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### ► **To cite this version:**

Thierry Sedran, Eric Gennesseaux, Julien Waligora, Philippe Klein, Mai Lan Nguyen, et al.. Development of a Permeable Removable Urban Pavement. 14th International Symposium on Concrete Roads, Jun 2023, Krakow, Poland. <hal-04354455>

**HAL Id: hal-04354455**

**<https://hal.science/hal-04354455v1>**

Submitted on 21 Dec 2023

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## DEVELOPMENT OF A PERMEABLE REMOVABLE URBAN PAVEMENT

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### ABSTRACT

Modular concrete pavements have been developed during the last years, for urban applications. Within this family of pavements, Eiffel University proposed the concept of removable urban pavement (RUP) whose purpose is to ensure an easy and fast access to the sub-base and to the networks underneath, for maintenance or extension needs.

Two RUP prototypes were tested during more than 10 years: one made of independent concrete slabs and the other with interconnected slabs. The second concept proved to be more resilient to traffic. Based on this experience, Eiffel University, in collaboration with Eiffage Infrastructures and Alkern companies, has been developing since 2017 a new type of RUP, which is also permitting high water drainability during rainfall as this property is becoming more and more pregnant in a context of climate change and violent climatic events.

The present paper first describes the concept of permeable RUP and the consequent design of concrete slabs in terms of mechanical and hydraulic behavior. The developed slabs are multi-layered: the top layer is made of porous concrete, while the base layer is made of plain concrete to ensure the durability of the structure.

After laboratory studies, a 3x9 m<sup>2</sup> prototype made of 39 slabs was submitted to 200 000 wheel passages on the accelerated traffic simulator available at the Eiffel University. Based on the good behavior obtained, a 200 m<sup>2</sup> demonstrator was constructed in Nantes Metropole in 2022 and submitted to real traffic. The paper describes the different development steps.

### KEY WORDS

Concrete slabs, porous concrete, excavatable cement treated aggregates, urban pavement

## 1. INTRODUCTION

Who has not faced a urban road in perfect condition in which a trench will be rapidly opened for network maintenance or connection needs? These works regularly leave unaesthetic and uncomfortable scars on the surface of pavements. It is to propose an innovative solution to this observation, that the concept of Removable Urban Pavements (RUP) was proposed. It is made up of precast concrete hexagonal slabs that can be quickly and easily dismantled and reassembled. These slabs are laid, via a granular bed, on an innovative material consisting of a cement treated aggregate designed to be easily excavated with a mechanical excavator or a manual pick as well (de Larrard et al., 2013). This concept thus allows access to the underlying networks without leaving visible scars on the surface after intervention. The hexagonal shape was chosen because, like the honeycomb, it is one of the rare geometric shapes (along with the triangle and the square /rectangle) which makes it possible to completely pave a flat area, while avoiding sharp angles thus ensuring better mechanical robustness. At the end of a research program led by the LCPC between 2003 and 2008, the results of which are summarized in (de Larrard et al., 2013), (Abdo et al., 2008) and (Collective, 2009), but also on <https://cud.iftstar.fr/>, two prototypes were built. The first, made up of large independent slabs (77 cm edge), was built in 2007 in Saint Aubin les Elbeufs (Figure 1). It had the advantage of being very easy to lay and to dismantle, but slab rocking was tend to appear under heavy vehicle traffic, affecting the life duration of the pavement and the comfort of use.

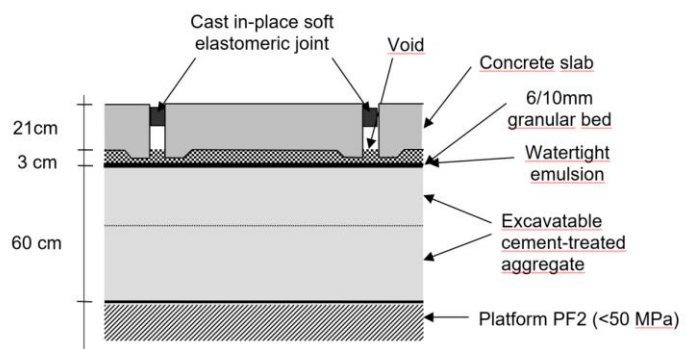


Figure 1: First RUP prototype with independent slabs, Saint Aubin les Elbeufs, 2007

