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Concrete modular pavement type selection based on application area

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Abstract. Roads and other trafficked areas infrastructure starts to deteriorate as far as it is opened to traffic. Thus, it has to be timely repaired and reconstructed. However, any interruption to traffic by implementing repair and rehabilitation works leads to user's discomfort and traffic congestion. Modular pavements also known as precast concrete pavements can be constructed at night, consequently they eliminate or reduce traffic flow limitation related to repair works. They consist of prefabricated concrete slabs that are transported to the construction site only after the curing period when the desirable concrete strength is achieved and installed on a prepared foundation. Slabs prefabrication in a plant results in better concrete quality, controlled concrete curing conditions, wider period for pavement construction, reduced time before opening to traffic, elimination of early-age failures and material segregation which may occur during concrete or asphalt mixture transportation to the project site and laying. Despite these advantageous, modular pavements are barely used in Europe. In order to enhance the usage of modular pavements in Europe, paper focuses on the identification of the most promising modular pavements application areas and their type selection. The most promising application areas such as motorways and arterial streets were identified on the basis of the conducted survey among high qualified researchers. Low volume roads, private roads, bicycle and pedestrian paths could be included as modular pavements special application areas with slightly different approach.

Keywords: modular pavement, precast concrete pavement, precast prestressed concrete pavement (PPCP), jointed precast concrete pavement (JPCP), application area.

Introduction

Transport infrastructure is not perpetual and need to be timely repaired, rehabilitated and eventually reconstructed. However, any disruption to traffic leads to traffic congestion. The time of lane or road section closure depends on the pavement type and damage severity. For example, 1 km length of concrete pavement in 7.5 m width is constructed and opened to traffic after minimum 94 days (Syed & Sonparote, 2017). While, asphalt pavement is ready to take traffic immediately after construction since curing is not needed unlike concrete pavement. However, asphalt pavements are prone to permanent deformations (rutting and etc.) especially where both hot climate and very high volume of heavy vehicles dominate. Acceleration and braking as well as long-term static loading significantly contributes to the development of permanent deformations (Vaitkus, Vorobjovas, Gražulytė, & Tumavičė, 2014; Vaitkus et al., 2014). Consequently, concrete pavements are preferable in those areas. Otherwise, asphalt pavements have to be repaired and rehabilitated prematurely and as a result traffic congestion is observed.

In the United States conducted feasibility study have shown that daily user delay costs exceed 300 000 Eur per day for 24-hour lane closure (Merritt, Mccullough, Burns, & Schindler, 2000). It results in more than 2 millions Eur per week and 0.1 billion per year. These costs are vastly increasing because of constantly growing traffic volume. According to European Union Road Federation passenger and freight transport from 2000 to 2014 annually grew 0.7% and 0.6%, respectively. Seeking to avoid or at least minimize user delay costs due to pavement repair, rehabilitation or reconstruction, atypical pavements have to be used.

One of them is concrete modular pavement also known as precast concrete pavement (PCP). This pavement is superior to typical asphalt and concrete pavements because both resistance to permanent deformation and fast construction (repair) are guaranteed. Typically, PCP is constructed and repaired at night (from about 8 p.m. up to about 6 a.m.). Thus, traffic congestion related to pavement repair, rehabilitation or reconstruction is reduced to minimum. PCP consists of prefabricated concrete slabs that are transported to the project site only after the curing period when the desirable concrete strength is achieved and installed on a prepared foundation. Slabs prefabrication in a plant results in better concrete quality, controlled concrete curing conditions, wider period for pavement construction, reduced time before opening to traffic, elimination of early-age failures and material segregation which may happen during concrete or asphalt mixture transportation to the project site and laying (Merritt, McCullough, & Burns, 2002; Smith & Snyder, 2017; Tayabji, Ye, & Buch, 2012a, 2012b; Tomek, 2017). Furthermore, correctly installed PCP is durable and may last for 30-35 years and even more.

The application of PCP has been become progressively popular in the United States during the last two decades. Canada, Indonesia, Japan, Russia, France and the Netherlands have also developed and implemented a concept of PCP (Tayabji, 2010). It is noticed that PCP is used in various areas (e.g. highways, airfields, urban areas and etc.). However, it is not clear in which application areas PCPs are the most suitable considering a need to minimize the disruption to traffic, traffic (especially heavy vehicles) volume, issues related to typical pavement performance (e.g. development of permanent deformations) and durability. Consequently, this paper focuses on the identification of the most promising application areas of PCP and on the PCP type selection depending on the application area. As a result, an algorithm of PCP type selection considering application area was created and is given in this paper. The use of this algorithm enables rational application of PCP and results in the highest economical and social benefit.

