COPS – concrete with open porous surface

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Abstract

Tire-road noise is the dominating sound source in road traffic. Therein, the air-pumping effect, the horn effect and the groove resonances assume an essential role within the noise development. Currently, the reduction of sound emissions from the concrete pavements is achieved by a sufficient surface roughness. In Germany, this is realized by the standard construction method with exposed aggregate concrete. In addition to the defined surface textures, it is also possible to produce an upper thin concrete layer with a near surface macro pore system accessible to the sound pressure. A high sound absorption can be achieved through the interconnected macro pore system in the near surface area.

Introduction

In road traffic the interaction between tire and pavement is the dominant source for noise. Therefore, the noise development should be reduced directly at this source. This relates primarily to highways in urban areas or in border directly to residential buildings.

An important aspect in this context is to achieve an acoustically effective surface without large additional measures directly in the construction process. For this purpose a rough surface with cavities is of advantage. Currently this is obtained in Germany in concrete pavements by exposed aggregate surfaces. Within a research project it was the basic idea for an alternative or even more effective method to design a concrete mix for the about 5 to 8 cm thick upper lift with a somewhat too low mortar content. During compaction of this concrete the mortar penetrates downwards and at the surface remains an open pore system with poked out coarse aggregates (max 8 mm).

This system can be applied also on old concrete pavements, when the surface is adequately pretreated. This offers not negligible economic advantages as there is no need to replace the entire structure. In addition, the one-step application using the conventional equipment (slipform paver) without further steps (e.g. brushing out the surface mortar) is additionally of economic advantage. In addition to the acoustic characteristics, with this concrete equal durability of the pavement can be achieved as with conventional concrete.

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Principles of noise reduction in pavement surfaces

Acoustic effectiveness of pavement surfaces. Sound emission of traffic is caused by the engines and by the tires rolling on the pavement (tire-road noise) as well. The proportion of these sources depends mainly on the speed. The rolling noise dominates at speeds of cars above about 40 km/h and that of trucks above 60 km/h (Beckenbauer, 2008) (Figure 1). So on highways, where the speed normally is quite above these values, the rolling noise is the most relevant parameter.

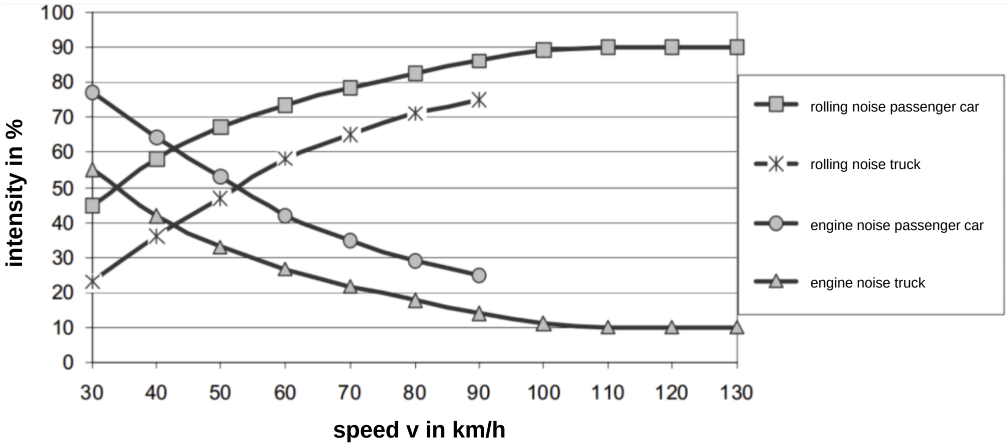

Figure 1. Proportion to the intensity of rolling noise and the engine noise of the total emissions in % separately for cars and heavy trucks in dense standard road surfaces (Beckenbauer, 2008)

The components of tire-road noise are sound stimulus, sound radiation and sound propagation in the relevant place. The acoustic incitation of the tire includes the mechanical and aerodynamic incitation. The mechanical one causes the deformation of the profile blocks of the tire against the contact surface when rolling out under the influence of the tangential and radial dynamic forces. At contact loss between tire and road, these begin to swing (Figure 2, a,b). The motion of the system "tire" is then consequently radiated as airborne sound (Beckenbauer, 2008).

