Bachelor Thesis

Development of Hydraulic Properties in PU-Bonded Pavement

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Aachen, August 2017

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Aachen, 27.07.2017

Aufgabe zur Bachelorarbeit

Für Herrn Jorge Gomez Carmona aus Zaragoza, Spanien, geb. am 03.12.1995

Untersuchung der hydraulischen Eigenschaften von PU-gebundenen Straßenbelägen

Development of Hydraulic Properties in PU-Bonded Pavement

To investigate the development of hydraulic conductivity and filtration property of Polyurethane bound porous pavement, by defining the particles clogging behaviour within the porous structure subjected to the urban pavement runoff. In the present study, it is hard to quantify the particles concentration of runoff. The test method and equipment for evaluating the clogging and filtration behaviour need to be re-designed and manufactured respectively.

To achieve the purpose of objectives above, the data collected from literature will be adopted to configure the solution sample of runoff. The evaluation methods for distinguishing the particle concentration between in-flow and out-flow will be focused, and the testing equipment will be designed and built. The data processing is needed for analysing the correlation between particle concentration and the development of hydraulic conductivity.

Im Einzelnen sind von Herr Jorge folgende Aufgabenpunkte im Rahmen der Bachelorarbeit zu bearbeiten:

- Literature review on national and international knowledge regarding the hydraulic conductivity of porous pavement.
- Objectives and proposed analysis: Development of an analysis concept for the systematic evaluation of the current state of the art.
- Methodology: The design of experiment and the test equipment manufacture to effectively quantify the development of hydraulic conductivity on porous media.
- Data processing: The processing and validation of obtained data, giving objective judgment of the proposed test method and the test results.

Die Versuche sind selbstständig in Abstimmung mit dem Institut für Straßenwesen durchzuführen.

The Chair and Institute of Highway Engineering will retain three bound copies, two copies with spiral binding and an electronic copy of the master thesis as well as all data on CD-ROM.

The most important findings of the work are in a published article in a journal, for example, the "Road and Highway" to an extent of about 6-8 pages.

After the evaluation of the master thesis by the Chair, the work will be presented and defended in an oral presentation (about 25 minutes) at a final appointment.

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1 Introduction

The huge expansion of the urbanisation in the last decades supposes a massive substitution of natural land covers, like grasslands and forests, by impervious surfaces, like roads, parking lots or streets. This process has a direct negative effect on the environment, as it reduces in a big way the areas where the water cycle occurs naturally. In order to solve such an inconvenience, the use of permeable pavement gains importance, since this kind of material allows rainwater to pass through it into the ground below, simulating the natural process which occurs on the ground's surface. Although conventional permeable pavements provide several benefits, the actual requirements of ensuring a high level of quality, functionality and sustainability, involve the need of improving this type of material. In this context, Polyurethane bound porous pavement, also known as PU-bonded pavement or PU-Asphalt, is developed by the Highway Institute of the RWTH Aachen University. Its innovation consists in the replacement of the conventional binders (bitumen) by polyurethane (PU), which is considered as a synthetic and high-performance binder. In several projects at the Institute, improvements regarding its mechanical strength have already been demonstrated. Moreover, the production of PU also meets the environmental criteria. Due to all these advantages, the PU-bonded pavement becomes a very promising material.

With the purpose of continuing to characterise the features of this material, the current thesis is carried out. The main goal is focused on evaluating the filtration property, by defining the particles clogging behavior within the porous structure subjected to the urban pavement runoff. In addition, the permeability is also checked.

In order to achieve this goal, several objectives have to be reached before. The first objective consists in the production of the specimens. This includes the selection of the grain size distribution, the calculation of the required components, and the appropriate manufacturing of the PU-Asphalt samples. Then, the second and most important objective of this study is the development of a whole filtration test. This starts with the searching of the right idea and its subsequent design. The next step is the building of the proper equipment, making sure that everything works as it was designed. Once everything functions correctly, the execution of the experiment is realized. Finally, the results of the test are analyzed and consequently an evaluation of the hydraulic properties of the material can be realized. On the other hand, the clogging effect is primarily emphasized during the literature research. Therefore, the last objective involves the characterisation of this important effect using the developed filtration test.

With the fulfilment and understanding of all these parts, the principal goal is achieved. As a result, the good hydraulic properties of the PU bound porous pavement are proved, which gives an advantage to this innovative material over the conventional asphalts.

2 Literature research

2.1 Permeable Pavement

Permeable pavement, also known as pervious or porous concrete, is a specific kind of pavement with a high porosity that allows rainwater to pass through it into the ground below. Through this movement, pervious concrete mimics the natural process which occurs on the ground's surface, consequently reducing runoff and returning water to underground aquifers. It also traps suspended solids and pollutants, keeping them from polluting the water stream (Go-gba.org). As a cornerstone for low impact development and sustainable site design, permeable pavement is considered a green infrastructure practice. It offers additional environmental benefits too, like better site design and enhanced safety of paved surfaces (Eisenberg et al. 2012).

Commonly used for walkways, driveways, patios, and low-volume roadways as well as recreational areas, parking lots, and plazas, porous concrete is appropriate for many different land uses, particularly in highly urbanized locations. Permeable pavement is hence an essential reference for engineers, planners, landscape architects, municipalities, transportation and regulatory agencies, and property owners planning to implement this best management practice for rainwater and urban runoff (Eisenberg et al. 2012).

2.1.1 History

Permeable pavement was first seen in the 1800s in Europe and was used for various structural purposes, including load-bearing walls, infill panels, and pavement surfacing. It became popular again overseas after World War II due to the scarcity of cement. Although not a new innovation, pervious concrete has only been implemented in the past fifty years. The concept was proposed in the 1960s in hopes of reducing floods, raising water tables, and replenishing aquifers. The first official design guide for permeable pavement was co-written in 1977 by Edmund Thelen and L. Fielding Howe in Philadelphia, PA. Titled "Porous Pavement" (Go-gba.org).

Pervious concrete is now used in most countries of Europe and America, and its number of applications has grown drastically over the past ten years, from driveways and sidewalks to commercial and enormous spaces. However, some countries do not have these pavements because they cannot afford them. In fact, permeable pavements are three times more expensive than regular asphalt paving. The climate is another reason why some countries do not use such a pavement. In countries where it hardly rains these pavements are not worth it.

2.1.2 General Characterization

Permeable concrete consists of cement, a coarse aggregate and water, with little to no fine aggregates (sand or clay). That is why permeable concrete has a very rough and uneven appearance. The *American Society for Testing and Materials (ASTM)* has a set of standards for both pervious and non-pervious concrete. ASTM calls for the following percentage of air content (or voids) within pervious concrete: 20% ± 5% - low porosity, high strength; 30% ± 5% - high porosity, low strength. When compared to the required void percentage of non-porous concrete, which ranges from 3% to 7,5%, the difference in overall structure can be easily seen. The high void percentage required for pervious concrete lets rainwater run easily through the material and seep into the ground below (Go-gba.org).

Water and aggregate are added in specific amounts to achieve pervious concrete with high air content and just enough cementitious paste to coat particles and interconnect voids. The low cement and high air content results in reduced strength, hindering pervious concrete from being used on highways, certain streets, or heavy loading areas. Nevertheless, the mixture of all added materials can be altered to allow sufficient strength for certain requirements.

2.1.3 Types of Permeable Pavement

For the purposes of this study, any pavement that is intended to let water pass through its surface and temporarily collect in an underlying aggregate storage zone is termed permeable pavement. However, among this broad definition of pavement, there are several specific types. Some of these varieties are defined and pictured below (Fig. 1).

- *Permeable concrete* (PC) is a mixture of Portland cement, fly ash, washed gravel, and water.

- *Permeable asphalt* (PA) consists of fine and course aggregate stone bound by a bituminous-based binder. Water passes through interconnected pores in both PC and PA, this is why they are used on highways to remove excess water.

- *Permeable interlocking concrete pavement* (PICP) is available in many different shapes and sizes. When it is laid, the blocks form patterns that create openings through which rainfall can infiltrate. This type of paving is popular in public areas due to its architectural appeal.

- *Concrete Grid Paver* (CGP) is more or less similar to PICP, but it has relatively larger open areas that are filled with gravel, sand, or even a loamy sand top soil.

- *Plastic reinforcement grid paver* (PG), also called geocells, consists of flexible plastic interlocking units that allow for infiltration through large gaps filled with gravel or topsoil planted with turf. A sand bedding layer and (more frequently) gravel base course are often added to increase infiltration and storage for many of these paver systems. These grids help to reinforce gravel driveways, parking lots and fire lanes.

- *Bound Recycled Glass Porous Pavement* is a mixture of post-consumer glass with resins and binding agents. Made by Filter Pave Products, this colourful pavement prevents glass waste from ending up in a landfill. Recycled glass pavement is appropriate for both pedestrian and vehicular traffic (Go-gba.org; Terhell et al. 2015).

Figure 1: Types of permeable pavement. Top L-R: Permeable concrete (PC), permeable asphalt (PA), permeable interlocking concrete pavers (PICP). Bottom L-R: concrete grid pavers (CGP), plastic reinforcing grids (PG) filled with gravel, PG filled with grass, and bound recycled glass porous pavement.

2.1.4 Benefits of Permeable Pavement.

Urbanization of the landscape has an appreciable negative impact on the quantity and quality of runoff water entering lakes and streams. By replacing natural land covers (like grasslands and forests) with impervious surfaces (like parking lots and streets), we lose the water retaining role of the soil and vegetation. Increased runoff from impervious surfaces causes dangerous floods, severe erosion damage to our stream channels, diminished recharge of groundwater, and degraded habitat for our fisheries. These same impervious surfaces can transport the many pollutants deposited in urban areas, such as nutrients, sediment, bacteria, pesticides, and chloride. In the worst cases, the amount of pollutants in urban runoff is high enough to prevent us from being able to swim or fish in our local waters (Usgs.gov).

Nevertheless, the use of permeable pavement prevents these incidents thanks to its hydraulic properties, which permit rainwater to pass through it into the ground below. It also provides more environmental advantages, but its profitability is questioning because of its cost. In spite of the fact that this cost is three times higher than the one of regular asphalt paving, it has clear financial benefits in the long term. Both environmental and financial benefits are explained below.

Environmental Benefits

The principal environmental benefit of permeable pavements is the elimination of runoff. These pavements help reestablish a more natural hydrologic balance and reduce runoff volume by trapping and slowly releasing precipitation into the ground instead of allowing it to flow into storm drains and out to receiving waters as effluent. This same process also reduces the peak rates of discharge by preventing large, fast pulses of precipitation through the rainwater system. The second benefit consists in reducing the concentration of some pollutants. This mitigation can be done either physically (by trapping it in the pavement or soil), chemically (bacteria and other microbes can break down and utilize some pollutants), or biologically (plants that grow in-between some types of pavers can trap and store pollutants). The third benefit is based on reducing the stress and impact on the stream or lake environment by slowing down the process (Usgs.gov). In this way, permeable pavements can cool down the temperature of urban runoff.

Financial Benefits

The main financial benefit of permeable pavement is related to eliminate the need for retention basins and water collection areas. This can be done by controlling the runoff at the source, such as a parking lot. It is also required lower installation costs because underground piping, storm drains or sloping are not needed (Go-gba.org). Other financial advantage of permeable pavement is the reduced need to apply road salt for deicing in the winter time. Researchers at the University of New Hampshire have observed that permeable asphalt only needs 0 to 25% of the salt routinely applied to normal asphalt (Houle et al. 2009). Other researchers have found that the air trapped in the pavement can store heat and release it to the surface, promoting the melting and thawing of snow and ice (Roseen et al. 2012). Finally, low life-cycle costs are expected due to an equal life expectancy to that of regular concrete: 20 to 40 years when correctly installed (Go-gba.org).

2.1.5 Community and Environmental Concerns

Although permeable pavements have many advantages over the regular asphalts, there are still some factors which have to be kept in mind.

The first concerning factor is the low mechanical strength of these pavements. Pervious concrete has such a high void content, this is why its overall strength is generally lower than that of regular concrete. As a result, it is not recommended for highways, high-volume streets, potential spill sites and heavy loading areas (Go-gba.org). Due to the strong increase in economic output and logistics, the proportion of heavy traffic increases enormously every year. Furthermore, higher temperatures as well as intensive, extreme weather events represent further heavy and constantly increasing loads for traffic routes which can lead to a sudden failure of the pavement system (Renken and Oeser, 2014).

Other important factor is the road safety*.* Permeable pavement is generally considered to be a safer surface than conventional pavement, providing less risk of aquaplaning, more rapid ice melt and better traction. Even so these features are not perfect and have to be controlled and improved in order to mitigate such difficulties. These problems are promoted due to the possibility that solids and particles may get trapped and clog pavement pores. If the proper maintenance is not carried out, pervious concrete will assume the traits of impervious concrete (Vwrrc.vt.edu).

Runoff volumes is other concerning factor that must be taken into account. A pervious pavement project should be properly designed to accommodate the amount of rainwater runoff that is expected in the area. If it is not adequately designed, the water table below the pavement can rise, preventing rainwater from being absorbed into the ground (Go-gba.org). Finally, it should not be missed that pavements, like everything, have to become more sustainable to respect and improve the environment.

