



DEFINITION OF CONCRETE AND COMPOSITE PRECAST CONCRETE PAVEMENTS TEXTURE

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Abstract. In the context of increasing traffic demands and emerging mobility trends road infrastructure has to shift towards the fifth generation of roads, which according to Forever Open Road (FOR) vision are envisioned as adaptable to traffic volumes, resilient to changing weather conditions, quickly built, effectively maintained, suitable for retrofitting, self-monitoring, self-repairing and recyclable. Concrete modular pavements can be defined as an example of such type of road infrastructure. Functional needs are mainly associated with implementation area/location, traffic and mobility demands, environmental constraints and etc. This also has a significant impact on the selection of Precast Concrete Pavements (PCP) texture formation method and materials. Concrete pavement surface texture affects both safety and tyre/road noise characteristics. Exposed Aggregate Concrete (EAC) and porous concrete are the most suitable noise reducing solutions for highways and streets wearing layer even in severe traffic and climate conditions. According to the literature analysis, the algorithm of highways and streets low noise concrete design was created. It is recommended to use the highest quality aggregates with maximum size up to 8 mm, gap-graded gradation, higher amount of cement and lower water/cement ratio. The most important characteristics of EAC are Mean Profile Depth (MPD), Mean Texture Depth (MTD) and profile count, while the most important characteristics of porous concrete are compressive strength, outflow and air void content.

Keywords: modular pavement, concrete texture, noise, noiseless pavements, microtexture, macrotexture, exposed aggregate concrete, porous concrete, road.

Introduction

In the context of increasing traffic demands and emerging mobility trends, road infrastructure has to shift towards the fifth generation of roads, which according to Forever Open Road (FOR) vision are envisioned as adaptable to traffic volumes, resilient to changing weather conditions, quickly built, effectively maintained, suitable for retrofitting, self-monitoring, self-repairing and recyclable. Additionally, next generation of roads has to be in line with infrastructure budget constraints and asset management systems (Morgan 2006).

Concrete modular pavements typically known as Precast Concrete Pavements (PCP) and can be named as an example of such type of road infrastructure. PCP are a precast (in some cases prestressed) pavement system where single slabs/panels with all the required properties and embedded systems are precasted in factory and then constructed on site on piles system or base layer (usually with special leveling grout). In general, the concept of PCP

is very old and can be associated with traditional concrete pavements (concrete slabs), but these traditional concrete pavements are not what it is called easily repaired, retrofitting, adaptable, self-monitoring. Advanced concept of PCP is based on enhanced concrete slabs that has in-built sensors, can be used for noise reduction or fast surface water drainage, have inside chambers for utilities and can be built/connected/replaced with other very fast.

This paper describes the novel approach on developing PCP with a “maintenance by design” philosophy, which considers maintenance needs and changing framework conditions already during planning and design phases. It brings more value or the investment costs, taking into consideration the whole lifetime. This probabilistic approach (reliable and approved deterioration prediction models for the materials and structures and the overall systems) ideally take into account a Life Cycle Cost Analysis (LCCA) of the whole design life of infrastructure to consider and

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balance all costs that may arise. Often, a solution, which may look at first-hand very expensive may be “cheaper” and offset this by presenting significant long-term advantages and reduced expenses for the maintenance during its whole lifetime. Figure 1 presents the key components of “maintenance by design” philosophy, which is further used as a basis for PCP development.

Development of PCP concepts using this “maintenance by design” approach it is necessary to define PCP application areas and desirable functionality and performance indicators. Comprehensive assessment of current and future needs, identification of specific location-based infrastructure performance demands is a first step for successful development of PCP concepts. Predicting functional needs (performance indicators) for future use of PCP is a complex task that requires balancing different surface characteristics, structural performance characteristics and potential needs for slab/panels improvement, retrofitting or integration with other systems (e.g., utilities, smart communication technologies).

Functional needs are mainly associated with implementation area/location, traffic and mobility demands, environmental constraints and etc. This also has a significant impact on the selection of PCP texture formation method and materials. For example, if PCP application area is logistic terminals or bus lanes and stops, then the main functional properties should be focused around structural strength and durability. Different balancing of functional properties might be relevant if PCP application area is streets or main roads (motorways) crossing residential areas. In such situations, environmental issues like tyre/road noise, CO emissions should be tackled by the means of PCP surface texture optimisation.

Different road surface characteristics can be associated with particular pavement texture wavelengths (megatexture, macrotexture, microtexture) meaning that different

pavement texture may have different influence on different properties. There are also few areas of overlaps between different road surface characteristics at particular texture wavelength ranges. Therefore, balancing of distinct road surface characteristics (tyre/road noise reduction, improvement of skid resistance, reducing rolling resistance and durability) is a very complex and sometimes contradictory task.

The aim of this article is to define the main precast concrete and composite pavement texture, give the recommendations for PCP texture characteristics and the concrete mixture design to achieve those texture characteristics according to potential concrete pavement application areas. The novelty of this work is created algorithm for PCP concrete design, which ensures good texture parameters providing noise reduction, friction and durability.