The aerodynamic incitation is based on the fact that air is a compressible medium. During a roll-over of the tire, the air is not completely displaced, but compressed at high dynamic pressure in the cavities. When the tire has passed the cavity it is exposed again and the air trapped therein may abruptly relax (air-pumping effect) (Figure 2, c) (LfU 2004, Beckenbauer 2008, Beckenbauer 2009). The rotation and movement of the tire and therefore the displacement of air at obstacles in the contact surface result in air currents of air through the cavities and boundary surfaces formed by profile and pavement. The intensity of this process increases with increasing speed. Thus, this effect is influenced decisively by the cavities in the tire and the pavement. Therefore, the three-dimensional shape of the pavement surface, especially of the macro pore system is the most significant parameter for the efficacy of these mechanisms.

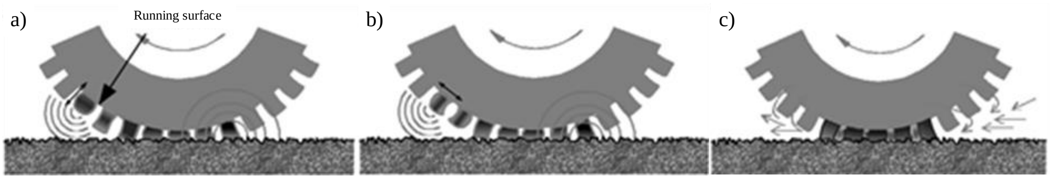

Figure 2. Mechanical vibration excitation at rolling tires. Formation radial oscillation (a), tangential vibrations (b) and air-pumping effect (c) (Beckenbauer, 2008)

Sound absorption. By partially reducing the portion of small and medium grain sizes in the aggregates composition, after compaction of the concrete in the surface zone remains an open-pore structure. This open porosity respectively the accessible void content in the surface is sound absorbing. The absorption capacity is mainly dependent on the open-pore layer thickness, the accessible void content and the flow resistance. Varying of these parameters allows to change and optimize the absorption frequency of an open-porous layer (LfU, 2004, Beckenbauer, 2008). Therefore by variation of the layer thickness, the position of the frequency response can be changed. By varying the void content and the flow resistance the absorption frequency response can be varied in height and width (Figure 3).

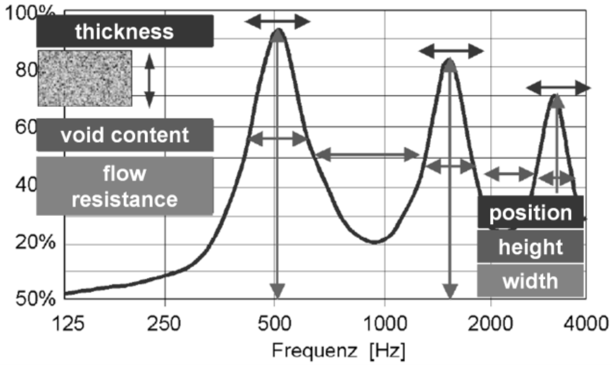

Figure 3. Absorption frequency response of open-porous surface (Beckenbauer, 2009)

The sound-absorbing effect of an open-porous surface is terminated in the case that these cavities are among themselves inaccessible. However, if there is a communicating cavity system the air-pumping effect is reduced because the air sucked in during passing of the tire can escape into the cavities down- or sideward. Furthermore, by an open-porous surface structure the noise, which is not caused by the tire-road noise but e.g. by the engine noise, can be absorbed too (Beckenbauer, 2008).

Texture. By a low roughness which can be obtained with a small maximum grain size, the mechanical excitation of the tire decreases. However, this does not necessarily lead to a reduction in the rolling noise level. With a decreasing roughness depth the air trapped between tire and pavement surface cannot escape and therefore the air-pumping effect is increased.