As we can see, not all about conventional permeable pavement are benefits and some of its features have to be improved, in order to get road safety and have more applications. To meet these challenges efficiently in the future, there is an urgent need for the development of new, innovative construction methods and materials. Sustainability, durability as well as a balanced energy efficiency already represent firmly established construction and socio-political conditions, to which the focus must be set in order to achieve the objectives. As part of an ongoing research project at the Institute of Highway Engineering, RWTH Aachen University, with the project title *"Simulation-Based Development of New Road Construction Materials and Innovative Manufacturing and Installation Methods"*, financed and promoted by the Federal Ministry of Transport and Digital Infrastructure, represented by the Federal Highway Research Institute (BASt), a completely new and innovative bonded material concept (PU-bonded pavement) was developed based on experimental analyzes. This material concept shall have a positive long-term behaviour as well as a sufficient bearing capacity and deformation resistance, even at high stresses (Renken and Oeser, 2014).

2.2 PU-Bonded Pavement

Traffic routes, as part of our living environment, form the basis of ensuring mobility and therefore have to meet criteria of sustainability and durability. In order to ensure a high level of functionality, the highest standards of production and process quality must be fulfilled and a strategically coordinated choice of material components and designs is required. In the conventional construction of infrastructures and traffic routes, mineral fillers (stones) and binders (bitumen) are used as material components. To meet the quality requirements in all respects, all components used must meet the highest quality standards. Since the optimization potential of the filler component is already largely exhausted, there is still need for optimization of the binder. Against this background, a substitution of conventional binders by high-performance and synthetic binders appears to be promising. In the context of several research projects at the Institute of Highway Engineering at the RWTH Aachen University, the suitability of polyurethane as a binder substitute has already been demonstrated (Renken and Oeser, 2014).

2.2.1 Biosynthetic Binder – Polyurethane

Polyurethanes are one of the most versatile plastic materials. The nature of the chemistry allows polyurethanes to be adapted to solve challenging problems, to be molded into unusual shapes and to enhance industrial and consumer products by adding comfort, warmth and convenience to our lives (Americanchemistry.com).

The multifunctional material polyurethane (PU) consists primarily of the raw materials polyol and polyisocyanate. If these two components contact each other, the reaction mixture polyurethane is formed by a polyaddition reaction (exothermic reaction). In this reaction, particularly the characteristic urethane group (-NH-CO-O-) is created. For 1-components, 2-components as well as for organic solvent systems the key substance is isocyanate, which has an enormous responsiveness with hydrogen-active compounds. In the reaction with polyvalent alcohols (polyol) the hydrogen atom (H), which is bonded in the hydroxyl group (-OH), migrates to the isocyanate group (Fig. 3-2). The solvent-free diisocyanatodiphenylmethane (MDI), which is commonly used in 2-componentreaction-adhesives, serves in the form of a 4,4'-MDI for the production of a material (adhesive compound) with elastic properties (Fig. 2) (Renken and Oeser, 2014).

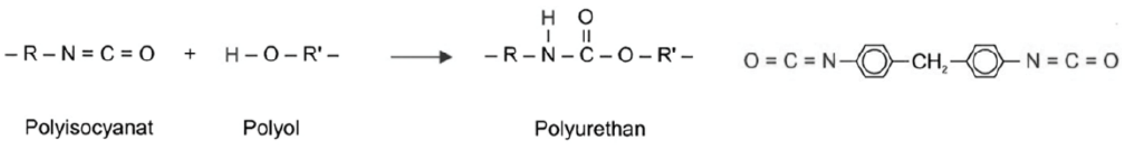

Figure 2: Structural formula of polyurethane (left) and diphenylmethane-4,4'-diisocyanate (MDI) (right) (Renken and Oeser, 2014).

In general, the used polyols with their characteristic hydroxyl groups are polyester polyols or polyether polyols. Polyester polyols are partially medium or highly branched molecular chains, while polyether polyols are constructed rather linear. Due to this property, polyether polyols can be distinguished from polyester polyols by their lower viscosity. With an additional use of waterfree organic solvents, it is possible to regulate the viscosity of the polyols for the corresponding application. Furthermore, material properties, in particular elasticity, can be regulated by a targeted adaptation of the formulation of individual components. Especially with regard to the mechanical and thermal dependence of the pavement structure, a regulation of the viscous and elastic property is of enormous importance (Renken and Oeser, 2014).

Polyurethane and its components mostly have a petrochemical origin, meaning that there are based on the finite raw material petroleum. However, it is also possible to generate polyurethanes oleochemically, that is on the basis of vegetable oils, wood, carbohydrates (cellulose and starch) and lignine (Beltrán and Boyacá, 2011). The main focus in the development of such polyurethanes on an ecological basis are the polyols. As already explained, polyols are organic compounds with polyvalent alcohols, the socalled hydroxyl groups. The production is based on natural oils and fats, which mainly consist of triglycerides and glycerol esters from saturated and unsaturated fatty acids (3,4,5). That means that such polyurethanes consist to 50% of renewable raw materials and the final product can be classified as fully compatible with the environment (Renken and Oeser, 2014).

2.2.2 Grain Size Distribution

As it was explained before, permeable pavement allows the fluids to pass through it due to its high porosity, which is directly related with its void contents. Therefore, the size and geometry of the pores as well as the distribution of pores substantially influence the permeability.

According to (LIN 1993) voids can be classified by three different types (Fig. 3). For a good hydraulic performance *Type A* and *Type B* are the most important. These types were described as “effective voids”, because they can absorb water and drain into underlying layers. While *Type A* voids are connected and create a pore system, *Type B* voids are accessible from the surface. On the other hand, *Type C* voids are enclosed. As a result, they do not influence the permeability significantly (Renken et al. 2015).

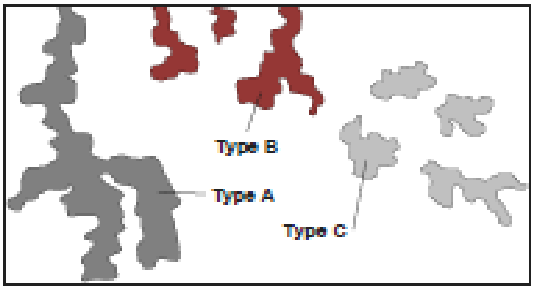

Figure 3: Schematic view of different pore structures ref. to (Bald et al. 2005). The top of the picture represents the surface of the material.

The size and geometry of the pores are mainly dependent on the aggregates size distribution. The aggregates consist in little stones or powder, whose size can vary from the microns to the millimeters. Porous asphalts are classified in different classes depending on the size of their aggregates. These categories are named with the initials PA (Porous Asphalt), following by a number, which is the maximum size of the aggregates which form the pavement. For example, PA 5 is used for asphalts whose biggest aggregate size is 5 mm. The other classes that are specified by the *Merkblatt für Versickerungsfähige Verkehrsflächen* are PA 8, PA 16 and PA 22.

Although high void contents are good for the permeability, they also bring to a worse mechanical performance. In the manufacture of Polyurethane-Asphalt (PU-Asphalt), it is necessary to completely coat the specific surface area of the minerals used with the polyurethane binder, thus the aggregates are permanently bonded at the contact points and form a monolithic, three-dimensional and stable structure. Since a very high material cohesiveness is developed only by this monolithic adhesion at the contact points, porous structures with high consistencies can be achieved easily (Renken and Oeser, 2014). As a result, good hydraulic properties as well as a good mechanical performance can be coupled by the same pavement. Even so it is still important to keep the relation between these factors, because when one of them is improved, the other one is minimized and vice versa.

For this study PA 5 and PA 8 have been selected as grain size distributions, because they provide initially both enough void content and mechanical performance. Their hydraulic properties are measured afterwards with the filtration test.

2.2.3 Advantages over Conventional Permeable Pavement

Permeable pavement is characterized by its high void content (20% to 30%) and the effects that it involves. For example, due to such a high void content a major contribution of the road construction to noise reduction can be achieved. Another essential aspect of porous construction designs is the water permeability, which contributes to an increased traffic safety due to the reduction of water spray and a reduction in the risk of aquaplaning. Nevertheless, this high void content has bad consequences too, which have to be overcome. The main weakness of conventional porous asphalt is its low mechanical strength, even lower than that of regular concrete.

Although porous asphalts have been optimized and further developed in terms of adhesiveness and durability within the last years, these remain limited in their lifetime due to a high susceptibility to grain ravelling (loss of aggregates) which is caused by mechanical shear stresses. Under high mechanical shear stresses, a failure of the adhesion can occur in the monolithic adhesive areas, resulting in a shift of the particle skeleton. Furthermore, the binder used shows an increased susceptibility to aging which is due to its large accessible surfaces. Generally, Porous Asphalt surfaces have a shorter lifetime than conventional road pavements. As a result of the functional principle of PU-Asphalts outlined in *Section 2.2.2*, a very high mechanical strength can be achieved despite a porous pavement (Renken and Oeser, 2014).

In the study carried out by the Institute of Highway Engineering “Innovative Material Concepts – Application Potentials and Characterization of Synthetic Road Pavements” it was found that PU-Asphalt, in addition to significantly higher strength values, can bear deformation up to a material failure, indicating a more ductile fracture behaviour. Moreover, it was also found that this material has a temperature-dependent strength behaviour, but the glass transition temperature range lies outside of the assumed operating temperature range of -20ºC to 50ºC. As a result, very high material strengths are still available even at critical temperatures and thus counteract an early material failure. On the other hand, mixture manufacture of PU-Asphalt can be carried out in cold state due to the hardening reaction. As a result, the energy required for the production can be significantly reduced compared to the conventional construction method with asphalt. The application range is outside of the glass transition due to the lower thermal dependence of the PU-Asphalt (Renken and Oeser, 2014).

PU-Asphalt is also considered as an environmentally friendly material. As it is explained in *Section 2.2.1*, PU is made by exothermic reactions between polyols and isocyanates, and these polyols can be generated from vegetable oils. As a result, polyurethanes which are derived from these ecological polyols consist to 50% of renewable raw materials, and the final product can be classified as fully compatible with the environment. Moreover, the long service life and seamless surface reduce the need for repairs, maintenance and cleaning.

2.3 Hydraulic properties

Permeability is the ability of a material to conduct moisture or another flowing medium through the porous structure. The characteristic of this property depends mainly on the hydraulic parameters of the material, as well as the moisture viscosity. The hydraulic properties of traffic pavements are largely dependent on the void content and the pore geometry (Renken and Oeser, 2014).

Permeable pavements, as a sustainable infrastructure material can be a filtration medium promoting hydrologic restoration, particulate matter (PM) and solute control. However, filtration and commensurate clogging are two aspects of continued interest and discussion (Sansalone et al. 2011).

2.3.1 Filtration

In general, filtration is considered as the separation of suspended impurities from liquid or gas by passing the fluid through a porous membrane that retains the particles on its surface or in its pores. In liquid filtration, the clarified liquid, called filtrate, is collected behind the filtration membrane. On the other hand, the separated solid phase, the sediment, forms a continuously growing layer on the filtration membrane surface. It commonly consists of randomly lying particles of different shapes (Thermopedia.com).

With regard to this project, the corresponding definition of filtration would be as follow: separation of the particulate matter that carries the water of study by passing the fluid through a PU-bonded pavement specimen that retains the particles on its surface and inside its pores.

Filtration Models

(McDowell-Boyer et al. 1986) presented three classes of mechanisms for PM separation: surficial straining, deep-bed filtration and physical-chemical diffusion, each as a function of the ratio of the media diameter d_m (an economical surrogate for pore diameter) to influent PM size d_p. These mechanistic classes give and idea regarding how the filtration occurs. One primary mechanism, *surficial straining* is when $d_m/d_p < 10$ with PM separated at the pavement surface; while *deep-bed filtration* is when d_m/d_p is between 10 and 20. In this case PM penetrates into the pavement eventually filling pore space resulting in clogging. A third class of separation mechanisms is *physical-chemical diffusion* when $d_m/d_p > 20$, where PM deposits in the permeable pavement do not significantly impact pore geometry. This is why the ideal mechanistic class is the physical-chemical diffusion, which can avoid the not desirable clogging effect (Sansalone et al. 2011).

2.3.2 Clogging

As permeable pavement and surfaces accumulates PM, the hydraulic conductivity and infiltration decreases until the filtered PM is removed through surficial maintenance practices (Sansalone et al. 2011). This process is what clogging means in this project.

Permeable pavements are very popular structures for the management of both urban runoff quality and quantity. As their name implies, they promote the infiltration of rainfall and urban runoff, either to the underlying soil or to a storage reservoir. Although these pavements are easily retrofitted and effective in improving water quality and hydrology, they are prone to clogging. Furthermore this is a major determinant in the lifespan of porous pavements. The effective life of a pavement is defined as the number of years it is in service, until which the hydraulic performance drops to a level where the drainage 'design storm event' (i.e. the event with return period of 1 in 5 years) is unmanageable and remedial works are required. This process is known as "pavement clogging", and it is the key issue associated with porous pavement implementation. Porous pavements when "new" often have infiltration capacities usually upwards of 4500 mm/h. While some systems (i.e. 15-20 years of operation) still provide infiltration rates far above the design storm requirements (100-1000 mm/h), many have reported clogging, with infiltration rates reduced to unacceptable levels within the same period (Young et al. 2012).