1. Surface texture element of concrete modular pavements

PCP is fast concrete pavement constructing or repairing technology, which uses prefabricated concrete panels. These panels are prefabricated in the factory, transported to the site and installed on prepared base layer. This technology provides better quality concrete pavement because PCP slabs are manufactured in the factory where all technological processes are strictly controlled. Technological mistakes during manufacturing process and environmental impact during hardening process are eliminated. Moreover, PCP can be installed in wider range of environmental conditions comparing to usual concrete pavements. Properly designed PCP systems and organized technological process allows short construction period and early traffic opening on the new PCP (Smith, Snyder 2018; Tayabji *et al.* 2013). There are several solutions of PCP construction:

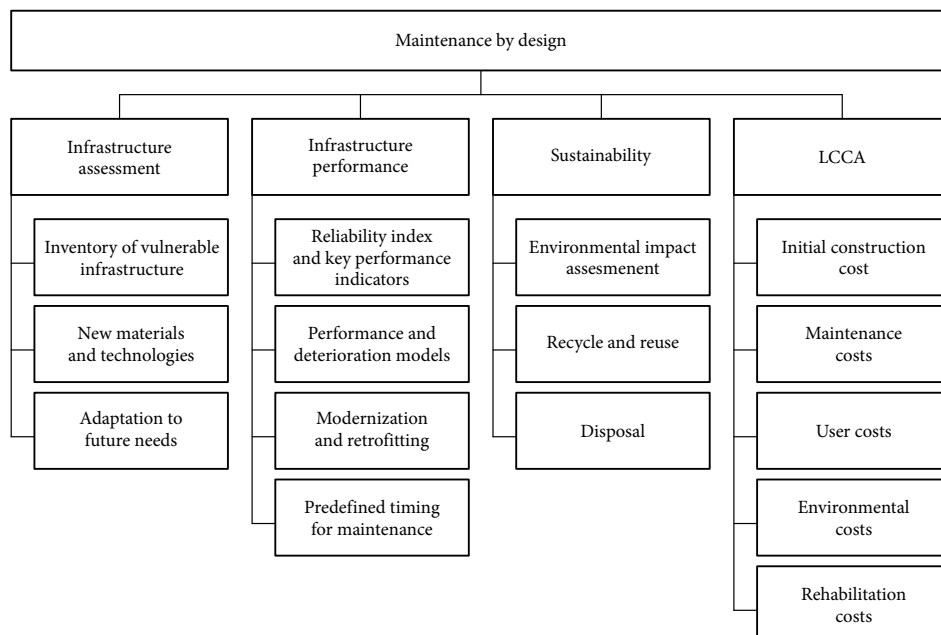


Figure 1. Key elements of “maintenance by design” philosophy

Two-layer systems were evolved to ensure low noise emission and high friction of concrete pavement for thinner wearing layer using the highest quality materials while for thicker base layer the lower quality materials are using. This economical solution allows to reduce noise, increase friction and resistance to freezing-thawing cycles of wearing layer and allows to use local cheaper materials (even recycled materials) for base layer concrete (Cackler et al. 2006; Cable, Frentress 2004; Fick 2010).

Thin overlays were evolved due cities particularity – simple and fast laying of thin overlays allows to reduce traffic limiting time and cost (PIARC 2016). This solution provides homogenous noise reducing surface with good friction (Anfosso-Lédée, Brosseau 2009). Thin overlays can be laid on existing concrete, asphalt or composite pavements. This economical solution can be used to increase the durability of the concrete pavement and enhance the driving conditions. Concrete overlays that thickness are below 152 mm usually are called “thin” concrete overlays, while concrete pavements thinner than 102 mm are called “ultra-thin” concrete overlays (Khazanovich, Tompkins 2017; Cole 1997; TxDOT 2018).

Two layer porous concrete pavement is solution ensuring durable low noise pavement performance. The wearing layer consists of finer aggregates and lower amount of air voids while the bottom layer contains courser aggregates and higher amount of air voids. The purpose of wearing lower amount of the air voids and smaller aggregate particles is to avoid clogging and ravelling. The air voids

in the wearing and bottom layers are interconnected to assure the water drainability. Moreover, air flow, which is squeezed by the rolling tyres, due high amount of the voids is absorbed and noise emission is reduced. Two layer porous concrete pavement involves the advantages of one layer porous concrete pavements and thin overlays (Liu et al. 2016; PIARC 2016; Rens 2015).

Main advantage of concrete pavements is durability and bearing capacity, but increase in durability means trade-offs in other properties such as tyre/road noise if compared to traditional Stone Mastic Asphalt (SMA) pavements. Practice shows that noise levels of traditional concrete pavements are much higher than asphalt pavements due to dense surface texture, high stiffness, and lack of surface porosity. Therefore, special attention has to be given to PCP surface texture optimisation.

Pavement surface characteristics as friction or noise reduction depends on surface characteristics (Smith, Snyder 2018). There are determined exact ranges of the texture wavelengths, which have the effect on the noise reduction, rolling resistance and friction characteristics. These texture regions are characterized by the texture wavelength λ [mm] of the pavement surface inequality (Morgan 2006):

- microtexture: $\lambda < 0.5$ mm;
- macrotecture: $0.5 < \lambda < 50$ mm;
- megatecture: $50 < \lambda < 500$ mm;
- roughness: $\lambda > 500$ mm.