Due to this contradictory behavior, the shape of the texture is an important indication of the efficiency of a noise-reducing surface. A concave shape has been found to be acoustically effective. By using a small maximum grain size in the concrete mix it is possible to minimize the resulting mechanical excitation of the profile blocks and tread of the tire.

Concrete Design

Concept. The concrete to be developed should be produced with common materials. Next to quartz sand within a fraction 0 - 2 mm crushed aggregates of 2 - 5 mm fraction should be used. The latter has proved itself in the field of noise-reducing in exposed aggregate surfaces. As cement an ordinary Portland cement 42.5 R is used. Furthermore, superplasticizer and air-entraining agents are included.

The basic idea for the mix design was that there is a deficiency in mortar so that after complete compaction indeed the voids between the coarse aggregates are completely filled with mortar in the lower zones, however in the near surface zone an adequate porous zone with exposed coarse aggregates remains. For this purpose the specific properties of the crushed aggregate and their void content plays an important role. In pre-tests the void content of the 2-5 aggregate fraction was determined. A typical value for the used basalt material (density 2.93 kg/dm³) was about 46 vol.-%, which served as a starting point for further modifications. On the other hand to obtain the targeted porous surface structure the necessary void content in the total mix was calculated to 9 vol.-% for a 6 cm thick concrete layer.

Thus the rest volume had to be filled with mortar. In the first experiments the ratio between sand content and cement paste content was varied whereas the w/c-ratio was kept constant at 0.45. In these investigations an optimal cement content in the range of 330 up to 360 kg/m³ and a sand content of 15 to 20 % related to the total aggregates volume was determined (Figure 4).

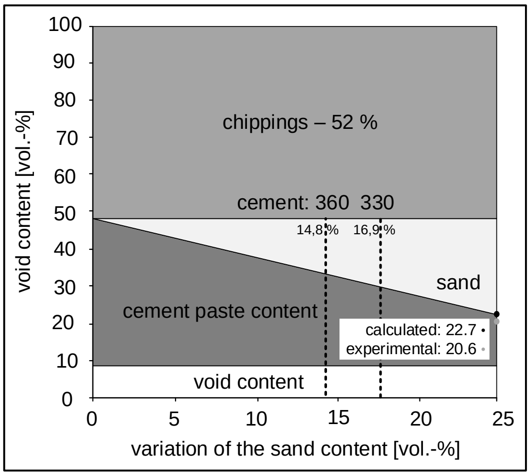

Figure 4. Overview of the volume fractions of the concrete by varying the mortar composition (based on a layer thickness of 6 cm and 1 cm open porosity); Shown here for basalt 2/5 mm with two executed mixtures (c = 360 / 330 kg/m³)

Based on these results further concrete mixes with varying the superplasticizer content were investigated with the focus on the – intended – sedimentation of the fine mortar (Figure 5).

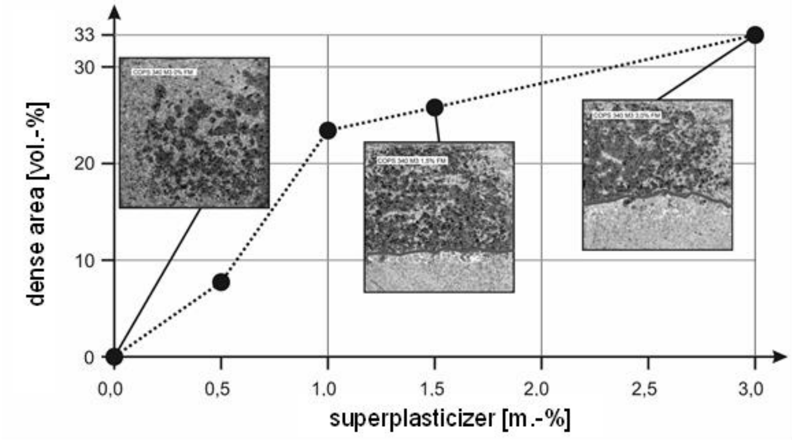

Figure 5. Sedimentation of the cement lime with varying contents of superplasticizer (m.-% related to the cement content)