Main Factors

Clogging can result from fine particles accumulating in the void spaces of porous pavements. The mass of sediment that enters the system is the most important factor. As smaller particles trap larger particles, the rate of clogging increases as more fines are trapped, suggesting that sediment particle size also plays a role. Sediment particles less than 6 µm are the main cause of clogging, bearing in mind that this is case specific with critical size being highly dependent on media size. The rate of clogging is also dependent on the conditions to which the pavements are exposed. Clogging is found to be highly correlated with cumulative volume and flow rate. Accordingly systems that received variable flow magnitudes, along with drying periods have almost doubled the lifespan of systems receiving continual wetting with the absence of drying periods (Young et al. 2012).

Consequences of Clogging

In porous asphalt, ponding is observed to occur right above the pavement, indicating the formation of a clogging layer at the surface. These ponds, which are generating due to the clogging effect, have direct consequences with regard to the traffic safety, as we cans see below.

- Aquaplaning:

  Aquaplaning, or hydroplaning, occurs when the water between the tyres and the road surface cannot be removed quickly enough. This layer of water builds up in front of the tyres until the pressure of the water exceeds the pressure of the tyre on the road, resulting in the tyres losing contact with the road surface. This loss of traction causes the wheels to slip and prevents the vehicle from responding to steering, braking or accelerating. As a result, the vehicle can go out of control, start to skid or spin, which are without a doubt potentially dangerous situations. It should be also taken into account that the deeper the water and the higher the vehicle speed, the greater the effect eventually affecting road holding. Moreover, the risk of aquaplaning accidents is greatest for large rut depths and during conditions of poor water drainage (small cross fall) (Michelin.co.uk).

- Driver behavior:

  Driver behaviour has been identified as the principal contributor to accidents, but the impact of road condition and maintenance is not negligible. In many circumstances, it is difficult to disentangle causality: there are accidents caused directly by the poor condition of the road, but there are also accidents caused by drivers' behaviour in reaction to the condition or the design of the road. There is, in fact, a correlation between road quality and driver behaviour; in some circumstances even careful drivers make poor choices as a result of the condition of the road or their reading of the road layout.

Although it is not the only way in which the condition of the road surface compromises the driver behaviour, the aquaplaning is the one related with this project because of its relationship with the hydraulic properties of the road's material. The aquaplaning leads to a poor wheel-road contact that fails to guarantee a sufficient skid resistance value. Other forms in which the condition of the road surface contribute the road safety are: localised anomalies, such as ruts, potholes and depressions, whose unpredictability make them dangerous for drivers; poor geometry and alignment design – i.e. inadequate design of the route of the road; poor level of service unable to accommodate existing traffic flows; poor signage or markings, e.g. incomplete or missing markings and signs, and poor lighting (European Parliament 2014).

2.3.3 Filtration and Clogging Measurements

Filtration and clogging are two related concepts. This is why when filtration takes place, the clogging effect appears due to the fact that PM is accumulated on the surface and the pores of the specimen. Therefore when filtration properties are measured, an idea about clogging can be directly deduced.

Hydraulic Conductivity, k_f

Studies have shown that *hydraulic conductivity,* k_f, is an appropriate tool to evaluate permeable pavement filtration and clogging. This coefficient describes the speed at which a quantity of water flows through a given area of a construction material at a given hydraulic gradient. As this parameter decreases due to the accumulation of PM on the surface and pores of the specimen, the clogging effect is taking place. As a result, a general idea about filtration and clogging can be obtained (Sansalone et al. 2011).

This is a useful way of measuring these properties because of its speed, simplicity and its application. For example, it can be used as a security measure, when this parameter decreases below a specific value and maintenance actions are realized in order to eliminate the PM retained and return to the initial conditions.

The structural and hydraulic requirements for water-permeable pavements of traffic areas are regulated in the German *Guideline for Permeable Traffic Areas* of the

Research Society for Road and Traffic Engineering (FGSV). Thus, a coefficient of permeability of $k_f \geq 5{,}4 \cdot 10^{-5}$ *m/s* for water-permeable asphalt is suggested (FGSV 2013). This is a recommended value which should not be passed, but other higher value can be used in terms of security and quality. A list with different permeability ranges and their quality is presented below (Renken et al. 2015).

Table 1: Permeability ranges (DIN 18130-1)

kf (m/s)	Range
under 10^{-8}	Very slightly permeable
10^{-8} to10^{-6}	Slightly permeable
over 10^{-6} to 10^{-4}	Permeable
over 10^{-4} to 10^{-2}	Highly permeable
over 10^{-2}	Very highly permeable

Strained Mass, m_s, and Particle Mass Separation Efficiency, η_m

In spite of its directly application, the hydraulic conductivity, k_f, does not provide an exact value for these properties. It is only a general rule that can be followed easily. For measuring exact values of filtration (and clogging), two concepts are taking into account throughout this project. These are the strained mass, m_s, and the particle mass separation efficiency, η_m.

On the one hand, the s*trained mass,* m_s, is just the mass of PM that is accumulated inside the specimen. The aim is both quantifying this mass and understanding how this index progresses over time.

On the other hand, *particle mass separation efficiency,* η_m is a parameter which indicates the quantity of particulate matter that goes through the specimen in relation to the one that was in the water at the beginning. This index is expressed as a percentage. While 0% means that all the particulate matter goes through the specimen and subsequently clogging effect does not take place, 100% means that all the particulate matter is retained inside the specimen and as a result, causing a total clog. As this index increases, the clogging does it as well. The corresponding equation is showed below.

$$\eta_m(t) = \left(1 - \frac{[m_e](t)}{[m_i](t)}\right) \times 100\% \qquad (1)$$

with:	$\eta_m(t)$	mass separation efficiency
	$[m_e](t)$; $[m_i](t)$	effluent and influent PM concentrations

Both strained mass and mass separation efficiency are studied and calculated in the filtration test developed in this thesis, which will be explained afterwards.

2.4 Maintenance of Permeable Pavement

Permeable pavements substantially and significantly reduce runoff volumes, limit peak flows, and sequester many types of pollutants. Many permeable pavements further improve ground water recharge, have high albedo (light reflectivity), reduce runoff temperature, and improve aesthetics. These pavements are able to achieve this by allowing water to pass through the surface layer and temporarily collect in underlying aggregate storage layers. This water then either is released back to the storm drain system through underdrains or infiltrates into the underlying soil, or a combination of both (Terhell et al. 2015).

To enable permeable pavements to function as intended, however, inspection and consequent maintenance are imperative. Although it is true that these actions are required, it is difficult to prescribe the specific types or frequency of maintenance tasks that are needed to maintain the hydrologic function of permeable pavement systems over time. Most installations work reasonably well year after year with little or no maintenance, whereas some have problems right from the start. The most frequently cited maintenance problem is surface clogging caused by organic matter and sediment. In order to know when this problem appears and the maintenance have to be done, inspections are usually carried out (Terhell et al. 2015; Vwrrc.vt.edu).

2.4.1 Maintenance Inspections

Permeable pavement maintenance is driven by inspections that evaluate the condition and performance of the practice. It is highly recommended that these inspections are conducted at each permeable pavement sit, particularly at large-scale applications (Vwrrc.vt.edu). Permeable pavement maintenance is rather straightforward when compared to other stormwater management practices (such as bioretention, wet ponds, and stormwater wetlands). The common inspection and maintenance tasks are: verifying that clogging has not occurred, preventive street sweeping, weeding, and stain removal. Additionally, some pavement type-specific tasks include: restorative street sweeping and mowing (Terhell et al. 2015).

Regular inspection is an essential part of permeable pavement maintenance. During the visit the pavement´s surface can be examined for accumulated dust, sediment, organic debris, staining or ponding that may indicate surface clogging. If any signs of clogging are noted, a vacuum sweeper is scheduled to remove deposited material. Then, tests are done by pouring water from a bucket or large bottle to ensure they work. Pavements which require from several seconds to minutes for the water to stop flowing are clogged to some degree. Other way to check this is by observing the pavement after a storm event. The drawdown rate should be measured for three days following the storm event in excess 3/5 cm in depth. If standing water is still observed in the well after three days, this is a clear sign that clogging is a problem.

Meanwhile the visit, the inspector can scout the structural integrity of the pavement surface, looking for signs of surface deterioration, such as slumping, cracking, spalling or broken pavers. Inlets, pretreatment cells and any flow diversion structures for sediment buildup and structural damage are also checked. Finally, if the permeable pavement is underdrained, the underdrain outlet should be checked to verify it is not blocked. If the visit occurs after a storm, a trickle of water would be expected from the underdrain (Terhell et al. 2015; Vwrrc.vt.edu).

2.4.2 Maintenance Methods

Maintenance is a crucial element to ensure the long-term performance of permeable pavement. Surface clogging caused by organic matter and sediment is the most important problem of these pavements. But it can be reduced or even eliminated by applying the right methods.

(Balades et al. 1995) suggested that the clogged depth is limited to the first several centimeters of permeable pavement, and compared four types of cleaning methods: moistening followed by sweeping, sweeping followed by vacuuming, vacuuming alone, and high pressure water jetting and vacuuming. Results indicate that vacuuming and high pressure water jetting could recover from 96% to 99% of the initial infiltration rate (Sansalone et al. 2011).

All these cleaning methods can be realized by the *street sweeping*, which is the most important maintenance task associated with permeable pavement. Even though it is true that street sweeping can serve both preventive maintenance and restorative maintenance, preventive street sweeping is preferred. Preventive sweeping is regular, scheduled passes by a street sweeper during a calendar year. While the exact frequency has yet to be determined, it appears two to four visits per year for most permeable pavement applications is sufficient. If the permeable pavement has been neglected for several years, however, preventive maintenance will not be sufficient, so restorative street sweeping will be required to restore a pavement’s ability to infiltrate water. The type of equipment needed to achieve either preventative maintenance or restorative maintenance is not the same. There are three main classes of street sweepers: mechanical, regenerative air, and vacuum. Examples of mechanical and vacuum sweepers are shown below (Fig. 4).

- *Mechanical street sweepers* are the most common street sweeper on the market. They employ a multiple brush approach to first move sediment and trash to the middle and then lift the deposits onto a conveyor belt for temporary storage. The brush bristles can penetrate some types of permeable pavements, but not most.

- *Regenerative air street sweepers* are the second most common street sweeper. They work by shooting air at an angle to the pavement, which effectively loosens dust and other fine particles at and near the surface of the pavement. Because air is blown across the carriage of the truck, a relatively minor vacuum is created, which then lifts the loosened particles into a hopper. This system removes surface-deposited sediments from all pavement types.

- *Vacuum street sweepers* are the least common and most expensive type of sweeper. They function by applying a strong vacuum to a relatively narrow area that lifts particles both at and below the surface of the pavement. Vacuum sweepers have the ability to restore infiltration to some types of pavements that have been grossly neglected (Terhell et al. 2015).

Figure 4: Mechanical street sweeper (left) and vacuum sweeper (right).

As it is observed, vacuum street sweepers are the less used in spite of being the best cleaning method. This is due to their high cost and the fact that it is not really needed a total recovering of the initial infiltration rate for a right performance of the permeable pavements. Therefore these sweepers are not worth it in most cases.

Apart from street sweeping, which is the most renowned maintenance method, other measures should be also taken into account. Among these different maintenance measures is the *protection of the reservoir layer's bottom*. There are two options to protect the bottom of the reservoir layer from intrusion by underlying soils. The first method involves covering the bottom with polypropylene geotextile that is permeable, although some practitioners recommend avoiding the use of filter fabric since it may become a future plane of clogging within the system. Permeable filter fabric is still recommended to protect the excavated sides of the reservoir layer, in order to prevent soil piping. The second method is to form a barrier of choker stone and sand. In this case, underlying native soils should be separated from the reservoir base/subgrade layer by a thin 5 to 10 cm layer of clean, washed, choker stone (ASTM D 448 No. 8 stone) covered by a layer of 15 to 20 cm of course sand. The other maintenance method is the building of a *observation well.* An observation well, consisting of a well-anchored, perforated 15 to 20 cm (diameter) PVC pipe that extends vertically to the bottom of the reservoir layer, should be installed at the downstream end of all large-scale permeable pavement systems. The observation well should be fitted with a lockable cap installed flush with the ground surface (or under the pavers) to facilitate periodic inspection and maintenance. The observation well is used to observe the rate of drawdown within the reservoir layer following a storm event (Vwrrc.vt.edu).

2.5 Hypotheses

Actual increasing requirements of high loads and maintenance demands imply the need of progress for permeable pavements. Consequently new improvements, which ensure a high level of quality, functionality and sustainability, have to be carried out. In this context, Polyurethane bound porous pavement, also known as PU-bonded pavement or PU-Asphalt, is developed by the Highway Institute of the RWTH Aachen University. Its innovation consists in the replacement of the conventional binders (bitumen) by polyurethane (PU), which is considered as a synthetic and high-performance binder. In other projects at the Institute, enhancements regarding its mechanical strength have already been demonstrated. In addition, the production of PU also meets the environmental criteria. Due to all these benefits, the PU-bonded pavement becomes a very promising material.

With the purpose of continuing to characterise the features of this material, the current thesis is carried out. The main goal is focused on evaluating the filtration property, by testing the following hypotheses, which were obtained after a detailed and complete study of the literature research.