Tyre/road interaction is a complex mechanism (Figure 2), which is induced by a lot of effecting factors bound-

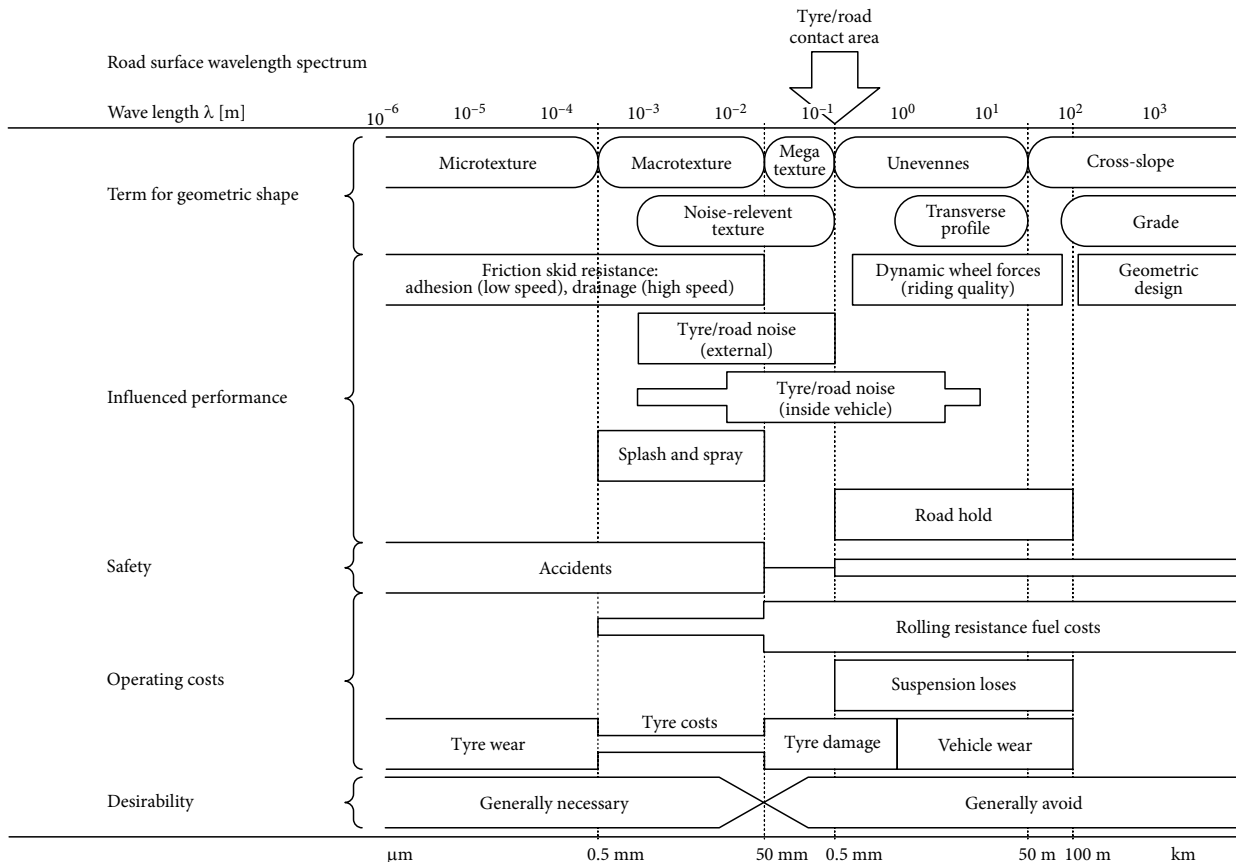


Figure 2. The effect of texture wavelength on tyre/road interaction (PIARC 2016)

ed by (Bendtsen, Andersen 2005; Sandberg, Ejsmont 2002; Morgan 2006; Kane *et al.* 2009; Descornet 2005): surface parameters (texture depth, aggregate properties, air voids, degradation level); tyre properties; environmental factors (temperature, water on the surface, wind); driving style (type of vehicle, velocity, speeding up). Different tyre/road generation processes that shows up at different frequency ranges and can be classified into vibrational and aerodynamic, depends on mentioned factors. Vibrational noise generation process is related to rolling tyre tread impacts and shocks with pavement surface inequalities and adhesion processes at the tyre/road contact area. These interaction mechanisms case tyre/road noise generation at the lower rate spectrum (less than 1000 Hz) (Plotkin *et al.* 1980). Aerodynamic noise processes are related to the air pumping over the contact area such as flowing air is trapped and compressed in the voids of pavement or tyre tread grooves and after moment is forced out. Noise generation is induced by air pressure and noise increasing mechanisms at the high frequency spectrum (more than 1000 Hz) (Hamet *et al.* 1990; Morgan *et al.* 2003).

Road surface characteristics are key element in optimising tyre/road noise generation. The most promising techniques of road surface characteristics optimisation for noise reduction are texture optimisation (to reduce noise in low frequency range) and increase of porosity (to reduce noise in high frequency range). From the combined porosity and texture optimisation to achieve noise reduction approach, road surfaces can be assorted to dense pavements (4...9% air void content), semi-dense (10...14% air void content), semi-porous (15...19% air void content) and porous (>19% air void content) as given in Figure 3 (Beckenbauer 2011).

Concrete pavement texture optimisation is limited because of a standard dense concrete pavement structure, therefore the potential to variate noise reduction by using porosity modification techniques is not as good as for asphalt mixtures. Nevertheless, there are few concrete pavement solutions that has porous structure.

To reduce tyre vibration caused noise generation processes pavement texture must be optimised, which

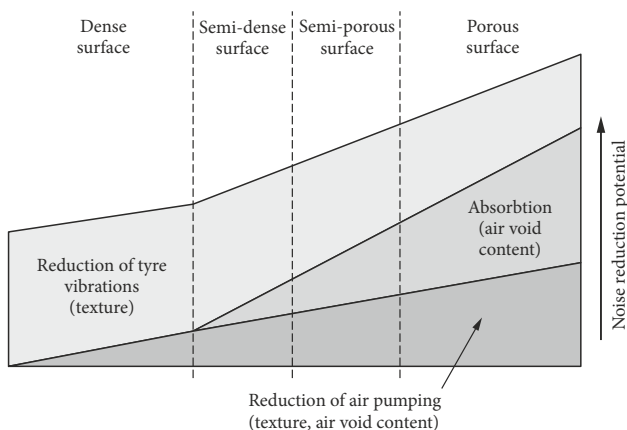


Figure 3. Noise reduction potential depending on the surface type (Beckenbauer 2011)

for concrete pavements are often linked with the texture shape and orientation. Texture orientation can be managed by selecting a texture formation technique, for example transverse concrete pavement texture provides higher skid resistance and better drainage but produces high noise levels comparing with other texture formation techniques (Parnell, Samuels 2006). Random transverse, skewed random transfer and longitudinal exhibit higher surface friction and lower tyre/road noise as compared to other tining configurations (Kuemmel *et al.* 2000).