It could be proven that the mortar accumulates – as expected – in the lower part by increasing the content of the superplasticizer. If not any plasticizer has been added a completely open porous concrete was obtained. At an addition of 3 m.-%/c. of super plasticizer the result was approx. 67% of open pore volume. To achieve the targeted pore structure in the near surface zone in preliminary investigations it became obvious that in addition to the "grading curve" the superplasticizer in relation with the cement content significantly affects the sedimentation and thus the structural design of COPS. As the result of the pre-laboratory tests and based on further systematic investigations concrete “A” was developed, which shows a good workability and the required differentiation of the structure after compaction. The concrete design is shown in table 1.

Further improvements in concrete design. Due to the experiences gained in the previous concrete studies the compacted granular structure of the grading curve was used as basis for further concrete investigations where the sand-basalt-ratio was varied. However, in these studies the void volume of the coarse aggregates was considered in a compressed state simulating the situation in compacted concrete. It was determined how much cavities of the basalt grains are available after compression in the installed state (Figure 6).

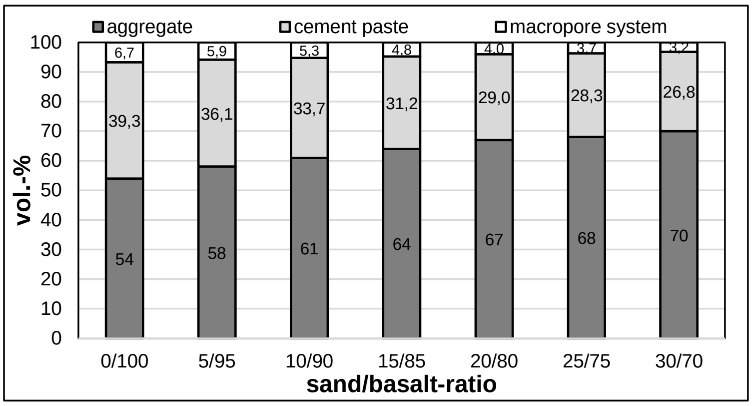

Figure 6. Concrete conception based on the packing density

For the further experiments a sand-basalt-ratio of about 15/85 was chosen as for this sufficient workability and compactibility was proven. Based on these results a further concrete "B" was developed, which was used in a second large-scale production. To this concrete, a basalt filler (80 kg/m³) was added to improve the workability and to reduce the voids in the dense region of the concrete layer. The cement content was 350 kg/m³, the w/c-ratio 0.40 and the superplasticizer content 0.70 m-%/c. Furthermore, an air-entraining agent was used.

Figure 7 shows the digitalized laser triangulation surface texture of the laboratory sample of concrete "B". A maximum roughness depth of 9 mm has been determined. Also, it is apparent from the diagram that uniformly distributed "gorges" are present and that the required evenness is given.