Concrete modular pavement types

Transport infrastructure is not perpetual and need to be timely repaired, rehabilitated and eventually reconstructed. However, any disruption to traffic leads to traffic congestion. The time of lane or road section closure depends on the pavement type and damage severity. For example, 1 km length of concrete pavement in 7.5 m width is constructed and opened to traffic after minimum 94 days (Syed & Sonparote, 2017). While, asphalt pavement is ready to take traffic immediately

Researchers are constantly improving the existing PCP technologies and now in the market exist more than 15 different PCP systems developed on the basis of on one type of three main PCP types. These main types of PCP are:

- precast prestressed concrete pavements (PPCP) with transversely prestressed concrete panels;
- jointed precast concrete pavements (JPCP) with either reinforced or prestressed concrete slabs;
- incrementally connected precast concrete pavements (ICPCP) with either reinforced or prestressed concrete slabs.

PPCP consists of wide and quite short panels, which are post-tensioned together in the longitudinal direction on the project site to form an effectively jointless slab. It is worth to mention that each panel is prestressed in the transverse direction during fabrication. The width of panel in PPCP is usually equal to full width of all traffic lanes and shoulders (if necessary), while length varies from 2.5 m to 4.3 m. Slab length depends on what length and how many panels are post-tensioned together. An effectively jointless length can be up to 99 m. In general, three systems of PPCP exist depending on the stressing: central stressing, end stressing at surface and end stressing at vertical joint face (Merritt et al., 2000, 2002; Merritt, McCullough, & Burns, 2005; Merritt, Rogers, & Rasmussen, 2008; Mishra, French, & Sakkal, 2013). Each system is described in details by Vaitkus, Gražulytė, Kleizienė, Vorobjovas, and Šernas (2019).

JPCP consists of reinforced or prestressed slabs that are connected together on the project site using different systems of dowel bars and slots. Since slabs of JPCP are not post-tensioned together in the longitudinal direction unlike panels of PPCP, they expand and contract at every joint. Thus, load transfer between adjacent slabs have to be ensured. Different systems of dowel bars and slots are used for this purpose. Typically, round, smooth, epoxy coated steel dowel bars or other systems (devices) are embedded in one side of the slab while in the other side at locations that match the dowel bars are formed slots. Fast-setting grout is used to fill these slots and the gap between adjacent slabs. The width of the slab usually is equal to the width of one traffic lane and the length varies from 1.8 m to 5.5 m. Slabs are reinforced or prestressed during fabrication (in a plant). Researchers have developed at least 11 systems of PCP based on the JPCP concept. Each system is described in details by Vaitkus et al. (2019). The main differences between them are the techniques to connect the adjacent slabs in order to get more efficient load transfer (>90%) and to level the slabs.

ICPCP consists of a series of either reinforced or prestressed slabs that are connected together using deformed dowel bars to achieve a section from 18.3 m to 30.5 m. Slabs are reinforced or prestressed during fabrication (in a plant). The width of each slab is equal to the width of one traffic lane and the length varies from 4.6 m to 9.1 m. Deformed dowel bars are used to lock the connected joint and to enable the load transfer across joints. This connection technique leads to a narrower expansion joints between connected slabs. Active joints are constructed only between sections (Smith & Snyder, 2017).

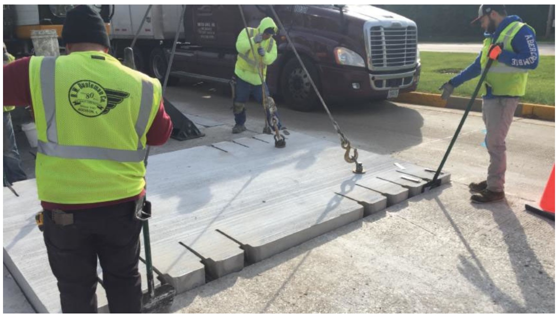
Each precast slab (panel) independently of PCP type is either reinforced (except panels for PPCP) or prestressed during slab (panel) fabrication. Reinforcement of slabs is used to ensure that slabs will not crack during handling and transportation. For this purpose, a double mat of epoxy-coated reinforcement that constitutes at least 0.2% of the slab cross-sectional area in transverse and longitudinal directions is used. It is important to note that reinforcement does not lead to thinner precast slabs as prestressing unless they are designed as reinforced concrete pavement (Smith & Snyder, 2017; Tayabji, Ye, & Buch, 2013).