Only from noise perspective, longitudinal texture would be preferred as it can provide similar escape channels for the trapped air, while significantly reducing tyre radial vibration but at the same time such texture comprises risk for skid resistance during heavy rain conditions as there are no escape channels for water lateral runoff (Sandberg, Ejsmont 2002).

There are quite a few surface texturing methods for concrete roads (Figure 4). Each of the method can provide advantages and disadvantages depending on the expected performance and construction location (Hall *et al.* 2009; Anderson *et al.* 2013; Gardziejczyk, Gierasimiuk 2018; Cackler *et al.* 2006):

- **Plastic Brushing/Brooming.** Texture is created using finishing broom in transverse or longitudinal direction. This method is easy and suitable for low volume roads, because the formed macrotexture is relatively small resulting in lower friction at higher speeds and likeliness to wear out rapidly;
- **Transverse and Longitudinal Dragging.** Texture is formed by dragging moistened burlap material across the surface of pavement. This method is easy to apply and cost-efficient, noise levels are quieter than transverse tining but friction is lower than transverse tining and texture wears off more rapidly;
- **Transverse and Longitudinal Tining.** Surface texture is achieved by mechanical device with metal rake that moves transversely or longitudinally to fresh concrete surface. The surface obtained by this method is durable, has very good impact on skid resistance and can reduce hydroplaning, because longitudinal or transverse grooves allows to flow water from under tyres;
- **Longitudinal Diamond Grinding.** Surface texture is obtained by removing a thin layer of hardened concrete pavement using nearly spaced diamond saw blades. This technology provides smooth pavement surface with high friction. Method significantly increase macrotexture, reduce tyre/road noise and improve initial friction. However, this technology does not fix concrete degradation caused by reactive aggregate, cracking or freeze-thaw cycles;
- **Transverse and Longitudinal Grooving.** Method is applied by sawing grooves on a cured surface as a mean to enhance macrotexture and reduce hydroplaning. Longitudinal grooving can be finished rapidly with only a single lane interruption while transverse is slower and more expensive. Method increases macrotexture and skid resistance of a low-texture

surface. Longitudinal grooving does not ensure water flow to the pavement shoulder;

- **Next Generation Concrete Surface (NGCS).** This method differs from conventional diamond grinding in that thin layer of the surface is ground with diamond blades to remove all macrotexture and megatexture. An additional step is added to construct longitudinal grooves to provide macrotexture. A smoother surface with a less positive or upward texture results in a lower overall noise level, while the grooves increase resistance to hydroplaning by moving water out of the tyre contact patch area. Concrete pavement surface obtained by this technology is defined as one of the quietest concrete surface (only porous concrete surface is quieter) (Beeldens, Rens 2017; Scofield 2017);
- **Exposed Aggregate Concrete (EAC).** It is a concrete pavement surface exposure technology, where retarder is sprayed on the fresh concrete surface, after few hours not hardened mortar is brushed or washed out and coarse aggregates become exposed. EAC surface is similar to SMA surface. This technology provides initial and long-term tyre/road noise reduction, suitable macro-texture for drainage, excellent friction;
- **Porous Concrete.** Porous concrete is special concrete mixture consisting of coarse aggregates, cement, additives and water. Usually porous concrete contains 15...25% air voids and typical design strength is more than 4.5 MPa (Nakahara et al. 2004; Beeldens et al. 2004). Porous concrete pavements provide good splash and spray characteristics, good friction and noise characteristics as a result of their absorptive properties. However, porous concrete surfaces tend to clog and requires special maintenance actions;
- **Shot-Abrading.** Technology is based on using steel abrasive materials in shotblasting equipment to

abrade pavement surface. This technology is generally used to restore surface texture and increase macrotexture related to friction;

- **High Friction Surface Treatment (HFST).** HFST technology is based on the use of the highest quality aggregates and epoxy resins for pavement surface treatment. A greater surface friction is achieved using this technique (Li et al. 2017b). This technique is very promising when PCP slabs are manufactured in the factory.

Scofield (2016) determined that transverse tining provides 103...110 dBA, longitudinal tining provides 101...106 dBA, conventional diamond grinding provides 100...104 dBA and NGCS provides 99...102 dBA, measured by On Board Sound Intensity (OBSI) method. Belgium experience shows that NGCS pavement decrease noise emission up to 6 dBA comparing to existing concrete pavement. Germany experience shows that diamond grinding provides 94.9 dBA noise emission measured by Close ProXimity (CPX) method (Beeldens, Rens 2017).

Among the mentioned texturing techniques, only EAC and porous concrete type of concrete surfaces can be named as noise reducing, therefore further assessment is provided only for these above mentioned types of concrete pavements.