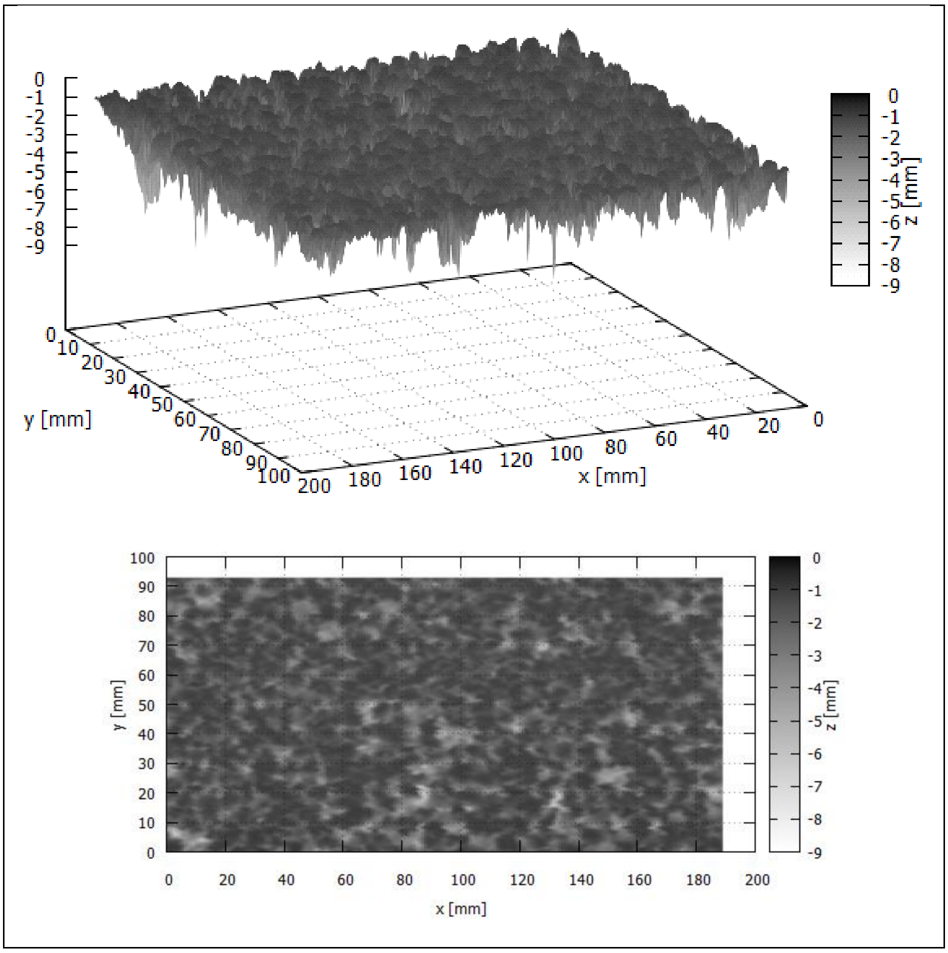

Figure 7. Digitalized surface texture of the concrete variation B. top: three-dimensional view; bottom: supervision of the surface

As a result from the laboratory tests, two open porous concretes "A" and "B" (Table 1) were developed which met within laboratory tests the requirements of the workability and compatibility and thus had the required structure respectively cavity distribution and surface texture. These concretes has been selected to be installed in the large-scale experiments.

Table 1. Composition of concretes A and B

material	dimension	Concrete A	Concrete B	density [kg/m³]
cement (CEM I 42,5 R)	kg/m³	350	350	3100
water w/c-ratio: 0.43 (0.40)	kg/m³	150 (140)	140	1000
basalt filler	kg/m³	0	80	2850
quartz sand 0/2 mm	kg/m³	352	200	2630
basalt 2/5 mm	kg/m³	1614	1475	2900
air-entraining agent	[m.-%/c]	0,2	0,2	1050
Superplasticizer	[m.-%/c]	0,7	0,7	1000
calculated air content	[m³]	0,07	0,132	-

Shear-Resistance. Additionally, on the two selected concretes rollover tests according to (Root, 2008) were performed, in which the shear-resistance was tested. The rollover test is in the original sense a method for assessing the resistance of asphalt layers to shear stresses at the surface. An oscillating rotary movement with a vertically loaded test wheel stresses the test specimens (26 x 26 x 6 cm) mechanically. This allows the simulation of two stress conditions at the same time. The changing direction of rotation without rolling of the tire corresponding to a stationary steering operation.

The additional oscillating movement in the horizontal axis simulates a variation in shear stress. This load case can be compared with the maneuvering of a car at a parking area or – in case of COPS – with tire movements during a jam. 20 double-shear-cycles were carried out with an oscillating movement and with a fixed load of 1000 N. Figure 8 shows the schematic structure of the experimental setup (left) and an ongoing trial (right).