- As the permeability of the PU-Asphalt has already been described as good, the filtration property is intended to be proper too, due to the connection between both characteristics.

- The clogging effect does not take place during the execution of the experiment, because of the supposed good filtration property of the material.

- Based on the results of similar filtration experiments, *particle mass separation efficiency* values are expected to be at least between 55% and 65% to demonstrate a good filtration property.

- Grain size distribution design is crucial for the performance of the material because it has to assure both good hydraulic and mechanical properties. Regarding the distributions selected for this project (PA 5 and PA8), PA8 is assumed to provide a better filtration property, although both of them are expected to be appropriate.

In order to test these hypotheses, several objectives have to be reached before. The first one consists in the production of the PU-Asphalt specimens. This includes the selection of the grain size distribution, the calculation of the required components, and the appropriate manufacturing of the samples. Then, the second and most important objective of this study is the development of a whole filtration test. This starts with the searching of the right idea and its subsequent design. The next step is the building of the proper equipment, making sure that everything works as it was designed. Once everything functions correctly, the execution of the experiment is realized. Finally, the results of the test are analyzed and consequently, a comparison with the previous hypotheses can be done. If these hypotheses are fulfilled, the good filtration property of the PU bound porous asphalt will be demonstrate, which gives an advantage to this innovative material over the conventional pervious concretes.

3 Methodology

3.1 Production of Specimens

The sample manufacturing took place in the laboratory of the Institute of Highway Engineering at the RWTH Aachen University. On one hand, PA5 and PA8 are the grain size distributions selected for this study, as it was mentioned in *Section 2.2.2*. Their specific distributions are shown in Tab. 2. On the other hand, the binder content is defined as B=6wt% (weight percent) based on experience. Hereby a strong, three-dimensional structure with a high strength was created.

Table 2: Grain size distributions of the PU-bonded pavement specimens. Porous Asphalt 5 (left) and Porous Asphalt 8 (right).

Aggregate	Proportion in Mixture (%)	
Kasteinfüller	7	6
Diabas 0/2	5	9
Diabas 2/5	88	35
Diabas 5/8	-	50

Regarding the manufacturing, the first step consists in the preparation of the mold (Fig. 5). It has to be covered by adhesive tape and some oil is spread along the mold's sides in order to get an easier removal of the specimens after the hardening process. Once the mold is correctly adapted, it is time to collect the aggregates. Different kinds of aggregates are stored in the laboratory, among which "Diabas" is the class used for this project. Following the previous calculations (Appendix), the right masses of each aggregate are gathered together in a bucket (Fig. 5). Then, the polyurethane has to be prepared, adding the right quantities of polyol and isocyanate into a small recipient and mixing them until a change of colour can be observed. It is important to mention that the polyol has to be shaked properly before the mixing. When the binder is ready, the material components are mixed together in a manner that the polyurethane binder completely coats the specific surface of the aggregates. Subsequently the manufactured mixtures were placed in the mold and compacted by means of a hand roller (Fig. 5). In this procedure there is a loss of mixture, therefore the masses are calculated with an extra of 10%. Finally, the specimen is kept in a secure place until the hardening process finishes and it can be removed from the mold.

Figure 5: Material used for the production of specimens. L-R: Mold covered with adhesive tape, weight and bucket where the aggregates are mixed with the polyurethane, hand roller.

There are different molds in the laboratory. During the first month helping a Research Engineer within his investigations, two different shapes were used. The first one was a cylinder mold with radius 10 cm and height 4 cm and the other one was a rutting table of dimensions 32×26×4 cm.

Finally, it was decided to use specimens with the cylinder mold for this study. The reason was basically the small sectional area of this mold, which was better for the filtration test: the smaller the area, the less quantity of water required and the smaller the containers needed for this experiment. Even though, the rutting tables were manufactured and cylinder specimens were cut from them in order to save time, due to the fact that with one rutting table, five cylinder specimens can be got (Fig. 6).

Figure 6: Rutting table (left) and cylinder specimens (right). Their material is PU-bonded pavement with grain size distribution PA5. The cylinder specimens are cut from the rutting table.

3.2 Filtration test

The filtration test is the main part of the project and it is developed in order to get exact results about the filtration properties and the clogging effect. As it was explained in the *Section 2.3.3*, the *hydraulic conductivity, k_f,* is very useful for having an idea about if the clogging is taking place or not, but it does not really provide exact results about its level. For this purpose, two new parameters are obtained throughout this experiment. The first one is the *strained mass, m_s*, which is just the mass of particulate matter (PM) which is accumulated inside the specimen. The other and really important factor is the *particle mass separation efficiency, η_m.* This parameter is the one that gives an exact result about the level of clogging.

3.2.1 Equipment

The idea of this test comes from (Sansalone et al. 2011). However, such an experiment was realized on a large scale, with both huge facilities and extremely accurate measurement equipment. Therefore, a new design had to be developed according to our means. The first change that was introduced was reducing the size of the machinery. The main part of the equipment, which caused the change of scale, were the containers. These containers were used for accumulating the water of study, and their size was decisive for the rest of the experiment. It was said that the test only could take containers as much 75 L for granted.

Then, (Sansalone et al. 2011) established a requirement of 22 L/m^2-min as influent flow rate, which simulates the effect of a soft rain. This parameter depends on the cross sectional area of the sample, therefore as this surface is reduced, the flow rate over the sample is reduced as well, containers take more time to be full and the experiment can last longer. As a result, the cross sectional area of the specimen was adjusted in order to have more time for the execution of the test and get more results. This is why the decision of working with cylinder specimens with diameter 10 cm and height 4 cm was made, although the first idea was to do the experiment with samples of dimensions 32×26×4 cm, which was the shape produced initially.

The other important component of the equipment was a peristaltic pump, which could pump the required flow rate of influent to the specimen's surface. Taking into account the dimensions of the cylinder specimen, a flow rate of 0,7 L/min was needed for the experiment. It was said that there was such a pump in the laboratory, so it was continued with the design. The rest of the equipment consisted in other container or recipient for collecting the effluent, which was smaller than the previous ones (~10 L), a supporting surface and some sticker for holding the PU-Asphalt sample, and smaller recipients and a weight for gathering data.

Keeping in mind all these components and restrictions, a schematic drawing (Fig. 7) was done for a better understanding of the design and its following building. This drawing was realized with the computer program *Autodesk Inventor Professional 2018*, and it is only specified on it the diameter of the sample, because it was the only certain value then. This drawing shows two big containers, the one on the left for the overflow and the one of the right for the influent; a small cylindrical container for the effluent; and the peristaltic pump, which transport the water of study from the influent container to the specimen's surface.

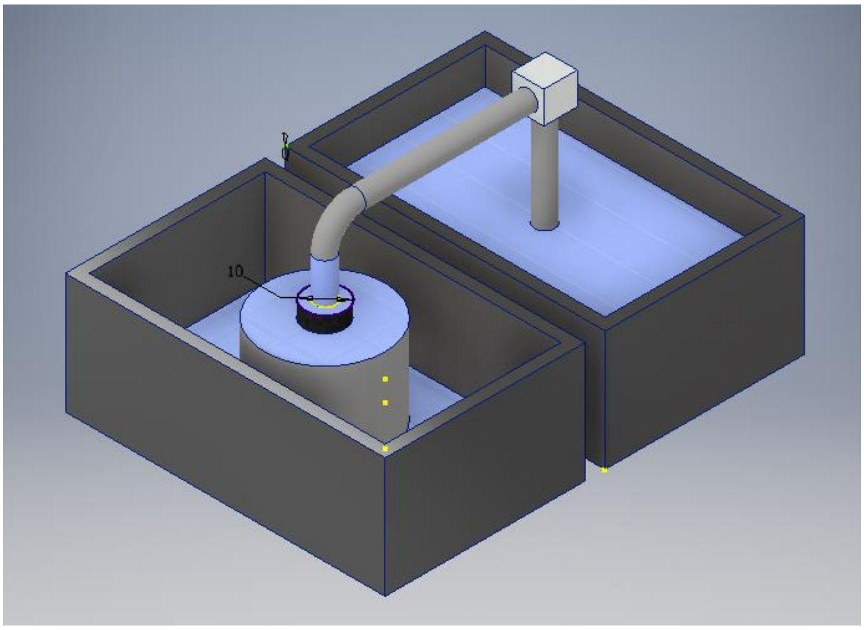

Figure 7: Schematic drawing of the filtration test.

Once the design was checked as feasible, it was time to confirm which components of the laboratory could be useful for the experiment. Firstly, the pump that was offered could pump the required flow rate of 0,7 L/min, so it was good for the experiment. It consisted in a hose of length 86 cm and two shower-shaped terminations, which simulates the common rain. For the filtration test only one of these terminations was used so that part of the influent did not go directly to the overflow. This is due to the fact that the diameter of the specimen is 10 cm, while the terminations of the pump are squares with side 20 cm. For the same reason, these squares were also reduced with some tape until the water poured from the pump only contacted the specimen's surface. Secondly, it was verified that two different containers of the laboratory could be used as influent and overflow containers, due to their appropriate size. Furthermore, the one that was going to be used as overflow container could support the termination of the pump perfectly. Then, it was checked the effluent container. After considering different possibilities, it was decided to use a tube opened by both sides. In one of the sides was placed the specimen and the other one was closed with a cap. However, this cap was really easy to remove, because when the effluent container was completely filled, it was needed to put this effluent in other recipients for its later analysis. These recipients just consisted in the buckets that are normally used for the collection of aggregates during the production of specimens.

With all these components the execution of the filtration test could be carried out. A picture of the final building of the experiment is shown afterwards (Fig. 8).

Figure 8: Final building of the filtration experiment. L-R: Influent container, pump, overflow and effluent containers (with specimen), and several recipients for keeping the effluent samples.

3.2.2 Particulate Matter

The water which is poured over the PU-Asphalt specimens contents a certain quantity of particulate matter (PM), in order to study the pass of these particulates through the sample. Solids in runoff usually have a wide particle size distribution ranging in size from less than 1 µm to greater than 10 mm at urban and highway sites (Sansalone et al. 1998). For this study, the powder that it is used as well for the production of the specimens, whose maximum wide particulate size is 0,063 mm, is selected as PM. On the other hand, (Sansalone and Teng, 2004) establishes different loadings of PM based on gathered data. These loadings, which characterized a standard runoff, go from 290 mg/L to 738 mg/L, depending on the region where the data were taken However, if these values were used in the experiment, it would probably have not worked because our measuring instruments are not extremely accurate. This is why a higher quantity of PM is needed for our project. Therefore, the decision of working with loadings between 5 and 6 g/L was taken.

3.2.3 Procedure

A constant influent (i) loading of this water (Mi) is pumped at constant head, flow rate (Qi) and concentration [mi] to the sample. Flow rate is held reasonably constant (~ 22 L/m^2-min). The cross sectional area of the specimen is 314,16 cm^2, so the flow rate pumped to the sample results in 0,7 L/min. Hydraulic head is maintained at 15 cm above the sample surface to ensure the continuous filtration of influent. As the experiment progresses, one part of the influent (effluent) passes through the sample and is collected in the effluent container, meanwhile other part that is not filtered (overflow) pours into the overflow container.

The experiment is suggested to last 30 minutes and measurements are done every 5 minutes in order to know how the parameters of study progress. In this way their evolution over time can be presented as a result.

Before starting the experiment, the equipment has to be prepared. The PU-Asphalt specimen is placed inside the effluent container, whose diameter is the same of the specimen. After that, the mass of every container has to be weighted and written down, since theses masses will be included in each weighing and they have to be subtracted in order to get the right values. Then, the influent container is filled with water (35-40 L) and the corresponding quantity of PM. It is very important to mix them properly, as the PM tends to remain at the bottom of the container. Once the influent is ready, a sample of 1L is weighted to get the density of this component.

At this moment, the experiment starts by turning on the pump, and the influent will start to be poured to the PU-Asphalt specimen. When the first 5 minutes pass, the test has to be stopped to do the measurements. For this purpose, the pump is switch off and the influent stops coming out.

The main values that have to be got from these measurements are the PM masses which pass through the specimen to the effluent container. For this, during each measurement the effluent has to be extracted from its container and kept in different recipients. The effluent is extracted just by removing a cap that was put at the bottom of the container to close it. Once the effluent is in the other recipient, it is weighted and then, a sample of 1L it is taken from it and is also weighted to get its density. Then, this sample is returned to the recipient, which is kept for a later analysis. Furthermore, both influent and overflow containers are also weighted. When all these steps are done, the experiment continues and this procedure is repeated each 5 minutes until the end of the test.

After the conclusion of the test, the effluent samples that was collected in different recipients and kept (6 per test), have to be evaluated. The important parameter that it is needed is the concentration of PM. For knowing the mass of PM of each sample, the water has to be evaporated. This is why samples of 1 L of each recipient are put in special metal recipients and introduced in the oven. When the water is totally evaporated, the metal recipients are extracted from the oven and weighted. They have been weighted before without PM, so the mass of PM is obtained as the difference.