The primary purpose of EAC solution is to ensure durability and friction of road pavement (especially at high speeds) (Wasilewska et al. 2018). There is also a possibility to reduce tyre/road noise levels if EAC pavement is designed with a focus on tyre/road noise reduction. Balancing different road surface properties in EAC pavements can be achieved with two layer EAC pavement system (Rens 2015):

- to achieve good skid resistance and the optimum macrotexture, the range of coarse aggregates particles size should be from 4 to 8 mm and Polished Stone

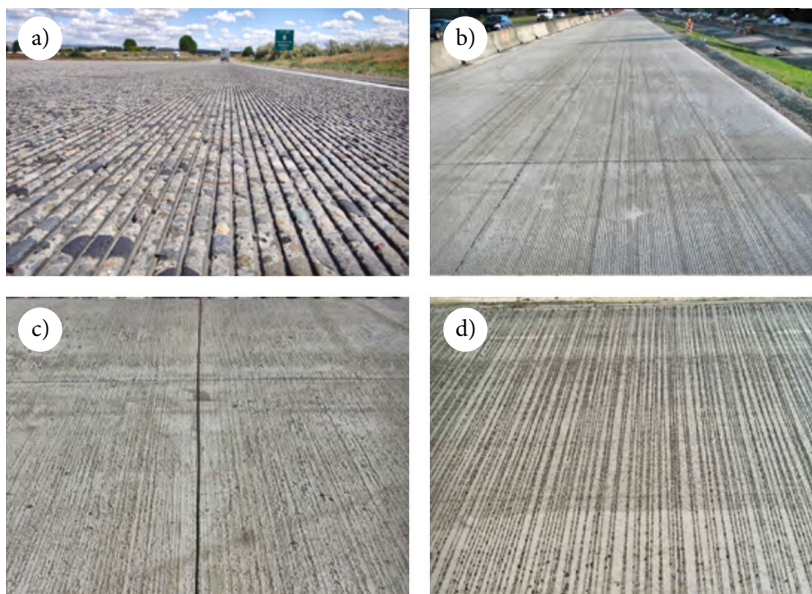


Figure 4. Different texturing methods: a – NGCS; b – longitudinal tining; c – carpet drag; d – transverse tining (Anderson et al. 2013)

Value (PSV) should be at least 55 to provide good microtexture;

- to reduce price, the highest quality aggregates are only used in the wearing layer when the base layer can be installed from normal road concrete (Haberl, Litzka 2006);
- to reduce the tyre/road noise level, for the wearing layer EAC the maximum aggregate particle size should be 8 mm, while the maximum aggregate particle size for the base layer concrete can be even 32 mm. The limitation of the maximum aggregate particles size in wearing layer concrete reduces noise level about 2 dBA comparing with conventional concrete pavements. Additionally, EAC pavements can retain its acoustic and structural durability for 20...30 years without considerable increase in noise levels (Rens 2015; Van Keulen, Duškov 2005);
- to assure frost resistance of the concrete pavement, air entraining agents should be incorporated in the mixture. This additive forms micro air voids in the concrete, which improves durability of the concrete, especially when concrete exposes to moisture during freezing/thawing period. Moreover, water/cement ratio should be below 0.45 and maximum air content should be limited considering the maximum aggregate particle size (when maximum aggregate particle size is 14 mm, air void content <4%; when maximum aggregate size is 8 mm, air void content <5%).

EAC is constructed in two layers system: when maximum aggregate particle size in the range from 8 to 16 mm, the thickness of the wearing layer commonly should be 38...70 mm. When wearing layer is constructed, concrete hardening retarder is sprayed on the surface, after few hours not hardened surface is brushed or washed out (Gardziejczyk, Gierasimiuk 2018). There is necessary to have huge experience to achieve designated texture depth. It is recommended to practice in trial section before (Tompkins *et al.* 2010). The recommended texture depth of EAC surface is 0.9 mm (Gardziejczyk, Gierasimiuk 2018). The 25 cm² square test (Figure 5) to calculate the number of exposed aggregate peaks should be performed – value of aggregate peaks should be 55 (Tompkins *et al.* 2010). EAC surface with 22 peaks in 25 cm²

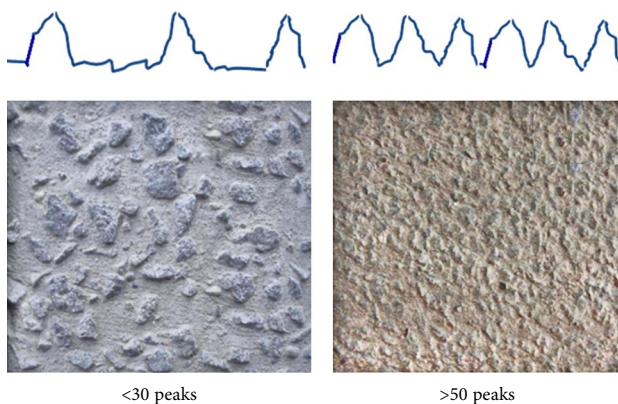


Figure 5. EAC surface textures (Höller 2017)

is inhomogenous, noisy (SPB noise level 84.7 dBA, while surface with 52 peaks is homogenous, silent (SPB noise level 82.4 dBA (Höller 2017). Skarabis and Stöckert (2015) determined that noise emission measured by CPX method is 97.2 dBA. EAC pavement provides 2 dBA noise reduction comparing to conventional pavement surface (Altreuther, Männel 2016).

In Austria the concrete pavements usually are constructed in two layers system, where the wearing layer of EAC is 3...4 cm thick. EAC contains at least 70% coarse aggregate fraction from 4 to 8 mm and about 30% of fine sand. Surface texture depth determined by sand patch test should be from 0.7 to 0.9 mm. It is recommended to use higher cement content (about 450 kg/m³), air entraining agent and plasticizer. These additives allows to achieve a low water/cement ratio and high strength. Following above mentioned recommendations, fine, rough and noise reducing concrete pavement texture is achieved (Hendrikx 1998).