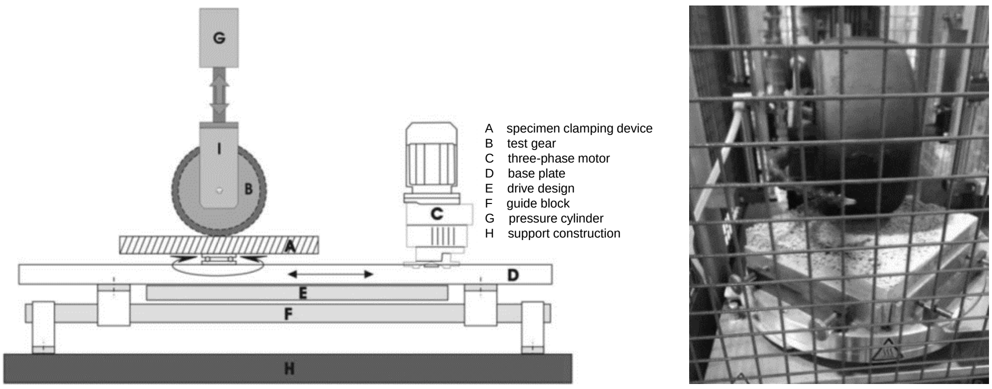

Figure 8. Left: schematic representation of the rollover test, right: running try

The loss of substance, determined by weighing before and after the test, was for both concretes less than 2 gram. This was the results of only two local grain outbreaks. For comparison, if a water-permeable asphalt is loaded by 5 double-shear-cycles the substance loss amounts to approx. 136 gram (Root, 2008).

Large Scale Applications in situ
In this project, also two large-scale tests were carried out. First, the concrete “A” from the pre-tests with a w/c-ratio of 0.43 was casted with a slipform paver to a lower lift, poured only about one hour before. By this way the practicability of COPS was examined. Two types of compaction (static, dynamic) were examined (Figure 9).

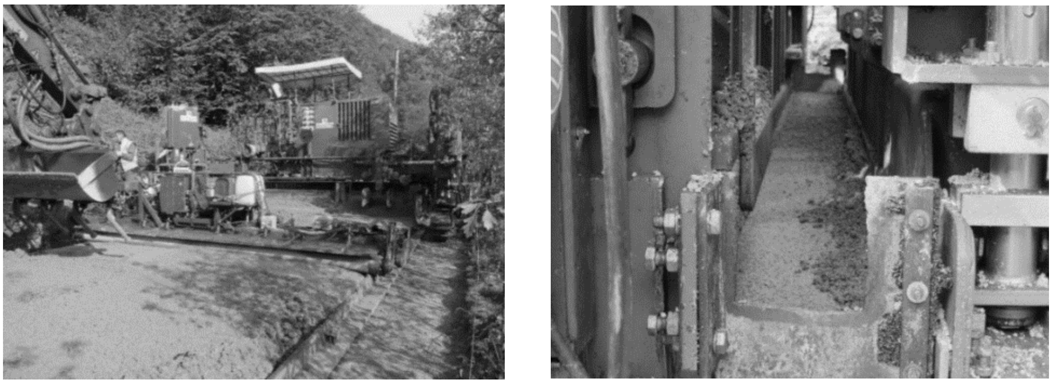

Figure 9. Casting of the lower-lift concrete (left); pouring of COPS (concrete A) in the upper lift (right)

After hardening drilling cores were taken from this pavement. At these specimens the concrete micro-structure, in particular the void content and their distribution were examined. Exemplary, a CT-scan was performed on a drilling core sample (Figure 10).