Slabs (panels) are prestressed either by pre-tensioning in the transverse direction during slab (panel) fabrication or by post-tensioning in the longitudinal direction during PPCP construction. Prestressed slabs (panels) withstand higher stresses than typical concrete pavements since some stresses are compensated by imposed internal stress to concrete during pre-tensioning or post-tensioning. As a result, thinner slabs (panels) can be fabricated. The thickness may be effectively reduced about 75−100 mm (Tayabji et al., 2012a, 2012b). However, Merritt et al. (2000) recommend to design slabs (panels) in thickness that is not less than 50−60% of the thickness used for cast-in-place concrete pavement. In practice pre-tensioning is more popular form of prestressing than post-tensioning (Smith & Snyder, 2017; Tayabji et al., 2013). Prestressing as well as reinforcement ensures that all prematurely developed cracks are held tight and slabs (panels) perform well and do not deteriorate faster.

All three PCP types are used to construct new concrete pavements (continuous construction) as well as to repair existing cast-in-place or precast concrete pavements (intermittent repair). Intermittent repair is carried out at specific areas where part of the pavement or slabs have failed. Two types of intermittent repairs exist: full-slab replacement of single or several failed slabs and full-depth repairs of deteriorated joints or cracking. Independently of repair type, it is always done in full-lane width (Smith & Snyder, 2017; Tayabji et al., 2013). In Figure 1 are given examples of PCP types.

a) PPCP continuous construction

b) JPCP continuous construction



c) JPCP intermittent repair

d) ModieSlab system (JPCP)

Figure 1. Examples of PCP types

Application areas of concrete modular pavements

From the literature, is known that PCP may be used for roads, aprons, taxiways, tunnels, ports, streets, industrial parks, bus lanes and bus stops as well as at bridge approaches and intersection (de Larrard, Sedran, & Balay, 2013; Merritt et al., 2002, 2005, 2008; Qu et al., 2017; Tayabji, 2010; Tayabji & Ye, 2014; Tayabji et al., 2012a, 2012b). However, not in all mentioned application areas and not in all cases PCP is a superior solution to typical asphalt and concrete pavements because there is a lack of PCP design and construction practice, slabs (panels) prefabrication causes additional cost (unique frames have to be produced), construction of curved sections becomes an issue and etc. Therefore, every time selecting pavement type, these aspects have to be considered:

- a need level to minimize the disruption to traffic;
- traffic volume (especially heavy vehicles volume);
- issues related to typical pavement performance (e.g. development of permanent deformations);
- pavement durability.

Despite PCP popularity in the United States and some experimental implementation of PCP in Europe, PCP application areas are still not prioritized. Seeking to significantly increase the use of PCP in Europe, there is a need to identify the application areas for which PCPs are the most suitable and lead to the highest economic and social benefit. Consequently, a survey among high-qualified researchers was conducted.

A questionnaire on the most promising PCP application areas was composed of seven application areas: motorways and arterial streets, aprons and taxiways, logistic terminals, roads (except motorways), streets (except arterial streets), low volume and private roads, bicycle and pedestrian paths. Researchers had to evaluate each application area from 0 to 3 according to Table 1. The results are given in Figure 2.

The survey revealed that the most promising application area of PCP is motorways and arterial streets. Motorways and arterial streets are the most important part of roads and streets network. Every day thousands of vehicles, especially heavy vehicles, use them. Any disruption to traffic in such heavily trafficked areas results in traffic congestions and millions euros are lost because of user delay costs. Consequently, these roads and streets have to be passable 24-hours and any disruption to traffic has to be minimized. On roads and streets where traffic volume is moderate, PCP is slightly suitable since the benefit of its construction does not compensate the issues related to slab fabrication and pavement construction. The second most promising application areas of PCP according to the survey are aprons and taxiways in airports as well as logistic terminals. Aprons, taxiways and logistic terminals closure is limited. Besides, there dominate extremely heavy loads (aircrafts, containers, reach stackers, cranes and etc.) which usually lead to permanent deformations if asphalt pavement is used. The least promising PCP application areas are low volume roads, private roads and bicycle and pedestrian paths because there traffic is often disrupted without negative effect on traffic flow.

It should be noted that PCP type was not considered in the given ranking (evaluation) of application areas. Evaluation was done focusing mainly on the traffic volume (especially heavy vehicles volume) in each area. The more trafficked area, the more suitable PCP because there exist a higher need to minimize disruption to traffic and eliminate traffic congestions. In addition to this, pavement type (asphalt mixture, cast-in-place concrete and precast concrete slab) was considered in each application area. If permanent deformation may appear or higher quality concrete is required, PCP usage is advantageous.