Belgium experience shows that EAC pavement with maximum aggregate particle size 6.3 mm can provide 98.0 dBA noise emission measured by CPX method while SMA surface provides 98.7 dBA (Beeldens, Rens 2017). Wasilewska *et al.* (2018) determined that EAC pavement containing about 50% coarse aggregate >4 mm with the highest PSV showed the best friction results.

Porous concrete pavement can offer good acoustical properties for the pavement at the same time maintain good frictional characteristics and durability comparing with asphalt pavements (Kuemmel *et al.* 2000). However, new problems occur with porous concrete surfaces. Porous pavement texture tends to clog with time resulting in increasing noise levels. Therefore, appropriate maintenance strategy and regular cleaning must be organised for porous concrete pavements. Lack of timely cleaning may also lead to faster pavement surface deterioration in winter due to freeze/thaw cycles. A good example of novel porous concrete solution is *ModieSlab* (Descornet, Goubert 2006; PIARC 2016), which is porous concrete system created in the Netherlands especially for noise decreasing. The wearing layer is with smaller aggregate size to act as filter to reduce clogging by not allowing dust and dirt to get into the base layer. At the same time smaller aggregate size of wearing layer concrete provides a smoother and optimised texture, which is important for tyre/road noise generation processes induced by tyre vibrations. The base layer of *ModieSlab* concrete system is constructed from coarse aggregate with larger air void content that allowing to absorb and dissipate sound waves that pas through the wearing layer. Research shows that *ModieSlab* double layer porous concrete systems allows to reduce noise from 6 to 7 dBA comparing to a dense-graded asphalt mixture. Additionally, high porosity of *ModieSlab* pavement ensures good drainage properties and, therefore, reduced splash and spray effect and improved wet friction. Other porous concrete pavement problem is resistance to freezing and thawing. Cementitious and polymer additives in the system ensures sufficient film covering the aggregates

surface and ensures adhesion between the aggregates. Therefore durability of porous concrete pavement could be improved using polymer additives with higher cement content (Cackler *et al.* 2006).

Another potential option to optimise PCP surface texture is to use composite pavement approach, where the slab is constructed of both asphalt and concrete materials. The idea of composite pavement is to use bottom part of a slab constructed of a concrete material to ensure the pavement is stiff and wear resistance while to use upper part of a slab constructed of asphalt materials to ensure advantages of asphalt pavement surface texture (e.g., reduce noise, rolling resistance, increase skid resistance) (Choi 2011).

With the respect to tyre/road noise reduction, another very important element of PCP is joints between different slabs and on bridges. Some studies reported that noise can increase around 5...10 dBA when a vehicle travels on joints. Therefore, the next stage of PCP development should be focused on silent joints design.

To sum up, transversely brushed finishing is still a good compromise for roads, where speed limit is below 70 km/h. However, the most common surface finishing technique, used in Europe is EAC with maximum aggregate size up to 8 mm. EAC pavement are very popular in Austria, Germany, Czech Republic, Poland, Belgium and the Netherlands. Other concrete pavement surface finishing technologies, which can be considered for the noise reduction are longitudinal tining, micro-milling, diamond grinding and the NGCS (Rens 2015). To obtain the highest noise reduction effect (noise emission less than 99/100 dBA), techniques as EAC and porous concrete, need to be developed (Cackler *et al.* 2006).

2. Slab surface texture element theoretical design

The most important surface characteristics, which influence tyre/road noise emission are pavement texture, porosity and stiffness. Pavement texture direction (longitudinal or transverse) and texture orientation (positive or negative) has the effect on noise reduction: longitudinally textured pavement surfaces are quieter comparing to transversely textured pavement surfaces (Izevbekhai 2016). Negative surface texture provides lower tyre vibrations comparing to positive textured surfaces and this effect depends on aggregates particles size (Izevbekhai 2016; Rens 2015; Abbott *et al.* 2010). However, pavement surface texture characteristics are significant not just for the noise reduction effect but also to reduce other surface characteristics as splash and spray, drainability, rolling resistance, reflection and provide sufficient friction. It is very important is to find and ensure the proper balance and compatibility between surface characteristics (Vaitkus *et al.* 2018; Abbott *et al.* 2010). Mainly the potential concrete pavement application area has the highest impact on concrete mixture optimization goal – if the traffic is heavy, concrete mixture should provide sufficient strength, if the environmental conditions are severe, concrete mixture should be resistant to environmental impact. Gražulytė *et al.* (2019)

distinguished potential PCP application areas:

- main roads (motorways) and main streets;
- bus lanes and bus stops;
- intersections;
- private roads;
- logistic terminals;
- national roads and less significant streets;
- airfields;
- bicycle and pedestrian paths.

However, the most potential PCP application areas are main roads (motorways) and main streets. Required characteristics of PCP surface mainly depends on application area – if PCP is used for the intersections, logistic terminals or bus stops, where traffic speed is low and loads are high, the main attention should be paid on the durability while texture characteristics are not very important. If PCP is used for the main roads (motorways) and main streets (speed ≥ 80 km/h), where traffic speed and loads are high, the main attention should be paid on durability and surface characteristics. The most important characteristics of main roads (motorways) and main streets pavement surface are (from the most important to the least important) (Gražulytė *et al.* 2019):

- smoothness;
- friction;
- noise reduction;
- drainage;
- durability.