The second prototype, constructed in 2008 at the entrance of a storehouse belonging to Nantes Metropole, corrected this defect (de Larrard et al., 2013), (Sedran et al., 2008). In order to bear the shear forces between slabs linked to road traffic, the slabs are cast with a system of keys on their edges, allowing them to fit into each other (Figure 2). As a result, the slabs can be smaller (46 cm edge), which facilitates their handling. On the other hand, the presence of the keys complicates a little the dismantling-reassembly, which must be done by sliding the slabs, from one of the edges after removal of the side paving stones (Figure 3). A visual evaluation of the prototype as well as a dismantling-assembly operation carried out ten years after its construction confirmed its good mechanical behavior and good evenness, after an estimated traffic of between 40,000 and 60,000 heavy goods vehicles. Noise measurements for low rolling speeds by the CPX method also confirmed that there were no particular noise related to the joints between slabs or to slab rocking and that the whole has a sound level comparable to a wearing course made of a classical medium coarse asphalt layer 0/10mm. These tests thus made it possible to validate the proof of concept of RUP with interlocking slabs.

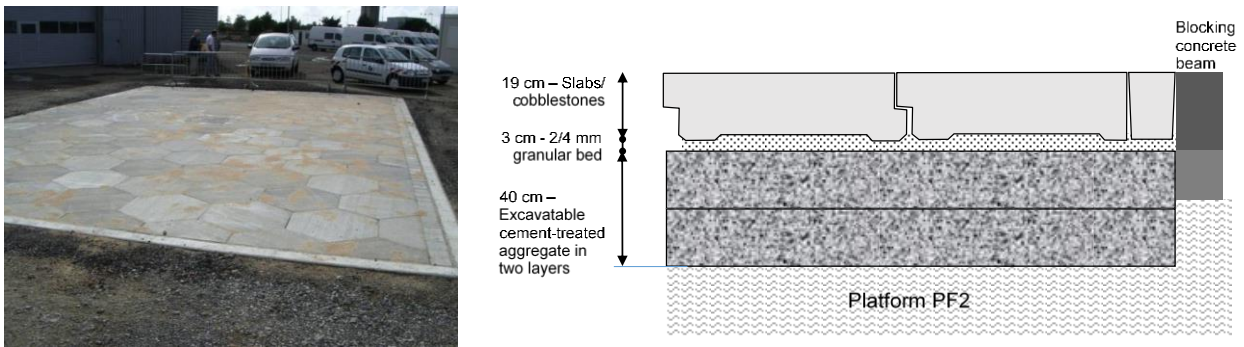


Figure 2 : Second RUP prototype with interlocked slabs, 2008



Figure 3 : Assembly-dismantling of the RUP with interlocked slabs.

Modern issues related to the urban environment suggest assigning new functions, other than mechanical, to pavements: dynamic charging for electric vehicles, energy harvesting, decrease of urban heat islands, dynamic signing, etc... Modular nature of the RUP and industrial precast of the slabs make it possible to envisage a fine functionalization of this type of structure, which would add interest to the concept.

In this context, a research concerning Removable Urban Roads with a Functionalized Surface (RUP-FS) was proposed as part of the I-Street (Systemic Innovations for Ecological and Energy Transitions in Road Infrastructures) research project. This project, funded as part of the PIA 3 "Roads for the Future" call and operated by ADEME, took place from 2017 to 2022. The partners of the RUP-FS research were Eiffage Route and Gustave Eiffel University, to which the Alkern precasting company was added. At a moment when innovative technical solutions in the road sector are focusing on limitation of urban soil waterproofing, better management and reuse of rainwater as well as the limitation of urban heat islands, the objective of the research was to develop a RUP demonstrator with interlocking slabs whose primary functionality is a quasi-transparency in terms of water. Beyond the advantages mentioned above concerning accessibility to the underlying networks, this type of RUP-FS is expected to minimize the risks of flooding and spraying of pedestrians and to maintain a good level of skid resistance, in case of heavy rain as well as good acoustic characteristics. The principle of slab functionalization is presented in Figure 4: it involves producing two-layer slabs made up of a porous concrete wearing course and a perforated plain concrete body. Porous concrete ensures surface permeability as well as absorption of road noise, while plain perforated concrete ensures the bearing capacity of the slabs while allowing water to pass through. The use of porous concrete over the entire height of the slabs would have led to excessive thickness given its low mechanical performance compared to plain concrete. RUP-FS slabs are not reinforced and can easily be recycled as such as elements if they have not reached their end of life, but also in the form of crushed concrete aggregate in the opposite case. To make the concept even more virtuous and improve the circularity of the slab economy, the partners have decided to replace 40% in mass of the natural coarse aggregate by recycled concrete aggregates in the concrete body. This was allowed under certain conditions by the recommendations of the National Recybeton Project, for XF2 class concrete, by anticipation of the new NF-EN 206+A2/CN standard published in November 2022.