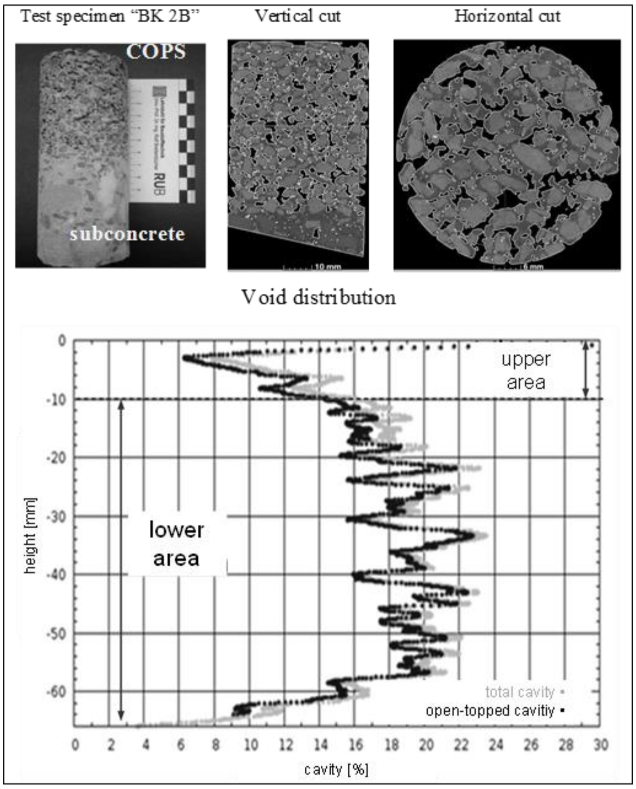

Figure 10. CT-scan of the drilled core and void-distribution

The analysis showed an increasing void content with increasing depth, quite contrary to the target. This mainly was caused by an insufficient compaction of the COPS-concrete in the upper lift. It can be assumed, that this is mainly influenced by the still flexible concrete in the lower lift at compaction the upper one. In consequence the mortar did not penetrate downwards as expected due to the absorption of the compaction energy.

The acoustic tests measurements (measurement of tire-road noise; cpx-method) show, when the concrete was compacted dynamically, an average sound pressure level in the amount of approx. 88-89 dB and very good surface textures can be achieved. However, simultaneously a high compaction energy can lead to a loss of macro pores and therefore to a loss of the acoustic effectiveness due to accumulation of mortar at the surface. The static compaction of the concrete resulted in very good acoustic results, but due to the high open porosity a reduced durability has to be assumed. These results are similar with a porous asphalt. This is due to the integrated networking of all voids over the height of the section.

As a direct consequence for the second in-situ test, the COPS-concrete was poured on an already hardened lower lift concrete. In this case concrete “B” with a w/c-ratio of only 0.40 was used. To avoid accumulation of mortar on the surface due to too strong compaction the COPS-layer was compacted only in static method. To improve the bonding properties between the already hardened lower-lift concrete and the new COPS-lift an adhesive bonding primer was applied before concrete casting. Both concretes showed a stiff consistency, the air content in the fresh concrete was approx. 5 vol.-%. The surface of the freshly paved concrete showed a high evenness and both concretes exhibited high green strengths. Macroscopically no irregularities in form of jutting grains (Figure 11, right) were visible.

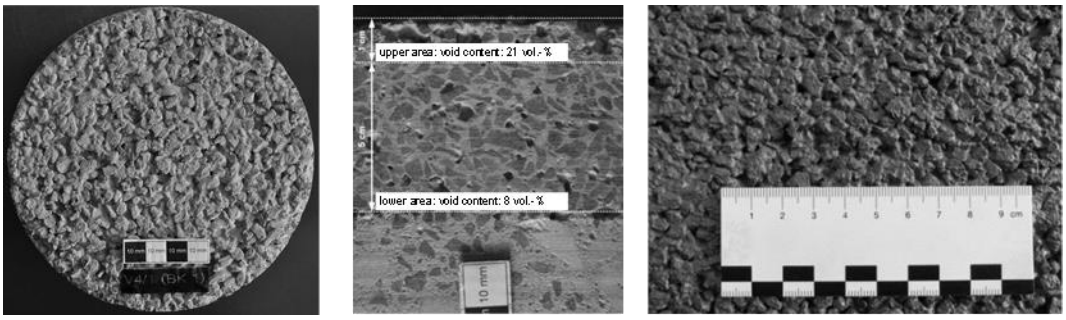

Figure 11. Concrete design: Var. B: left: drilling core, middle: lateral surface, right: fresh concrete surface