According to literature analysis, porous concrete pavements, EAC pavements and NGCS, obtained by innovative diamond grinding, can offer the best noise reducing effect comparing to other solutions. Porous concrete is more suitable for high speed areas and other areas where good noise reduction, friction and drainability characteristics are required. EAC and NGCS can be applied for all areas, where strength, good noise reduction, friction, durability and macro-texture for drainage characteristics are required.

The most important surface characteristic is of EAC is Mean Texture Depth (MTD) and profile point count. The suggested MTD value for this surface is 0.8...1.0 mm (Gardziejczyk, Gierasimiuk 2018; Tompkins *et al.* 2010). To increase strength and durability, higher cement content (450 kg/m^3), air entraining agent, plasticizer and durable aggregates (PSV50) should be used (Hendrikx 1998). Profile point test helps to ensure an optimal amount of exposed aggregates. This is necessary to ensure proper tyre contact with pavement surface and sufficient space between the tyre and surface for water drainage. If the point count value is too high, sufficient drainage between aggregates will not be ensured. If the point count value is too low, the tyre and surface contact will be too big and noise emission will be too high. According to literature recommendations for EAC surface texture, the appropriate number of aggregate peaks in a specific 25 cm^2 square area should be ≥ 55 , the minimum aggregate PSV should be ≥ 50 and the maximum aggregate size should be ≤ 8 mm to reduce noise level. Moreover, MTD should be 0.8...1.0 mm,

while the optimal macrotexture is when Mean Profile Depth (MPD) is about 1.2 mm (Tompkins *et al.* 2010; Hendrikx 1998; Altreuther, Männel 2016; Gardziejczyk, Gierasimiuk 2018). Skarabis and Stöckert (2015) recommends to use 430 kg/m³ of cement CEM I 42.5 N, 423 kg/m³ of fine sand fraction 0...2, 1277 kg/m³ of coarse aggregate fraction 2...8 and 180 L/m³ of water for EAC manufacturing. It means that EAC should contain 65% of course aggregate, 35% of fine sand and water/cement ratio should be less than 0.42. Wasilewska *et al.* (2018) recommend to use 423 kg/m³ of cement CEM I 42.5 R, 50...70% of coarse aggregate fraction 4...8 ensuring water/cement ratio lower than 0.37. Additionally, air entraining additives and superplasticizers should be used for EAC manufacturing. These characteristics should ensure durable performance of PCP with wearing layer of EAC.

Porous concrete is a type of concrete containing interconnected pores (usually air void content is from 5 to 25% by volume) with typical water permeability rate of ≥ 200 L/min/m² (Sonebi *et al.* 2016; Kováč, Sičáková 2018; Tennis *et al.* 2004). Maximum aggregate size of wearing layer porous concrete should be 8 mm or less (Kováč, Sičáková 2018; Hendrikx 1998). Typical compressive strength of porous concrete is from 3.5 to 28.0 MPa, though 17 MPa is usual (Tennis *et al.* 2004). Acceptable value of flexural strength is 3.5 MPa. In various geographic areas required water/cement ratio is 0.27...0.34 (Sonebi *et al.* 2016; Mahboub *et al.* 2009; Tennis *et al.* 2004; Elliot 2010; Kováč, Sičáková 2018). However, porous concrete with compressive strength around 17 MPa is more suitable for light traffic areas – for highways and other heavy

traffic areas is necessary to use much more stronger porous concrete. Strength and durability of porous concrete can be improved optimizing composition (cement/water ratio, porosity, maximum aggregate particle size) and using additives (e.g., silica fumes, silica powders, superplasticizers, etc.). According to Zhong and Wille (2016), the use of additives and optimization of the composition can improve porous concrete compressive strength up to 174 MPa. Other research showed similar tendencies – gradation optimization and chemical additives improves porous concrete strength up to 61.37 MPa (Li *et al.* 2017a). It means that high strength porous concrete can be used for the most severe traffic conditions ensuring sufficient strength, drainability and noise reduction.

According to the literature and fact that the most potential PCP application areas are highways and streets, algorithm of suitable solutions selection for low noise concrete composition design was created. This algorithm is presented in Figure 6.

According to this algorithm, the most suitable solutions for highways and streets are two-lift pavement with wearing EAC layer and base common concrete layer either multi-layer with two porous concrete layers and base concrete layer. According to literature, EAC is more suitable solution for highways and streets comparing to porous concrete in terms of strength and durability while porous concrete pavement is more effective in terms of noise reduction and drainability. The further experiment will be focused on these two pavement structure solutions. All given requirements for concrete mixtures and components are based on literature analysis.