Figure 4: Principle of porous and draining RUP-FS slabs

## 2. Development of an excavatable porous cement treated aggregate

To ensure water transparency, it is not enough for the slabs to be permeable, the base layer must also be. Thus, a new type of excavable cement-treated aggregate with high porosity while providing sufficient bearing capacity was developed as part of the project. For this study, we applied the method for characterizing the excavability of a material in the laboratory developed during two PhD at Gustave Eiffel University (Morin et al., 2013), (Morin et al., 2018) (Gennesseaux et al., 2018) and based on a punching test. The method is summarized in the guide (IFSTTAR et ENGIE, 2016). The punching test consists of penetrating a 13mm in diameter cylindrical punch into the material, which is confined in a metallic  $\text{\O}16 \times 16 \text{ cm}^3$  cylinder. The measurement of the penetration and the force during the test makes it possible to determine a penetration by the punch at an energy of 350 Joules; energy corresponding to the average impact energy of a manual pick. This measurement then makes it possible to predict the penetration depth of the head of a pick in-situ in the material and to calculate the volume that would be excavated by this pick blow. This volume is then used to determine a level of excavation difficulty. About ten draining cement treated aggregate were tested according this procedure, with different grading size ( $D_{\max}$  from 12 to 31.5cm) and different void contents (from 10 to 30%). After identifying a mix following the requirements in the laboratory, a full-scale implementation test was carried out to ensure the ease of placing of the material (Figure 6). A complete description of the experimental campaign is given in (Gennesseaux et al, 2023).



Figure 5 : Punching test in laboratory and manual pick excavation test

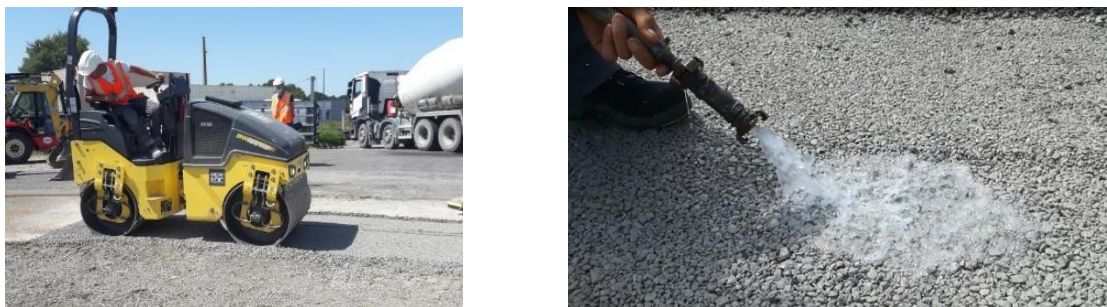


Figure 6 : In situ placing of the excavatable porous cement treated aggregate and visual observation of its high draining capacity

### 3. Slab design

General data from Météo France show that extreme rainfall can reach up to 100 mm/h in France, i.e. around 0.03 mm/s. Numerical flow simulations, assuming an isotropic permeability of the porous concrete layer, led us to impose a permeability of the porous concrete of the order of 5 mm/s (according to standard NF EN 12697-19) and 6 evacuation holes in the plain concrete, to deal with these severe weather. Further experimental validation of overall draining capacity was carried out on a real size slab, by evaluation of the water flow rate necessary to maintain approximately a 1mm layer of water at the surface of the slab (Figure 7).

