayed a reduction of 23.8 %.

The difference between the maximum and minimum values of the structure-vibration response increased with the increasing ball-drop height, but declined with the increase in the thickness of the flexible function layer, as shown in **Figure 7c**. In other words, initially the vibration amplitude reduced significantly with the increasing thickness, but became slower when a certain thickness was achieved.

The declining rate of the vibration response declined with the increasing ball-drop height, as shown in **Figure 7d**. Taking PCC-4 as an example, the declining rate decreased from 55.96 % to 18.22 % when the ball-drop height was gradually increased from 40 cm to 140 cm. Moreover, initially the declining rate reduced significantly with the increase in the ball-drop height, but the reduction later turned to be less significant.

4.3 Variation rule of the vibration response with respect to the change in the impact height

First, a magnetic-electric vibration sensor was placed onto the slab and then the test piece was impacted, with the ball-drop height set at (40, 60, 80, 100, 120 and 140) cm, to investigate the variation rule of the vibration response with respect to the changing ball-drop height.

Figures 8 to **10** show the variation curves for the ball-drop heights when the pavement structure was

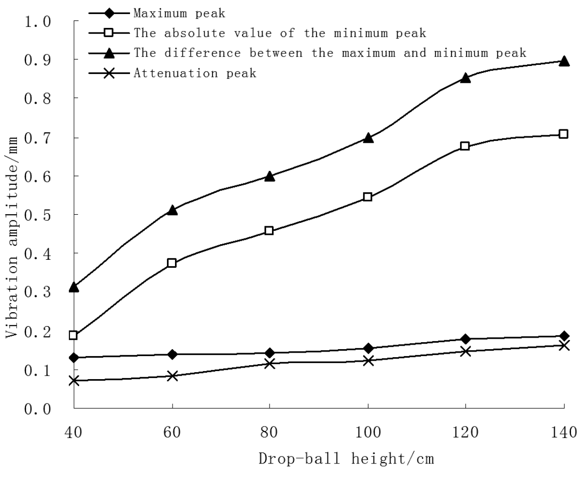

Figure 8: Variation rule of PCC vibration amplitude
Slika 8: Spreminjanje PCC-amplitude vibracij

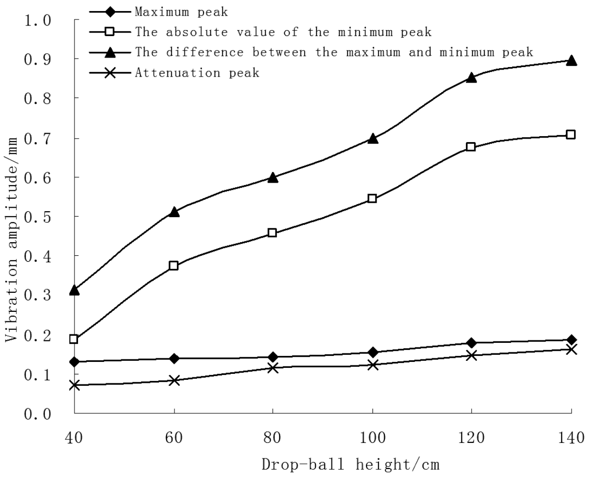

Figure 9: Variation rule of PCC-2 vibration amplitude
Slika 9: Spreminjanje PCC-2-amplitude vibracij

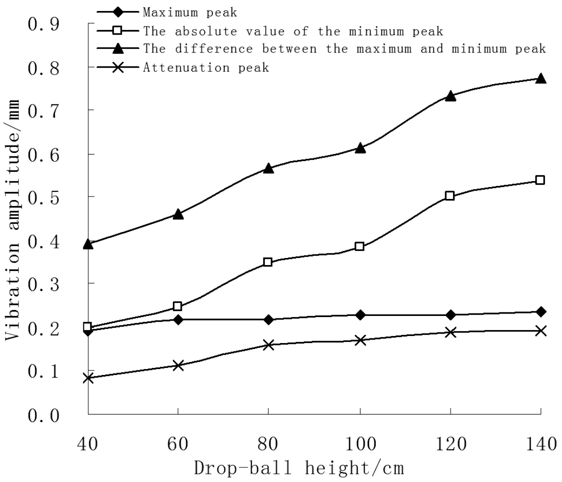

Figure 10: Variation rule of PCC-4 vibration amplitude
Slika 10: Spreminjanje PCC-4-amplitude vibracij