3.2.4 Calculations

The main goal of this test is to calculate the *particle mass separation efficiency,* η_m, whose equation is as follow:

$$\eta_m(t) = \left(1 - \frac{[m_e](t)}{[m_i](t)}\right) \times 100\% \qquad (1)$$

with: $\eta_m(t)$ mass separation efficiency

$[m_e](t)$; $[m_i](t)$ effluent and influent PM concentrations

In order to obtain this index, the effluent and influent PM concentrations are needed. The influent PM concentration is already known, but it is not the effluent one. For getting this effluent PM concentration, both effluent particulate mass and volume are required. The effluent volume, as well as the influent and overflow ones, cannot be directly measured because the containers are not calibrated, so it is calculated as the ratio between their mass and their density.

$$V_e = \frac{M_e}{\rho_e} \qquad (2)$$

with: V_e total overflow and effluent volumes

M_e total overflow and effluent masses

ρ_e overflow and effluent densities

The density is calculated just as the quotient between the mass contained in a calibrated recipient and the volume calibrated.

$$\rho_e = \frac{M_{e,c}}{V_{e,c}} \qquad (3)$$

with: $M_{e,c}$ effluent mass of the calibrated volume

$V_{e,c}$ effluent calibrated volume

Then, the effluent PM concentration is calculated as the quotient between the effluent particle mass and the effluent volume. Subsequently, the particle mass separation efficiency can already be determined with all of this data.

$$[m_e] = \frac{m_e}{V_e} \qquad (4)$$

$$\eta_m(t) = \left(1 - \frac{[m_e](t)}{[m_i](t)}\right) \times 100\% \qquad (1)$$

On the other hand, for the calculation of the *strained mass, m_s*, influent, overflow and effluent particle masses are required.

$$m_S = m_i - m_O - m_e \quad (5)$$

with:	m_S	strained mass
	$m_i,\ m_O, m_e$	influent, overflow and effluent particulate mass

Firstly, the *influent particle mass*, m_i, is determined as the product of the influent PM concentration and the influent volume, which are already known. Secondly, the overflow particle mass can be obtained assuming that the overflow and influent PM concentration are the same, $[m_O] \approx [m_i]$.

$$m_i = [m_i] \cdot V_i \quad (6)$$

$$m_O = [m_O] \cdot V_O \quad (7)$$

with:	m_i , m_O	influent and overflow particle mass
	$[m_i]$, $[m_O]$	influent and overflow PM concentration
	V_i, V_O	influent and overflow volume

Influent and overflow volumes are calculated dividing their masses by their densities.

$$V_i = \frac{M_i}{\rho_i} \quad (3)\ ; \quad V_O = \frac{M_O}{\rho_O} \quad (8)$$

with	V_i ; V_O	total overflow and effluent volumes
	M_i ; M_O	total overflow and effluent masses
	ρ_i ; ρ_O	overflow and effluent densities

It is also assumed that the influent and overflow densities are the same, because their PM concentrations do not change. Influent density is obtained as the quotient between the mass contained in a calibrated recipient and the volume calibrated.

$$\rho_i = \frac{M_{i,c}}{V_{i,c}} \qquad (9)$$

with: $M_{i,c}$ influent mass of the calibrated volume

$V_{i,c}$ influent calibrated volume

Finally, effluent particulate mass is a value which is obtained during the test. Therefore, the *strained mass,* m_s, can be already calculated.

$$m_S = m_i - m_O - m_e \quad (5)$$

As the data is gathered during the test, they are introduced in an Excel sheet which has been prepared before with these calculations. In this way, the results are got faster for its later discussion.

3.2.5 Execution

The PU-bonded pavement specimens that had been previously produced were the subject of study during this test. As it was mention in *Section 2.2.2*, two different kinds of grain size distribution were analyzed (PA5 and PA8). For each distribution, three identical experiments were executed, in order to get reliable results by calculating the average of them. All the data, calculations and results of each experiment are presented in the Appendix. It is important to mention that the tests are named with two numbers. The first one is related to the grain size distribution of the specimen, and the second one just corresponds with the order of execution. For example, the test 5-1 corresponds with the first one that was realized with a sample of distribution PA5. In addition to these experiments, other two tests were carried out in order to study the clogging effect (Test 5-4 and Test 8-4).

On the other hand, each experiment lasts around 90 minutes, taking into account the preparation of itself (15 minutes), the elapsed time of 30 minutes while the test is working, the required time to collect the data each 5 minutes (20 minutes) and the following effluent evaluation (25 minutes). Moreover, it is required to wait until the water of the effluent samples is evaporated, which can suppose between 6 and 7 hours extra depending on the temperature of the oven.

4 Results and Discussion

4.1 Design and Equipment

Design and building of the equipment were relevant steps that had to be carried out in detail. During the course of such processes, several options were considered and thoroughly studied. In the end, these proceedings were fulfilled as it was previously explained in *Section 3*, but some of the most troubling decisions are more elaborate described below.

The first of these issues appeared during the design of the experiment, and it was related with the effluent container. While the test was realized, the effluent samples had to be placed in different recipients each five minutes in order to analyze each one individually later. For this reason, a container which could allow an easy and fast removal of its content had to be developed. After considering different possibilities, it was decided to use a tube that was opened by both sides. In one of them was placed the PU-bonded pavement specimen, and the other one was closed with a cap. However, this cap was really simple to insert and remove from the tube, so it can be said that it worked as a gate. As a result, an objective of the design was achieved, at the same time that a saving of time was introduced for the execution of the experiment.

The next problem that had to be overcome took place during the building of the equipment. The challenge was that the pump did not possess a controller to adjust the flow rate. This flow rate depended on both the strength of the pump and the difference of heights between the pump itself and the termination of the hose. In this way, it was really difficult to get the desired flow rate and a decision had to be taken. The solution consisted in adding a gas valve to the hose, which could regulate the flow rate. Although it was a valve made for working with gases, it also could control the output of the evaluated liquid influent because this type of valves can function with liquids too, when the required flow rate is low, as the intended range of flow rates for the filtration test was.

Other important concern that was checked was associated with the concentration of particulate matter. Although the loadings of PM depend on many factors, like the place and its weather, these values usually go from 290 mg/L to 738 mg/L (Sansalone and Teng, 2004). Such PM concentrations, which define the standard rainwater, are quite small and it had been really difficult to get accurate measurements with the equipment of the laboratory. Consequently, higher PM concentrations were required for the right development of the filtration test. Finally, the selected range was between 5 and 6 g/L, because taking into account these concentrations, the elapsed time of the experiment, and the required influent flow rate, it was concluded that the experiment would work.

The last relevant dilemma that was discussed before the execution of the test was related with the method that should be used to measure the strained particle mass, which is the one that remains inside the specimens. As it was explained in *Section 3.2.3*, the selected process consisted in the calculation of this parameter as the difference between the influent particle mass and both the overflow and effluent particle masses. For this, all these masses were previously obtained by taking the proper measurements during the execution of the filtration test and doing the subsequent calculations. On the other hand, other option was also suggested, but it was finally refused because of its complexity. This method was based on drying the PU-Asphalt specimen after the execution of the experiment. In this way, its content of water is eliminated and the strained particle mass is directly calculated by the difference between the specimen's mass after the drying and the initial specimen's mass before the execution of the test. Although this procedure seems quite easy, it was considered as unfeasible taking into account that during each experiment six measurements had to be realized in order to analyze the evolution of certain parameters over time. Subsequently, each PU-Asphalt sample would have been dried six times per experiment, which results in a large waste of time.

4.2 Execution

The main objective of the filtration test is obtaining exact results about the filtration properties and the clogging effect. Specifically, this experiment focuses on two parameters that can describe the filtration behavior of the material, which are the *strained mass,* m_s, and the *particle mass separation efficiency,* η_m. Furthermore, it is also interesting to observe the development of each volume (influent, overflow and effluent) over time, in order to evaluate the permeability of the samples. The following is a summary of the most important results, which are presented in tables and charts (Tab.3; Tab.4; Fig. 9), and they are discussed afterwards.

Table 3: Summary of the experimental results obtained from the analysis of PU-bonded pavement specimens with grain size distribution PA5.

Elapsed time, t (min)		5	10	15	20	25	30
Volume, V (L)	Influent	2,53	2,28	2,57	2,20	2,69	2,23
	Overflow	0,29	0,27	0,27	0,20	0,44	0,25
	Effluent	2,24	2,02	2,29	2,00	2,25	1,99
PM concentration, [m] (g/L)	Influent	5,72	5,72	5,72	5,72	5,72	5,72
	Effluent	2,00	2,00	2,50	2,03	2,53	2,13
Particle mass, m (g)	Influent	14,46	27,52	42,21	54,79	70,19	82,95
	Overflow	1,67	3,19	4,76	5,88	8,42	9,82
	Effluent	4,48	8,49	14,32	18,38	24,07	28,29
Strained particle mass, m_s (g)		8,31	15,84	23,13	30,53	37,70	44,84
Particle mass separation efficiency, η (%)		65,03	65,03	56,29	64,45	55,71	62,70

Table 4: Summary of the experimental results obtained from the analysis of PU-bonded pavement specimens with grain size distribution PA8.

Elapsed time, t (min)		5	10	15	20	25	30
Volume, V (L)	Influent	2,30	2,06	2,17	2,03	2,18	2,04
	Overflow	0,07	0,04	0,04	0,04	0,08	0,03
	Effluent	2,23	2,03	2,14	1,99	2,10	2,01
PM concentration, [m] (g/L)	Influent	5,71	5,71	5,71	5,71	5,71	5,71
	Effluent	2,03	2,13	2,10	2,13	2,50	2,23
Particle mass, m (g)	Influent	13,12	24,89	37,31	48,90	61,37	73,04
	Overflow	0,40	0,61	0,81	1,06	1,53	1,70
	Effluent	4,57	8,90	13,35	17,55	22,76	27,21
Strained particle mass, m_s (g)		8,14	15,37	23,15	30,30	37,08	44,12
Particle mass separation efficiency, η (%)		64,39	62,64	63,22	62,64	56,22	60,89

With regard to the volumes, it is seen that a large part of the influent passes through the specimens becoming effluent. This demonstrates the good permeability of both kinds of PU-bonded pavement. Even though it is true that the samples with grain size distribution PA8 show a better behavior, since they present insignificant values of overflow (0,0293 L – 0,0836 L). As a result, almost 98% of the influent is filtered for the PA8 samples, meanwhile this value remains in 88% for the PA5. In this way it is determined that the clogging effect does not take place during the 30 minutes of elapsed time. This effect would appear if the overflow and effluent volumes change their values, or in other words, when the overflow volume would be high while the effluent would remain too low.

Then, it is observed that the PM concentrations of each sort of PU-Asphalt are quite similar, staying between 2 g/L and 2,5 g/L. This little variation means that the filtration process presents the same characteristics during the whole experiment, which are related with the standard situation where the filtration process develops continuously without any problem. The *particle mass separation efficiency,* η_m, is based on this PM concentration values and it is dependent of them. The range of this parameter goes from 55% to 65%, which can be understood as adequate percentages for these grain size distributions, as well as for the PM concentration and size evaluated.

On the other hand, the development of the *strained mass,* m_s, over time is also much the same for both grain size distributions. But it can be observed that the one of PA5 is proportionally a bit lower due to its higher amount of overflow. In this way less particles penetrates the specimen, so the PM which is captured inside it is lower too.

Finally, influent particle mass values may be a bit lower because of the difficulty of getting a perfect and constant mixture of the water and the particles inside the influent container, since the particles tend to remain at the bottom of it. This is why the strained mass could be a bit lower too. For the same reason, the particle mass separation efficiency values may be a bit lower, because as the influent PM concentration decrease, they do as well. However, these variations would be minor and would not change the analysis of the permeability and filtration properties of this material.