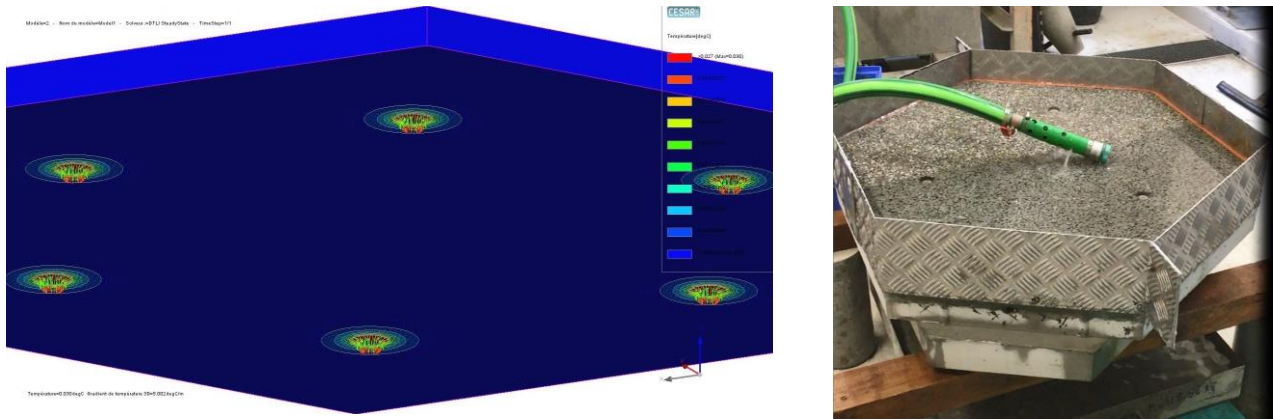


Figure 7 : Simulation of water permeability (by analogy to thermal diffusivity) - Laboratory permeability test on a slab (on right)

The mix design of the porous concrete (maximum aggregate diameter, void content related to the permeability) as well as its thickness were optimized on the acoustic point of view with a theoretical approach according to the following stages as precisely described in (Klein et al., 2022):

- measurement of the absorption with the impedance tube (or Kundt tube) (Figure 8);
- measurement of the texture of different porous materials;
- calibration of the HyRoNE rolling noise prediction model at urban and peri-urban speeds, simulation of rolling noise spectra.

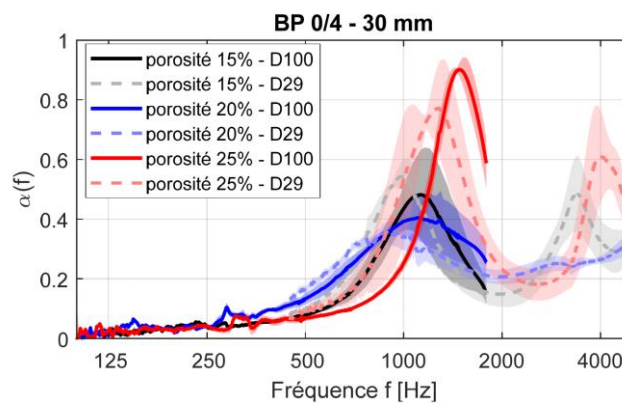


Figure 8 : Absorption curves in plane wave and normal incidence measured with the Kundt tube for porous concretes with a maximum diameter of aggregate of 4mm and different porosities. Measurements on cores with a diameter of 100 mm (D100) and 29 mm (D29) and 30 mm in height (from (Klein et al., 2022))

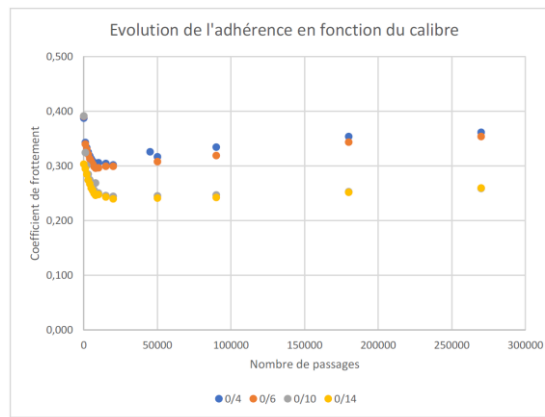


Figure 9 : Influence of the maximum aggregate diameter of porous concrete on skid resistance as a function of wearing cycles with the Wehner and Schulze apparatus (from Edjeaou et al., 2021).  
Y-axis: friction coefficient

Similarly, the maximum size of aggregate of the porous concrete was optimized with respect to skid resistance, using a Wehner and Schulze test for a void content of 25% which was pre-selected at the acoustic stage (Figure 9).

Finally, the risk of tearing of the aggregates was assessed by a triboroute test.

To pre-design the structure, we relied on finite element simulations (Figure 10), taking into account the presence evacuation holes for rain water. They made it possible to evaluate the bending stresses in the slabs and in the excavatable porous cement treated aggregate, which were compared with the admissible values obtained with the Alizé software, according to the French pavement design method.