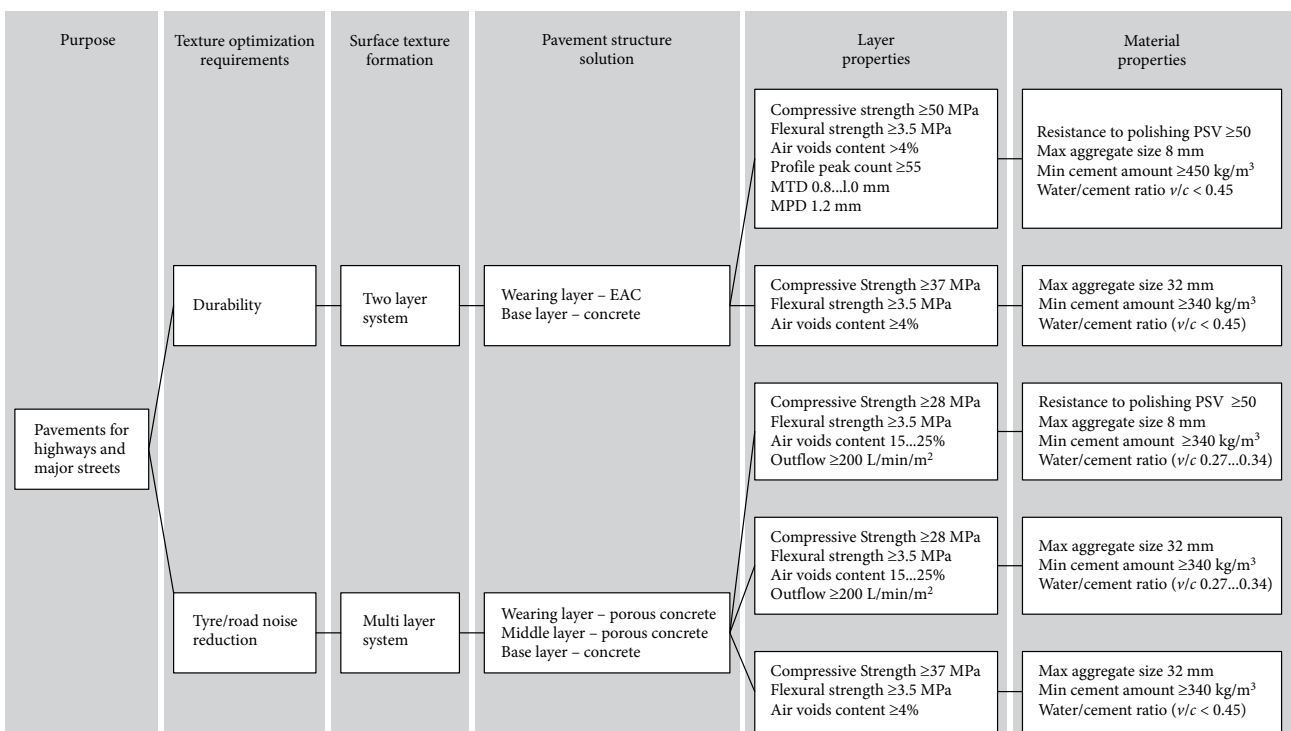


Figure 6. Algorithm of highways and streets low noise concrete selection

3. Plan for further experimental testing

As it explained above, experimental research will be focused on two-lift concrete pavement consisting of wearing layer EAC and base layer from usual concrete either multi-layer system consisting of double porous concrete layer and base layer from usual concrete. Experimental research plan is represented in Figure 7.

The experimental research will consist of 4 stages. At the first stage, EAC, wearing and base layer porous concrete, usual base layer concrete will be designed and tested in the laboratory. These characteristics of wearing layer concrete will be determined:

- compressive and flexural strength after 7 and 28 days;
- resistance to freezing and thawing;
- resistance to abrasion;
- density;
- depth of water penetration;
- MTD;
- MPD;
- profile peak count (only for EAC);
- outflow (only for porous concrete).

These tests are planned to perform on base layer concrete:

- compressive and flexural strength after 7 and 28 days;
- density.

According to laboratory testing results, the optimal composition of each type concrete will be selected. In the second stage slabs will be manufactured using these selected concrete compositions. These characteristics of slabs are planned to determine:

- compressive strength;
- flexural strength;
- density;
- resistance to abrasion;
- sound absorption.

In the third stage optimal composition PCP slabs will be prepared and delivered to partner institute, where texture will be scanned using 3D laser scanner. Obtained results will be analysed and evaluated – Hybrid Road Noise Emission (HyRoNE) model will be used to model texture and predict noise emission of concrete slabs. Moreover, obtained data will be evaluated using tyre/road contact models.

Conclusions and recommendations

Development of PCP concepts using “maintenance by design” approach it is necessary to define desirable functionality and performance indicators. Comprehensive assess-

ment of current and future needs, identification of specific location-based infrastructure performance demands is a first step for successful development of PCP concepts. Predicting functional needs (performance indicators) for future use of PCP is a complex task that requires balancing different surface characteristics, structural performance characteristics and potential needs for slabs improvement, retrofitting or integration with other systems (e.g., utilities, smart communication technologies).

The analysis of existing practice of concrete pavement noise reducing technique showed that EAC and porous concrete are the most effective techniques. Innovative grinding technique – NGCS – has smoother surface and the grooves, which increase resistance to hydroplaning and reduces noise emission. However, more experience using this technique is necessary.

Because of fact that porous concrete pavement durability in high traffic load areas and severe climate conditions still not proven, the composition of porous pavement must be optimised in terms of durability. EAC is the most suitable noise reducing solution for highways and streets wearing layer in terms of durability. To reduce the cost of materials without pavement quality impairing, two-lift paving. This solution can provide quality surface characteristics, reduce materials costs, and consume recycled aggregates.

For wearing layer EAC composition these recommendations are given:

- the highest quality aggregates (PSV ≥ 50), gap-graded gradation, maximum size of aggregates 8 mm;
- higher cement amount (minimum $\geq 420 \text{ kg/m}^3$);
- lower cement/water ratio ($v/c \leq 0.45$).

For wearing layer EAC texture these recommendations are given:

- MPD – 1.2 mm;
- MTD – 0.8...1.0 mm;
- profile peak count ≥ 55 .

For wearing layer porous concrete composition these recommendations are given:

- the highest quality aggregates (PSV ≥ 50), gap-graded gradation, maximum size of aggregates 8 mm;
- higher cement amount (minimum $\geq 340 \text{ kg/m}^3$);
- lower cement/water ratio ($v/c 0.27...0.34$);
- polymer additives should be used.

EAC and porous concrete optimisation using noise prediction models would ensure durable pavement texture with reduced noise and low rolling resistance.



Figure 7. Project experimental research plan

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