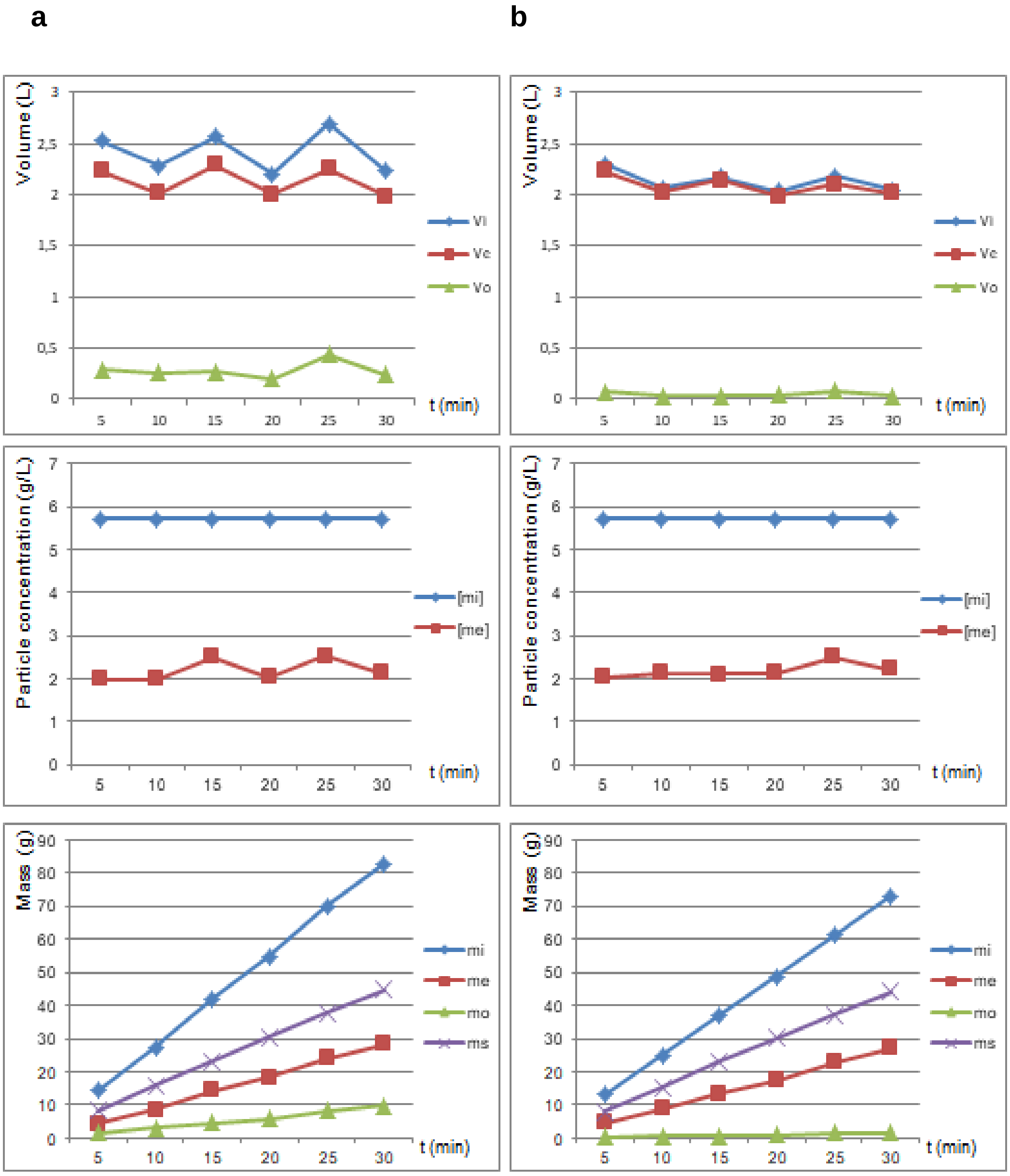

Figure 9: Charts on the experimental results of the filtration tests. Top: Volume of influent, effluent and overflow as a function of elapsed time. Middle: Related cumulative strained particle mass trapped on the specimens. Mass of influent, effluent and overflow as a function of elapsed time. Bottom: PM concentration of influent and effluent as a function of elapsed time. The subscript "i" represents influent, "e" represents effluent, "o" represents overflow and "s" represents strained. a. Experimental results obtained from the analysis of PU-bonded pavement specimens with grain size distribution PA5. b. Experimental results obtained from the analysis of PU-bonded pavement specimens with grain size distribution PA8.

4.3 Clogging

Previous results show the great hydraulic performance of the PU-bonded pavement, which is the main goal of this thesis. Nevertheless, a special emphasis about the clogging effect has been done during the literature research, and consequently such a process was also evaluated with the developed filtration test. The objective just consisted in characterising its behavior and contrasting it with the standard situation, where the clogging effect does not take place. For this purpose, some specimens with the same grain size distribution but a different type of isocyanate (component of the binder) were produced. This defect in the binder deteriorated the permeability and filtration properties of the samples and the clogging effect took place during the 30 minutes of the experiment, which was impossible with the PU-Asphalt specimens due to their good filtration property. As it was done in the last section (*Section 5.2*), a summary of the most important results is presented below (Tab. 5; Tab.6; Fig.10), and they are discussed afterwards.

Table 5: Summary of the experimental results obtained from the analysis of the clogged specimen with grain size distribution PA5.

Time elapsed, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,65	2,52	2,75	2,85	2,69	2,58
	Overflow	0,98	1,78	1,68	2,26	1,95	2,00
	Effluent	1,67	0,74	1,07	0,59	0,74	0,58
PM concentration, [m] (g/L)	Influent	5,71	5,71	5,71	5,71	5,71	5,71
	Effluent	2,30	2,00	2,10	1,60	1,70	1,50
Particle mass, m (g)	Influent	15,13	29,53	45,23	61,50	76,86	91,59
	Overflow	5,62	15,78	25,40	38,32	49,45	60,85
	Effluent	3,83	5,31	7,55	8,49	9,75	10,63
Strained particle mass, ms (g)		5,68	8,43	12,28	14,69	17,66	20,12
Particle mass separation efficiency, η (%)		59,72	64,97	63,22	71,98	70,23	73,73

Table 6: Summary of the experimental results obtained from the analysis of the clogged specimen with grain size distribution PA8.

Elapsed time, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,50	2,19	2,58	2,70	2,37	2,61
	Overflow	0,90	0,69	1,03	1,19	2,08	2,41
	Effluent	1,60	1,50	1,55	1,51	0,29	0,20
PM concentration, [m] (g/L)	Influent	5,70	5,70	5,70	5,70	5,70	5,70
	Effluent	2,60	2,20	2,50	2,60	2,07	1,50
Particle mass, m (g)	Influent	14,27	26,73	41,42	56,83	70,33	85,20
	Overflow	5,15	9,06	14,92	21,72	33,56	47,29
	Effluent	4,16	7,46	11,33	15,26	15,86	16,16
Strained particle mass, ms (g)		4,96	10,21	15,17	19,85	20,90	21,74
Particle mass separation efficiency, η (%)		54,39	61,40	56,14	54,39	63,70	73,68

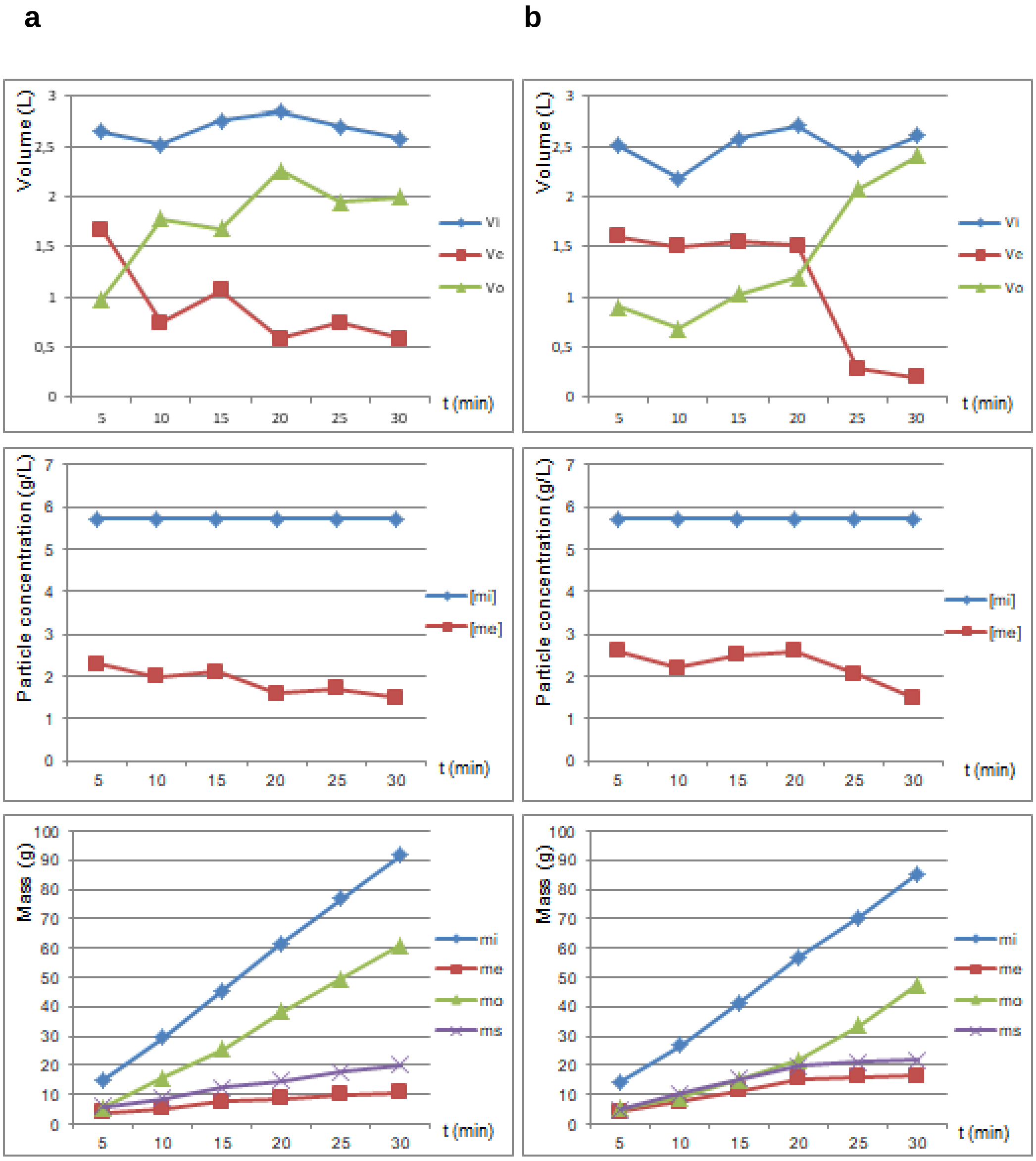

Figure 10: Charts on the experimental results of the filtration tests about the clogging effect. Top: Volume of influent, effluent and overflow as a function of elapsed time. Middle: Related cumulative strained particle mass trapped on the specimens. Mass of influent, effluent and overflow as a function of elapsed time. Bottom: PM concentration of influent and effluent as a function of elapsed time. The subscript "i" represents influent, "e" represents effluent, "o" represents overflow and "s" represents strained. a. Experimental results obtained from the analysis of specimens with grain size distribution PA5. b. Experimental results obtained from the analysis of specimens with grain size distribution PA8.

The clogging effect takes place in both cases, although its speed and strength are different. Regarding the specimen with grain size distribution PA5, it is seen that in the beginning of the experiment (first 5 minutes) the effluent volume is higher than the overflow one. However, this behaviour changes after the second measurement (10 minutes), becoming the overflow quite higher than the effluent, and it persists in the same manner until the finish of the test. Therefore, it is determined that the clogging effect takes place during the second measurement. Even so this clogging is not considered really extreme, because the strained mass continues to increase gradually.

Therefore, the reason of such difference between the overflow and effluent volumes consists in both the clogging effect and the bad permeability of the specimen.

On the other hand, the test realized with the grain size distribution PA8 specimen was a clear example of a fast and hard clogging effect. As it is observed in Fig. 11b, the first 20 minutes of the experiment correspond with a standard situation where the specimen is filtering the higher part of the influent. However, after the fourth measurement, the behaviour of the process changed utterly. From that moment, only a little part of the influent (7-12%) passed through the sample becoming effluent. This performance demonstrates clearly the appearance of the clogging effect. Furthermore, it is also perceived, that the strained mass hardly increase after the first 20 minutes, which is another evidence of the clogging effect's manifestation. Even though it is true that there is a significant volume of overflow since the beginning of the test, this occurs due to the worse permeability of the specimen, and its great increase after the fourth measurement justifies the clogging effect.

It is important to highlight too, that the range of particle mass separation efficiency which is related with the appearance of the clogging effect goes from 65% to 75%, meanwhile this percentages remain between 55% and 65% for the standard situation. Such a small difference is explained easily for both cases. In the test with grain size distribution PA5, the clogging effect is not too severe, therefore the effluent PM concentration does not vary too much in spite of the alteration of its volume. This is why the values of this index do not change too much. Then, the explanation for the test with grain size distribution PA8 just consists in the short time of this experiment in the presence of the clogging effect (last 10 minutes). Furthermore, there is an important increase in the particle mass separation efficiency between the measurements 4 and 6 (from 54,39% to 73,30%), which predicts a continued increase of this parameter.

Finally, some pictures of tested samples are presented. The first ones (Fig.11) show a PU-bonded pavement specimen with grain size distribution PA5, which has been already tested. Nevertheless, it looks as it had not been tested, considering that there is not any presence of particle matter in both its surface and its pores. This evidences its good filtration property.

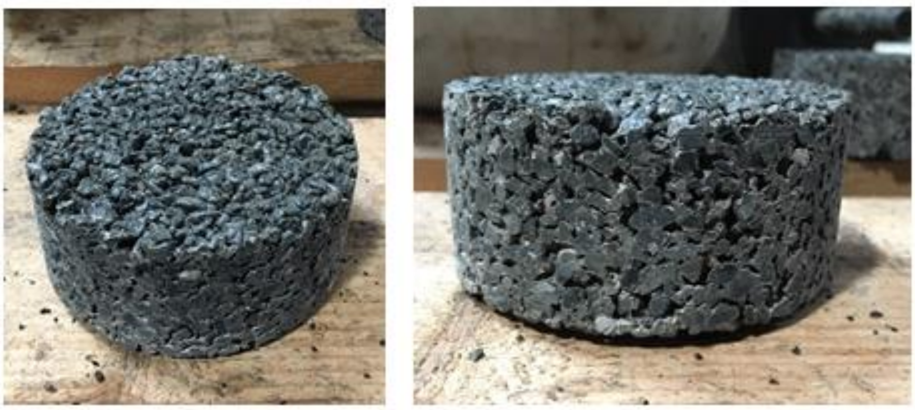

Figure 11: Tested PU-bonded pavement specimen with grain size distribution PA5.