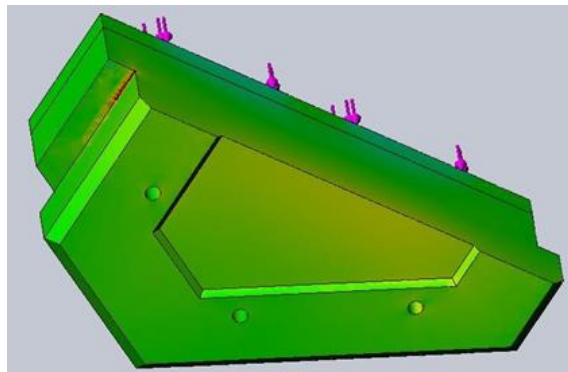


Figure 10 : Finite element simulation of the mechanical behavior of the slabs

In conclusion, slabs with a 46 cm edge, 23 cm thick were selected, made up of:

- 19 cm of plain concrete of class XF2 according to EN206+A2/CN standard and a mean compressive strength of 40 MPa. The concrete includes 40kg/m<sup>3</sup> of steel fiber in order to avoid fragile rupture of the interlocking keys;
- 4 cm of porous concrete with a maximum diameter of the about 6 mm, a void content of 26% and a min compressive strength of about 15 MPa.

It is important for durability of the slabs that the layer of porous concrete is firmly attached to the plain concrete. For this, the following casting method has been developed: compaction of the porous concrete in the bottom of the mold, then casting fresh on fresh of a self-compacting concrete to ensure a partial interpenetration of the two layers (Figure 11). The bonding between the two layers was checked by pull out tests (NF EN 1542).



Figure 11 : Vertical section of a slab. The plain concrete interpenetrates partially the upper porous concrete layer. Metallic cylinder installed for pull-out test.

In the initial concept of RUP, the slabs were handled using a suction pad. This was no longer possible because of the permeability of the slabs in RUP-FS system. A handling tool was therefore developed as part of the project (Figure 12).

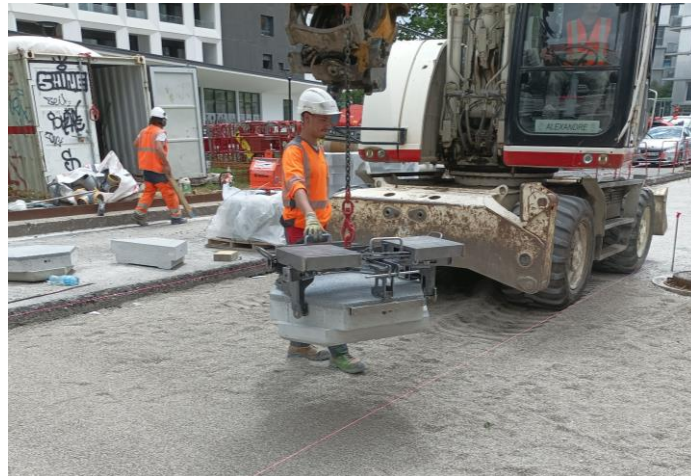


Figure 12 : Special tool developed for slab handling

#### 4. PROTOTYPE TRIAL ON THE FATIGUE CARROUSSEL

An abacus was used to design the plain slabs of the initial concept of RUP (Abdo et al., 2008). The relevance of this chart was confirmed thanks to the good behavior of the demonstrator produced with Nantes Metropole in 2008 for RUP slabs of 46 cm edge and 19 cm thick subjected to traffic for 10 years. However, the new generation of porous RUP-FS raises new questions on the mechanical level. Indeed, the presence of vertical holes in the body of the slabs leads to stress concentrations in the finite element calculations which are difficult to analyze and whose impact on the fatigue strength of the slabs remains unknown. The same problem of stress concentration arises at the level of the concrete keys, which allow the slabs interlocking. Finally, it is difficult to estimate the risk of spalling of the upper edges of porous concrete slabs under the effect of traffic. Even if it has few to do with the stability of the slabs, this phenomenon could harm the aesthetics and rolling comfort of the urban road, but also cause an increase in rolling noise. At the level of the base layer made of excavatable porous cement treated aggregate, the failure mechanism is not really well identified (behavior between an untreated well-graded aggregate and a cementitious material).