designed without a flexible function layer (PCC), with a 2 cm thick flexible function layer (PCC-2) and with a 4cm thick flexible function layer (PCC-4), respectively.

As can be seen in **Figures 8** to **10**, the vibration response amplitude assumed a linear growth trend with the increasing ball-drop height. Taking PCC-2 as an example, the maximum peak, the absolute value of the minimum peak, the difference between the maximum and minimum peaks and the attenuation peak increased from (0.129, 0.186, 0.315, and 0.071) mm to (0.188, 0.708, 0.896, and 0.163) mm, respectively, when the ball-drop height was increased from 40 cm to 140 cm. Moreover, the corresponding amplification rates were (0.0006, 0.0052, 0.0058 and 0.0009) mm/cm, respectively.

4.4 Analysis of the pavement-slab breakdowns

The pavement slab without a flexible function layer appeared to break down under the impact vibration of the steel ball when the ball-drop height was set to 140 cm, as shown in **Figure 11a**, whereas the pavement slab with a 2 cm thick flexible function layer remained unchanged, as shown in **Figure 11b**. These results show that the addition of a flexible function layer to a rigid pavement structure has a significant effect on the vibration damping and energy absorption and efficiently reduces the breakdowns caused to the pavement.

5 CONCLUSIONS

1) The pavement vibration under the impact load was a declining process. The measured vibration-waveform signals remained consistent, except for the occurrence of a significant variation in the vibration peak.
2) The maximum peak of the structure vibration response increased with an increase in the thickness of the flexible function layer. Initially, the vibration amplitude had larger reductions, but the reduction became slower when the flexible function layer achieved a certain thickness.
3) The vibration-response amplitude assumed a linear growth with the increasing ball-drop height.
4) The test results show that a flexible function layer has a significant effect on the vibration damping and energy absorption. The cement-concrete pavement structure with a flexible function layer can efficiently reduce the breakdowns and cracks to the pavement caused by the wheel-impact vibrations.

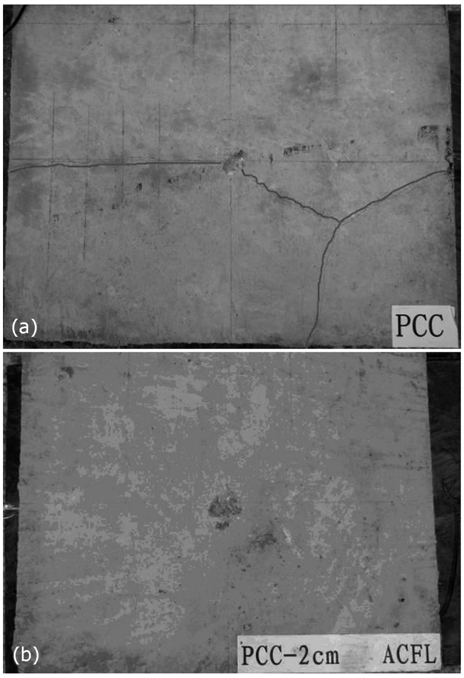

Figure 11: Crack comparison diagram of the pavement slab with and without flexible function layer: a) pavement structure without flexible vibration-damping function layer, b) pavement structure with flexible vibration-damping function layer
Slika 11: Primerjava slike razpok na plošči za pločnik z gibljivo funkcionalno plastjo in brez nje: a) struktura pločnika brez gibljivega fleksibilnega sloja za dušenje vibracij, b) struktura pločnika z gibljivim fleksibilnim slojem za dušenje vibracij

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