The compressive strength after 28 days of 48.2 MPa for concrete “A” and 58.5 MPa for concrete “B” confirm that the used concretes fulfill the required strength class C30/37. In addition, the splitting tensile strength with about 6.7 MPa for both concretes lies within an adequate range. To assess the freeze-thaw resistance separate specimens produced during construction were tested with the CDF-test. The maximum mass-loss after 28 freeze-thaw cycles was about 930 g/m². This value is significantly below the acceptance criterion of 1500 g/m².

On drilled cores also the distribution of cavities was examined. Unlike the first production there was a clear distinction between open-pored and dense area (Figure 12).

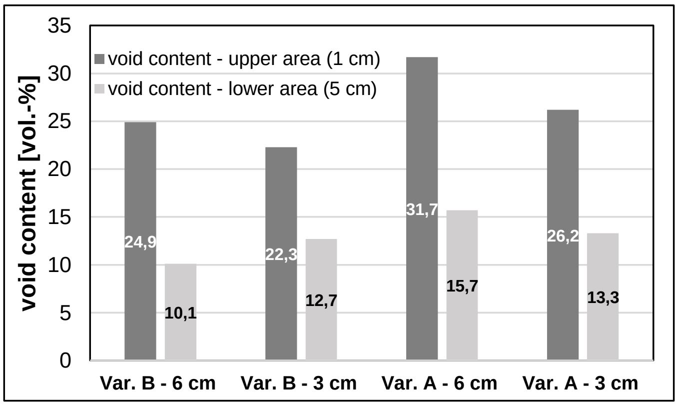

Figure 12. Void content of the modified concrete variation A and the concrete variation B at the second large scale installation

Based on the results of the cavity allocation and compared to the results of the large scale tests a differentiated distribution of voids could be achieved. It was found that the concrete altogether has a reduced void content in the upper (1 cm) and lower region compared to the first test. The higher void content of the concrete “A” compared to concrete “B” can be the consequence of its lower cement paste content and insufficient compactibility.

When the thickness of the upper COPS-lift was reduced to 3 cm a somewhat lower void content was determined for concrete ”A” as well as for concrete “B”. It can be assumed that the concrete has undergone a stronger compaction over the entire height and the void content was reduced by stronger grain rearrangements.

The results of the acoustic measurements (CPX) showed a slightly higher sound level of 90-92 dB in comparison to the first in-situ test.

Final Discussion and Conclusion

The investigations show that the production of an acoustically effective concrete surface, which does not require an additional processing step is possible. Within the framework of an economic consideration, the concrete design requires a compromise concerning the acoustic effectiveness and a sufficient durability due to environmental exposures and traffic loads.

As part of the laboratory tests, it has been shown in the concept of COPS that several interactive parameters must be coordinated in order to meet the concrete technology but also to meet the structurally engineered requirements. An essential precondition for this is the inclusion of the parameter "air volume" within the near surface zone. It also requires some fine-tuning of the viscosity of the cement paste and the grading curve. A suitable lime must be able to sink downwards due to compaction.

To ensure the durability of the pavement, the cavity rich layer must be able to carry the traffic load in all its facets. With regard to the near-surface macro pore system a total void content of about 20 vol.-% within the COPS-concrete can be seen as an acoustically effective value in combination with a sufficient durability. The acoustic measurements have fundamentally shown that COPS exhibit high potential for the production of low-noise concrete pavements. The installation of COPS on the already hardened subconcrete with a slipform paver with a rigid (non-variable) paving screed has been proven.

ACKNOWLEDGMENTS
The authors are grateful to the Federal Ministry of Transport and Digital Infrastructure and the Federal Highway Research Institute (Germany) for financial support of this research project. The authors wish to acknowledge the cooperation with the Heinz Schnorpfeil Bau GmbH whose experience in the field of road constructions was an important part of this project.

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