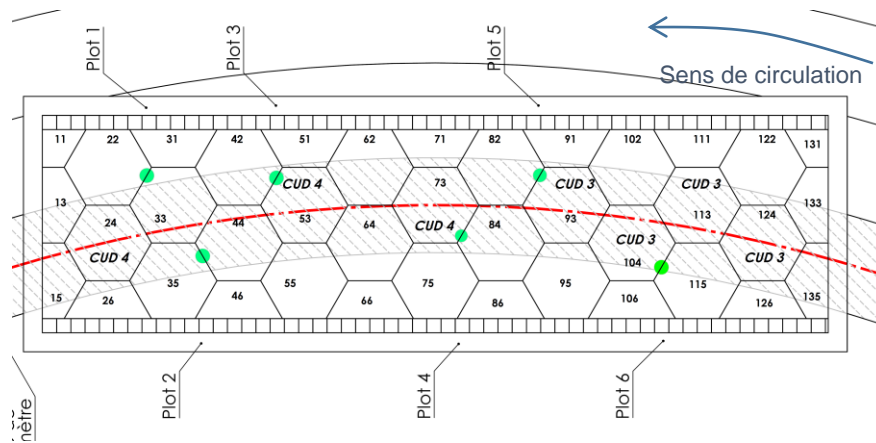


Figure 13 : Detail of the CUD-SF layout. Green dots indicate slab rocking measurement areas. The shaded area represents the 1m wide wandering the wheel

For all these reasons, it was deemed necessary to validate the pre-design carried out by a test on the fatigue carousel available at the Gustave Eiffel University, before moving to the demonstrator scale in an urban area. A section of RUP-FS with dimensions of 2.31x 8.35 m<sup>2</sup> was therefore planned among other trial sections carried out within the scope of the I-Street project (Figure 13). A time lapse of the construction is available on <https://youtu.be/PWk6YtjSbqk>

This section was subjected to 200,000 passages of a half-axle with twin wheels loaded at 65 kN (Figure 14) between November 9, 2020 and January 5, 2021. With an estimated aggressivity coefficient (CAM) between 0.3 and 0.6 this represents between 333,000 and 667,000 bus passages, i.e. traffic of between 45 and 91 buses/day/direction for 20 years.



Figure 14 : Test on a RUP-SF prototype on the fatigue carousel available at Gustave Eiffel University

During the test, follow-up measurements of skid resistance (SRT pendulum, etc.), slab rocking, evenness and visual appearance of the slabs were carried out. In particular, the structure was partially dismantled in order to assess any damage to the slabs and interlocking keys. At the end of the carousel test, it was possible to validate the overall mechanical behavior of the system, which showed no visible deterioration under or on the surface of the slabs (in particular at the edges of the porous concrete). The solution retains a level of skid resistance higher than the commonly accepted requirements and the draining aspect was qualitatively confirmed during various rainy periods (Figure 15).

This fatigue carousel test also confirmed the need to fulfill the joints between slabs with a 0/2mm sand, to consolidate the structure and prevent slab rocking.

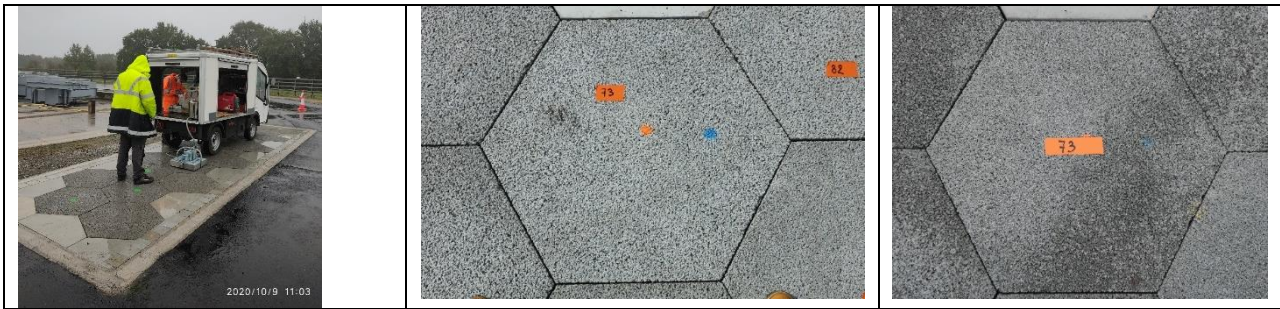


Figure 15 : State of the RUP-SF surface after a rain. The prototype plays its role of drainage well – Zoom on slab n°73 before and after the completion of the 200,000 cycles.