On the other hand, Fig. 12 and Fig.13 show the specimen with grain size distribution PA8 which clogged during the execution of the experiment. It is seen that there are several accumulations of particulate matter in its surface and inside its pores, which is a clear evidence of clogging effect.

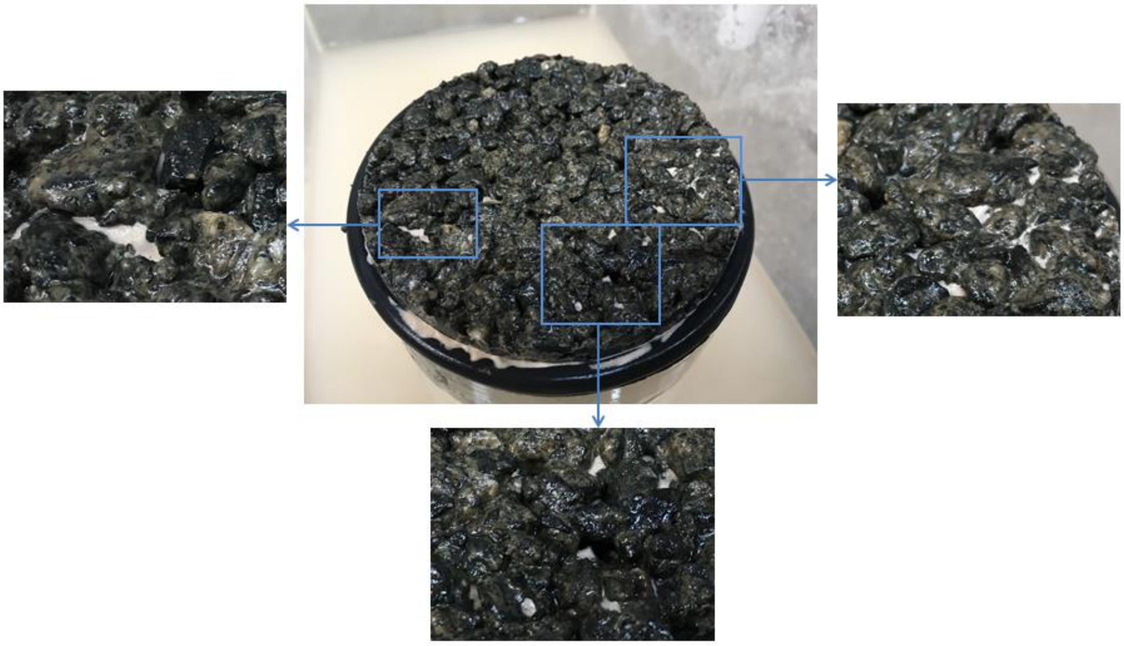

Figure 12: Accumulations of particle matter in the surface of the clogged specimen with grain size distribution PA8.

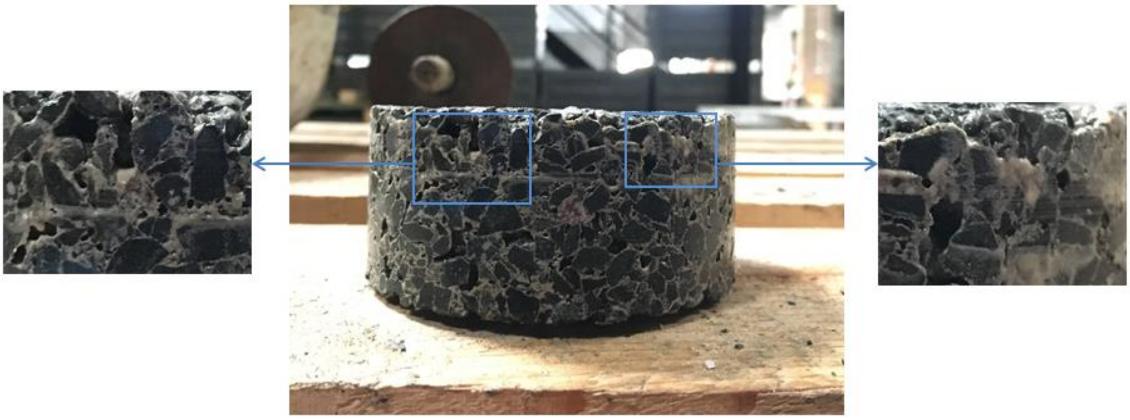

Figure 13: Accumulations of particle matter inside the pores of the clogged specimen with grain size distribution PA8.

5 Conclusion

Polyurethane bound porous pavement, as a kind of permeable pavement, possesses a high porosity that allows rainwater to pass through it into the ground below. As an infiltration surface that promotes hydrologic restoration, PU-Asphalt also functions as a filter and therefore is exposed to clogging. This study examines the filtration behaviour of the PU-bonded pavement, by defining the particles clogging behavior within the porous structure subjected to the urban pavement runoff.

Following from the goal of determining the hydraulic properties of this material, a whole filtration test was developed. This included the searching of the right idea, the design of the experiment, the building of the equipment and its consequent execution. Then, the results of the test were extensively analyzed and discussed. Two types of PU-bonded pavement were evaluated with this experiment, whose difference was related with their grain size distribution. One of them was Porous Asphalt 5 (PA5), whose biggest aggregate's size remained in 5 mm, meanwhile the other was Porous Asphalt 8 (PA8), which allowed aggregate's size until 8 mm.

The results of the test confirm the hypotheses that were presented in *Section 2.5*. Firstly, they show qualitatively the permeability of both kinds of PU-Asphalt. Although in both cases this characteristic is considered as really good, it is true that the one of the specimens with grain size distribution PA8 is better. Then, it is also proved that the clogging effect did not take place during the execution of the experiments, due to the good filtration property of the material.

Regarding the results of the *particle mass separation efficiency* (parameter directly related with the filtration property of the material), it is observed at first sight that the values for both distributions do not seem really good. In fact, the range of this parameter during the tested standard situation (without the appearance of the clogging effect) goes from 55% to 65%, which means that less than the half of the initial particles pass through the specimen. However, these results have to be analyzed in detail. This requires a comparison with other information sources, where the filtration property was also examined for other types of permeable pavements. In those experiments the proportion of effluent particles is quite similar to the one of our results. Consequently, the obtained range of values is understood as proper. In addition, our tests were carried out with high PM concentrations, which harm the filtration property of the specimens, since the separation of particles increases with the higher loadings (for the same PM size) (Sansalone et al. 2011). Therefore, it is concluded that the range of the *particle mass separation efficiency* would be lower if this material was subjected to common rainwater. As a result, the good filtration property of the polyurethane bound porous pavement is proved.

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APPENDIX

Production of Specimens

Previous calculations used for the production of specimens. The mass of both aggregates and binder is calculated with an extra 10%, due to the loss of mixture during the manufacturing.

Parameter	PA5	PA8
Aggregates density (g/cm3)	2,85	2,85
Binder density (g/cm3)	1,09	1,09
Proportion of aggregates (%)	6	6
Proportion of binder (%)	94	94
Density of the mixture (g/cm3)	2,59	2,59
Void content (%)	26	26
Calculated density (g/cm3)	1,92	1,92
Volume of the mold (cm3)	3328	3328
Mass of the specimen (g)	6388,62	6388,62
Mass of aggregates (g)	6005,30	6005,30
Mass of binder (g)	383,32	383,32

Aggregate	Proportion in Mixture (%)	
Kasteinfüller	7	6
Diabas 0/2	5	9
Diabas 2/5	88	35
Diabas 5/8	-	50

Aggregate	Mass (g)	
Kasteinfüller	462	396
Diabas 0/2	330	594
Diabas 2/5	5813	2312
Diabas 5/8	-	3303

Binder	Mass (g)	
Polyol	228	228
Isocyanate	194	194

Filtration Test 5-1

Summary of the experimental results obtained from the execution of the test 5-1.

Elapsed time, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,42	2,28	2,65	2,25	2,58	2,12
	Overflow	0,27	0,38	0,28	0,33	0,38	0,37
	Effluent	2,15	1,90	2,38	1,93	2,20	1,75
PM concentration, [m] (g/L)	Influent	5,7	5,7	5,7	5,7	5,7	5,7
	Overflow	5,7	5,7	5,7	5,7	5,7	5,7
	Effluent	2,6	2,5	2,8	2,6	2,6	2,2
Particle mass, m (g)	Influent	13,78	26,78	41,89	54,74	69,45	81,53
	Overflow	1,52	3,69	5,27	7,15	9,31	11,42
	Effluent	5,59	10,34	16,99	22,00	27,72	31,57
Total mass, M (g)	Influent	2350	2220	2580	2195	2510	2065
	Overflow	260	370	270	320	370	360
	Effluent	2083	1873	2273	2043	2103	1783
Strained particle mass, ms (g)		6,67	12,75	19,63	25,60	32,42	38,55
Particle mass separation efficiency, η (%)		54,39	56,14	50,88	54,39	54,39	61,40

Mass + Container (g)	Influent (t-1)	38260	35910	33690	31110	28915	26405
	Influent (t)	35910	33690	31110	28915	26405	24350
	Overflow	11170	11540	11810	12130	12500	12860
	Effluent	2310	2100	2500	2270	2330	2010
Volume calibrated, Vc (L)	Influent	1					
	Effluent	2,15	1,90	2,38	1,93	2,20	1,75
Mass calibrated, Mc (g)	Influent	973					
	Effluent	2083	1873	2273	2043	2103	1783
Density, ρ (g/L)	Influent	973					
	Effluent	968,84	985,79	957,05	1061,30	955,91	1018,86
Container's mass (g)	Influent	3698					
	Overflow	10910					
	Effluent	227					

Filtration Test 5-2

Summary of the experimental results obtained from the execution of the test 5-2.

Elapsed time, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,37	2,31	2,08	2,16	2,66	2,40
	Overflow	0,25	0,29	0,11	0,21	0,36	0,18
	Effluent	2,13	2,03	1,98	1,95	2,30	2,23
PM concentration, [m] (g/L)	Influent	5,72	5,72	5,72	5,72	5,72	5,72
	Overflow	5,72	5,72	5,72	5,72	5,72	5,72
	Effluent	1,4	1,5	1,9	1,6	2,4	2
Particle mass, m (g)	Influent	13,58	26,82	38,74	51,09	66,30	80,06
	Overflow	1,43	3,08	3,71	4,90	6,96	7,98
	Effluent	2,98	6,01	9,77	12,89	18,41	22,86
Total mass, M (g)	Influent	2385	2325	2080	2170	2665	2410
	Overflow	250	290	110	210	360	180
	Effluent	2023	1913	1883	1853	2193	2123
Strained particle mass, ms (g)		9,18	17,73	25,27	33,30	40,94	49,22
Particle mass separation efficiency, η (%)		75,52	73,78	66,78	72,03	58,04	65,03

Mass + Container (g)	Influent (t-1)	37410	35025	32700	30620	28450	25785
	Influent (t)	35025	32700	30620	28450	25785	23375
	Overflow	11160	11450	11560	11770	12130	12310
	Effluent	2250	2140	2110	2080	2420	2350
Volume calibrated, Vc (L)	Influent	1					
	Effluent	2,13	2,03	1,98	1,95	2,30	2,23
Mass calibrated, Mc (g)	Influent	1003					
	Effluent	2023	1913	1883	1853	2193	2123
Density, ρ (g/L)	Influent	1003					
	Effluent	952,00	944,69	953,42	950,26	953,48	954,16
Container's mass (g)	Influent	3698					
	Overflow	10910					
	Effluent	227					

Filtration Test 5-3

Summary of the experimental results obtained from the execution of the test 5-3.

Elapsed time, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,79	2,26	2,96	2,18	2,84	2,17
	Overflow	0,36	0,13	0,43	0,05	0,59	0,19
	Effluent	2,43	2,13	2,53	2,13	2,25	1,98
PM concentration, [m] (g/L)	Influent	5,74	5,74	5,74	5,74	5,74	5,74
	Overflow	5,74	5,74	5,74	5,74	5,74	5,74
	Effluent	2,0	2	2,8	1,9	2,6	2,2
Particle mass, m (g)	Influent	16,02	28,97	45,99	58,52	74,82	87,25
	Overflow	2,07	2,80	5,30	5,60	8,98	10,04
	Effluent	4,86	9,12	16,20	20,25	26,10	30,46
Total mass, M (g)	Influent	2630	2130	2795	2065	2675	2025
	Overflow	340	120	410	50	555	175
	Effluent	2328	2043	2448	2033	2258	1903
Strained particle mass, ms (g)		9,09	17,05	24,49	32,67	39,74	46,75
Particle mass separation efficiency, η (%)		65,16	65,16	51,22	66,90	54,70	61,67

Mass + Container (g)	Influent (t-1)	37820	35190	33060	30265	28200	25525
	Influent (t)	35190	33060	30265	28200	25525	23500
	Overflow	11250	11370	11780	11830	12385	12560
	Effluent	2555	2270	2675	2260	2485	2130
Volume calibrated, Vc (L)	Influent	1					
	Effluent	2,43	2,13	2,53	2,13	2,25	1,98
Mass calibrated, Mc (g)	Influent	943					
	Effluent	2328	2043	2448	2033	2258	1903
Density, ρ (g/L)	Influent	943					
	Effluent	958,02	959,15	967,59	954,46	1003,56	961,11
Container's mass (g)	Influent	3698					
	Overflow	10910					
	Effluent	227					

Filtration Test 8-1

Summary of the experimental results obtained from the execution of the test 8-1.