Table 1. Evaluation methodology of PCP suitability for application area

	Level of PCP suitability			
	most suitable	moderate suitable	slightly suitable	suitability is questionable
Points	3	2	1	0

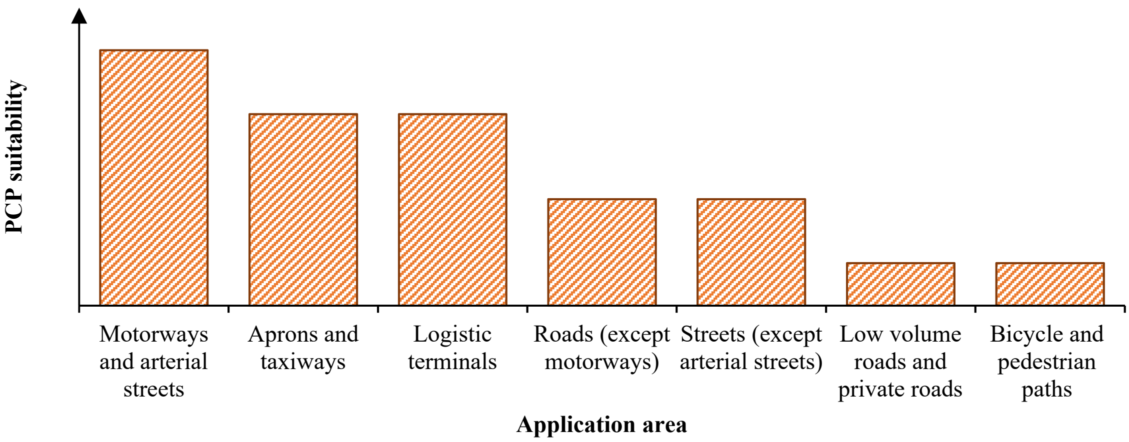


Figure 2. PCP suitability for application area on the basis of the conducted survey among high qualified researchers

Algorithm for PCP type selection

Not all PCP types may be used in each application area because panels/slabs prefabricated for different PCP types significantly differ in geometry (especially width). Panels/slabs that are prefabricated in full width of two and more traffic lanes are not suitable for areas where traffic is not organized in lanes (e.g. aprons, ports, logistic terminals). Besides, at horizontal and vertical curves as well as at intersections non-planer (warped) panels/slabs are required and it may become an issue especially if panels/slabs are very wide or have to be posttensioned. A PCP type selection considering application area is the first step in successful PCP design, panels/slabs prefabrication and construction. An appropriate PCP type for specific application area eliminates issues related to longitudinal and transverse (active) joints (number of joints), non-planer (warped) panel/slab prefabrication, posttensioning and etc. As a result, an algorithm for PCP type selection considering application area was created and is given in Figure 3.

On roads and streets all types of PCP are used. PPCP usage eliminates longitudinal joints because panels are prefabricated in full width of all traffic lanes. They are transversely prestressed, thus thinner panels are produced. However, PPCP usage on roads and streets with varying cross slopes is not known to date. PPCP application at curved sections is possible, but non-planer (warped) panels have to be prefabricated, the minimum curve radius that can be posttensioned have to be determined and the impact of panel warping on stress loss due to tendon or duct friction during the posttensioning have to be considered (Tayabji et al., 2012a, 2012b). If PPCP projects have curved sections, but cross slopes are constant, the use of ICPCP approach is recommended. In this case, prestressed panels are rigidly connected at the panel transverse joints or shorter PPCP along the curved sections is constructed (Tayabji et al., 2012a, 2012b). Using JPCP, slabs width is equal to the width of one traffic lane, thus non-planer (warped) slabs are easily produced and assembled on the site, but due to much lower width than panels of PPCP, longitudinal joints have to be constructed. For both JPCP and ICPCP slabs are produced either reinforced or prestressed. At aprons and logistic terminals traffic is not organized in lanes. Consequently, PPCP is not suitable and there are constructed JPCP or ICPCP with either prestressed or reinforced slabs. Engineers have the highest experience in design, prefabrication and construction of JPCP. It suits all application areas. While ICPCP was developed under Strategic Highway Research Program 2 Project R05 "Modular Pavement Technology" in 2012 and have not been widely used, yet. For low volume roads and private roads as well as for bicycle and pedestrian paths JPCP is the most suitable PCP type. Since those pavements have to be easily constructed and they are exposed to light loads, prestressing is not necessary and even a plain concrete slab can be fabricated.