## 5. CONSTRUCTION OF A DEMONSTRATOR

Based on the good results obtained during this trial, Nantes Metropole agreed at the end of 2021 to pay for a demonstrator of approximately 185 m<sup>2</sup> under a negotiated bid with Eiffage Route without advertising or competitive bidding according to the procedure of the decree 2018 -1225 of December 24, 2018. This demonstrator is located on rue de l'Allier near the center of Nantes, which is trafficked by bicycles and light vehicles as well as by buses. It is therefore a prime location for testing the RUP-FS innovation in real traffic conditions. For the construction of the demonstrator, 351 slabs were produced in precast plant between 22<sup>nd</sup> of october 2021 and 7<sup>th</sup> of march 2022, including a few additional slabs, if necessary for maintenance. Four types of slabs were produced for the purposes of the experiment:

- 32 monolithic slabs intended for the manufacture of half-slabs and quarter-slabs. These slabs are only made of steel fiber reinforced self-compacting concrete (SCC) and are not equipped with vertical drains for handling purposes;
- 314 two-layer draining slabs composed of porous concrete and steel fiber reinforced SCC equipped with 6 water evacuation holes;
- 5 draining two-layer slabs made up of porous concrete and fiber-free SCC equipped with 6 water evacuation holes. These 5 slabs were introduced on the demonstrator to check whether the use of fibers is really essential to ensure the good behavior of the interlocking keys under traffic. Indeed, the elimination of fibers in the self-compacting concrete mix would have the double advantage of simplifying the manufacture and implementation of SCC and reducing costs and environmental impact of the material.

330 blocks (concrete cobblestones) were also manufactured in fiber-free SCC to manage the longitudinal edges of the demonstrator as well as the perimeter of a network access located in the middle of the demonstrator. When needed, these blocks are first removed to give space to move the slabs by sliding. It should be noted that 40% of the mass of gravel from the SCC was recycled concrete aggregate as explain above.

The following figures illustrate the construction of the demonstrator.



Figure 16 : (Left) Placing of the excavatable porous cement treated aggregate. (Right) insertion of the slab with the handling tool specifically developed



Figure 17 : (Left) Insertion of the slab along the block line. (Right) Encapsulation of a network access. The concrete blocks ensure the removability of the slabs around the access



Figure 18 : (Left) Joint filling with 0/2 mm sand before the casting of surrounding concrete edge beams to confine the slab movements. (Right) Final aspect of the demonstrator



Figure 19 : Drone overview of the finalized RUP-FS demonstrator (Credits Eiffage Route)

The construction site of the demonstrator lasted 2 weeks (for the RUP-SF zone) and notably confirmed it is possible to implement the draining excavatable cement treated base layer and the

slabs on a substantial surface. A manhole, located in the center of the zone, was also successfully treated to allow access without preventing the dismantling ability of the RUP.

## 6. CONCLUSIONS AND PERSPECTIVES

The entire I-Street project with laboratory measurements, numerical simulations, the carousel test and the construction of the demonstrator in Nantes Metropole has been rich in lessons on Removable Urban Pavement with Functionalized Surface. In particular, it made it possible to:

- validate the concept from a mechanical point of view;
- to specify the design of the slabs, the concrete mix design and to validate the two-layer concept to achieve the objectives of drainability, durability, skid resistance and low rolling noise emission;
- to develop a suitable draining excavable cement treated aggregate as base layer;
- to validate the industrial feasibility of the innovation at the level of the prefabrication of a large number of elements and at the level of the implementation on real urban pavement as well.

The demonstrator will now be subjected to regular monitoring, including in particular measurements of rolling noise, drainability, skid resistance and general monitoring of the condition of the slabs for at least 1 year. This draining variant of RUP will then be fully validated and can be distributed more widely. A life cycle analysis is also underway to clarify the environmental impact of the solution. Within the framework of this project, the Removable Urban Pavement concepts open new perspectives in our way of thinking about urban roads with the possibility of going further in the functionalization of concrete elements, while optimizing the carbon impact of such solutions by maximizing the use of recycled concrete aggregates and low-carbon cements.

## ACKNOWLEDGMENTS

The authors would like to thank Nantes Metropole for making the experimental site available and financing the demonstrator.

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