Then appropriate PCP type is selected, pavement is designed considering climate conditions, loading conditions, concrete mixture properties, prestressing or reinforcement, slab geometry (especially thickness), systems of dowel bars and slots or other load transfer systems, pavement surface texture and etc. The highest and the lowest day and year temperatures are the most important input data to describe climate conditions, since concrete slabs curl and warp due to temperature gradient between the top and bottom of slab. Type of loading, gross weight, contact load, load frequency, load-pavement contact area, contact pressure and load data forecasting (history) have to be defined in terms of loading conditions irrespective of application area. Slab thickness and concrete mixture properties are crucial factors leading to pavement bearing capacity. In addition to this, joints have to ensure appropriate load transfer between adjacent slabs. Tayabji et al. (2012a, 2012b) concluded that in highly trafficked areas load transfer has to be at least 90%. Reduction in noise, induced by interaction between tyre and pavement, and carbon dioxide emissions, generated by vehicles, keeping high skid resistance are three main aspects on which road researchers, designers and even road authorities are focusing. Appropriately designed pavement surface absorbs noise, reduces rolling resistance and ensures high skid resistance at the same time. It leads to noise and carbon dioxide emissions mitigation. It should be noted that consideration of pavement surface texture in PCP design depends on application area. In logistic terminals PCP may be designed without focusing on pavement surface texture in terms of reduction in noise and rolling resistance since there vehicles move slowly and traffic volume is significantly lower than on roads. Contrary to logistic terminals, PCPs for motorways and arterial streets have to incorporate pavement surface texture that reduces noise and carbon dioxide emissions. Skid resistance has to be ensured in all application areas.

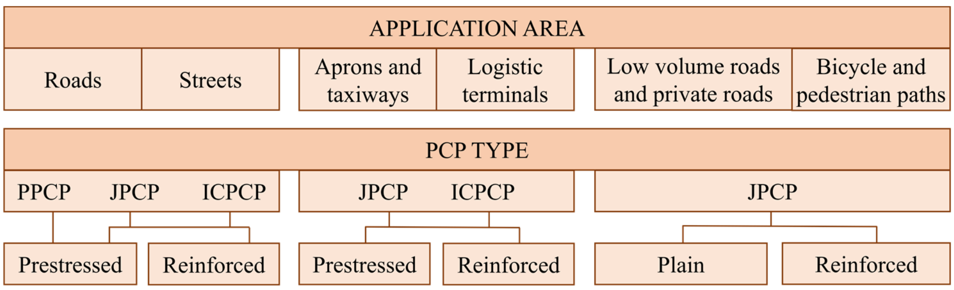


Figure 3. Algorithm for PCP type selection considering application area

Conclusions

More than 15 different PCP systems developed on the basis of PPCP, JPCJ and ICPCP are used for either rehabilitation or for both rehabilitation and continuous construction in the United States, Canada, Indonesia, Japan, Russia, France and the Netherlands. In those countries, PCP have been successfully applied on roads, streets, aprons, taxiways, tunnels, ports, industrial parks, bus lanes and bus stops as well as at bridge approaches and intersection.

The conducted survey among high qualified road researchers revealed that motorways and arterial streets are the most promising PCP application areas giving the highest economic and social benefit in terms of traffic volume (especially heavy vehicles volume) and pavement type (PCP type was not considered in the survey). PCP usage at aprons, taxiways and logistic terminals seems also beneficial. Whereas PCP suitability for low volume roads, private roads and bicycle and pedestrian paths should be considered as special application areas with slightly different approach. This ranking will help to enhance PCP usage in Europe by focusing only on the most promising application areas.

An algorithm for PCP type selection considering application area simplifies PCP type selection and is useful guidelines for inexperienced designers and engineers. On roads and streets all types of PCP may be used while at aprons and logistic terminals PPCP is not applied since panels width of PPCP is typically equal to full width of all traffic lanes and there traffic is not organized in lanes. JPCP is superior to PPCP and ICPCP because it suits all application areas and engineers have the highest experience in its design, prefabrication and construction.

PCP has to be designed considering climate and loading conditions, concrete mixture properties, prestressing or reinforcement, slab geometry (especially thickness), systems of dowel bars and slots or other load transfer systems, pavement surface texture and etc. Pavement surface texture is a crucial factor reducing tyre-pavement noise and rolling resistance, and keeping high skid resistance simultaneously. Consideration of pavement surface texture in PCP design mitigating noise and carbon dioxide emissions is vital for motorways and arterial streets. As for logistic terminals and other low speed areas surface texture is not a primary feature.

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