Elapsed time, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,18	2,01	2,42	2,03	2,31	2,27
	Overflow	0,06	0,01	0,02	0,03	0,01	0,02
	Effluent	2,13	2,00	2,40	2,00	2,30	2,25
PM concentration, [m] (g/L)	Influent	5,74	5,74	5,74	5,74	5,74	5,74
	Overflow	5,74	5,74	5,74	5,74	5,74	5,74
	Effluent	0,9	1,8	1,7	0,6	2,1	1,8
Particle mass, m (g)	Influent	12,52	24,06	37,95	49,58	62,84	75,84
	Overflow	0,32	0,38	0,50	0,64	0,70	0,79
	Effluent	1,91	5,51	9,59	10,79	15,62	19,67
Total mass, M (g)	Influent	2145	1975	2385	1990	2275	2230
	Overflow	55	10	20	25	10	15
	Effluent	2073	1963	2448	1948	2243	2073
Strained particle mass, ms (g)		10,29	18,17	27,86	38,14	46,51	55,38
Particle mass separation efficiency, η (%)		84,32	68,64	70,38	89,55	63,41	68,64

Mass + Container (g)	Influent (t-1)	36290	34145	32170	29785	27795	25520
	Influent (t)	34145	32170	29785	27795	25520	23290
	Overflow	10965	10975	10995	11020	11030	11045
	Effluent	2300	2190	2675	2175	2470	2300
Volume calibrated, Vc (L)	Influent	1					
	Effluent	2,13	2,00	2,40	2,00	2,30	2,25
Mass calibrated, Mc (g)	Influent	984					
	Effluent	2073	1963	2448	1948	2243	2073
Density, ρ (g/L)	Influent	984					
	Effluent	975,53	981,50	1020,00	974,00	975,22	921,33
Container's mass (g)	Influent	3698					
	Overflow	10910					
	Effluent	227					

Filtration Test 8-2

Summary of the experimental results obtained from the execution of the test 8-2.

Elapsed time, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,27	1,98	2,00	1,87	2,30	1,89
	Overflow	0,05	0,06	0,06	0,03	0,18	0,05
	Effluent	2,23	1,93	1,94	1,84	2,13	1,84
PM concentration, [m] (g/L)	Influent	5,68	5,68	5,68	5,68	5,68	5,68
	Overflow	5,68	5,68	5,68	5,68	5,68	5,68
	Effluent	3,0	2,2	2,2	3,2	2,7	2,2
Particle mass, m (g)	Influent	12,90	24,16	35,51	46,15	59,24	69,98
	Overflow	0,27	0,59	0,91	1,11	2,12	2,42
	Effluent	6,68	10,91	15,18	21,07	26,80	30,85
Total mass, M (g)	Influent	2190	1905	1925	1805	2220	1820
	Overflow	45	55	55	33	172	50
	Effluent	2153	1858	883	1783	2073	1788
Strained particle mass, ms (g)		5,96	12,66	19,41	23,98	30,31	36,71
Particle mass separation efficiency, η (%)		47,18	61,27	61,27	43,66	52,46	61,27

Mass + Container (g)	Influent (t-1)	38990	36800	34895	32970	31165	28945
	Influent (t)	36800	34895	32870	31165	28945	27125
	Overflow	10955	11010	11065	11098	11270	11320
	Effluent	2380	2085	1110	2010	2300	2015
Volume calibrated, Vc (L)	Influent	1					
	Effluent	2,23	1,93	1,94	1,84	2,13	1,84
Mass calibrated, Mc (g)	Influent	963					
	Effluent	2153	1858	883	1783	2073	1788
Density, ρ (g/L)	Influent	963					
	Effluent	967,64	965,19	455,15	969,02	975,53	971,74
Container's mass (g)	Influent	3698					
	Overflow	10910					
	Effluent	227					

Filtration Test 8-3

Summary of the experimental results obtained from the execution of the test 8-3.

Elapsed time, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,44	2,19	2,11	2,19	1,94	1,97
	Overflow	0,11	0,04	0,03	0,07	0,06	0,02
	Effluent	2,33	2,15	2,08	2,13	1,88	1,95
PM concentration, [m] (g/L)	Influent	5,71	5,71	5,71	5,71	5,71	5,71
	Overflow	5,71	5,71	5,71	5,71	5,71	5,71
	Effluent	2,2	2,4	2,4	2,6	2,7	2,7
Particle mass, m (g)	Influent	13,92	26,44	38,46	50,98	62,04	73,29
	Overflow	0,62	0,86	1,03	1,42	1,77	1,89
	Effluent	5,13	10,29	15,27	20,79	25,85	31,12
Total mass, M (g)	Influent	2360	2125	2035	2120	1875	1910
	Overflow	105	40	30	65	60	20
	Effluent	2268	2083	2028	2063	1833	1893
Strained particle mass, ms (g)		8,18	15,29	22,16	28,77	34,42	40,29
Particle mass separation efficiency, η (%)		61,47	57,97	57,97	54,47	52,71	52,71

Mass + Container (g)	Influent (t-1)	37765	35405	33280	31245	29125	27250
	Influent (t)	35405	33280	31245	29125	27250	25340
	Overflow	11015	11055	11085	11150	11210	11230
	Effluent	2495	2310	2255	2290	2060	2120
Volume calibrated, Vc (L)	Influent	1					
	Effluent	2,33	2,15	2,08	2,13	1,88	1,95
Mass calibrated, Mc (g)	Influent	968					
	Effluent	2268	2083	2028	2063	1833	1893
Density, ρ (g/L)	Influent	968					
	Effluent	973,39	968,84	977,35	970,82	977,60	970,77
Container's mass (g)	Influent	3698					
	Overflow	10910					
	Effluent	227					

Average of the Filtration Tests 5-1, 5-2 and 5-3

Elapsed time, t (min)			5	10	10	20	25	30
Test 5-1	Volume, V (L)	Influent	2,42	2,28	2,65	2,25	2,58	2,12
		Overflow	0,27	0,38	0,28	0,33	0,38	0,37
		Effluent	2,15	1,90	2,38	1,93	2,20	1,75
	PM concentration, [m] (g/L)	Influent	5,7	5,7	5,7	5,7	5,7	5,7
		Effluent	2,6	2,5	2,8	2,6	2,6	2,2
	Particle mass, m (g)	Influent	13,78	26,78	41,89	54,74	69,45	81,53
		Overflow	1,52	3,69	5,27	7,15	9,31	11,42
		Effluent	5,59	10,34	16,99	22,00	27,72	31,57
	Strained particle mass, ms (g)		6,67	12,75	19,63	25,60	32,42	38,55
	Particle mass separation efficiency, η (%)		54,39	56,14	50,88	54,39	54,39	61,40
Test 5-2	Volume, V (L)	Influent	2,37	2,31	2,08	2,16	2,66	2,4
		Overflow	0,25	0,29	0,11	0,21	0,36	0,18
		Effluent	2,13	2,03	1,98	1,95	2,3	2,23
	PM concentration, [m] (g/L)	Influent	5,72	5,72	5,72	5,72	5,72	5,72
		Effluent	1,4	1,5	1,9	1,6	2,4	2
	Particle mass, m (g)	Influent	14	26,82	38,74	51,09	66,30	80,06
		Overflow	1,43	3,08	3,71	4,90	6,96	7,98
		Effluent	3	6	10	13	18	23
	Strained particle mass, ms (g)		9,18	17,73	25,27	33,3	40,94	49,22
	Particle mass separation efficiency, η (%)		75,52	73,78	66,78	72,03	58,04	65,03
Test 5-3	Volume, V (L)	Influent	2,79	2,26	2,96	2,18	2,84	2,17
		Overflow	0,36	0,13	0,43	0,05	0,59	0,19
		Effluent	2,43	2,13	2,53	2,13	2,25	1,98
	PM concentration, [m] (g/L)	Influent	5,74	5,74	5,74	5,74	5,74	5,74
		Effluent	2	2	2,8	1,9	2,6	2,2
	Particle mass, m (g)	Influent	16,02	28,97	45,99	58,52	74,82	87,25
		Overflow	2,07	2,8	5,3	5,6	8,98	10,04
		Effluent	4,86	9,12	16,2	20,25	26,1	30,46
	Strained particle mass, ms (g)		9,09	17,05	24,49	32,67	39,74	46,75
	Particle mass separation efficiency, η (%)		65,16	65,16	51,22	66,9	54,7	61,67
Average	Volume, V (L)	Influent	2,53	2,28	2,57	2,20	2,69	2,23
		Overflow	0,29	0,27	0,27	0,20	0,44	0,25
		Effluent	2,24	2,02	2,29	2,00	2,25	1,99
	PM concentration, [m] (g/L)	Influent	5,72	5,72	5,72	5,72	5,72	5,72
		Effluent	2	2	2,5	2,03	2,53	2,13
	Particle mass, m (g)	Influent	14,46	27,52	42,21	54,79	70,19	82,95
		Overflow	1,67	3,19	4,76	5,88	8,42	9,82
		Effluent	4,48	8,49	14,32	18,38	24,07	28,29
	Strained particle mass, ms (g)		8,31	15,84	23,13	30,53	37,70	44,84
	Particle mass separation efficiency, η (%)		65,03	65,03	56,29	64,45	55,71	62,70

Average of the Filtration Tests 8-1, 8-2 and 8-3

Elapsed time, t (min)			5	10	10	20	25	30
Test 8-1	Volume, V (L)	Influent	2,18	2,07	2,49	2,11	2,42	2,39
		Overflow	0,06	0,07	0,09	0,11	0,12	0,14
		Effluent	2,13	2,00	2,40	2,00	2,30	2,25
	PM concentration, [m] (g/L)	Influent	5,68	5,68	5,68	5,68	5,68	5,68
		Effluent	3,0	2,2	2,2	3,2	2,7	2,2
	Particle mass, m (g)	Influent	12,90	24,16	35,51	46,15	59,24	69,98
		Overflow	0,27	0,59	0,91	1,11	2,12	2,42
		Effluent	6,68	10,91	15,18	21,07	26,80	30,85
	Strained particle mass, ms (g)		8,14	15,37	23,15	30,30	37,08	44,12
	Particle mass separation efficiency, η (%)		64,39	62,64	63,22	62,64	56,22	60,89
Test 8-2	Volume, V (L)	Influent	2,27	1,98	2	1,87	2,3	1,89
		Overflow	0,05	0,06	0,06	0,03	0,18	0,05
		Effluent	2,23	1,93	1,94	1,84	2,13	1,84
	PM concentration, [m] (g/L)	Influent	5,68	5,68	5,68	5,68	5,68	5,68
		Effluent	3	2,2	2,2	3,2	2,7	2,2
	Particle mass, m (g)	Influent	13	24,16	35,51	46,15	59,24	69,98
		Overflow	0,27	0,59	0,91	1,11	2,12	2,42
		Effluent	7	11	15	21	27	31
	Strained particle mass, ms (g)		5,96	12,66	19,41	23,98	30,31	36,71
	Particle mass separation efficiency, η (%)		47,18	61,27	61,27	43,66	52,46	61,27
Test 8-3	Volume, V (L)	Influent	2,44	2,19	2,11	2,19	1,94	1,97
		Overflow	0,11	0,04	0,03	0,07	0,06	0,02
		Effluent	2,33	2,15	2,08	2,13	1,88	1,95
	PM concentration, [m] (g/L)	Influent	5,71	5,71	5,71	5,71	5,71	5,71
		Effluent	2,2	2,4	2,4	2,6	2,7	2,7
	Particle mass, m (g)	Influent	13,92	26,44	38,46	50,98	62,04	73,29
		Overflow	0,62	0,86	1,03	1,42	1,77	1,89
		Effluent	5,13	10,29	15,27	20,79	25,85	31,12
	Strained particle mass, ms (g)		8,18	15,29	22,16	28,77	34,42	40,29
	Particle mass separation efficiency, η (%)		61,47	57,97	57,97	54,47	52,71	52,71
Average	Volume, V (L)	Influent	2,30	2,06	2,17	2,03	2,18	2,04
		Overflow	0,07	0,04	0,04	0,04	0,08	0,03
		Effluent	2,23	2,03	2,14	1,99	2,10	2,01
	PM concentration, [m] (g/L)	Influent	5,71	5,71	5,71	5,71	5,71	5,71
		Effluent	2,03	2,13	2,1	2,13	2,50	2,23
	Particle mass, m (g)	Influent	13,12	24,89	37,31	48,90	61,37	73,04
		Overflow	0,40	0,61	0,81	1,06	1,53	1,70
		Effluent	4,57	8,90	13,35	17,55	22,76	27,21
	Strained particle mass, ms (g)		8,14	15,37	23,15	30,30	37,08	44,12
	Particle mass separation efficiency, η (%)		64,39	62,64	63,22	62,64	56,22	60,89

Filtration Test 5-4

Summary of the experimental results obtained from the execution of the test 5-4, which corresponds with the clogged specimen with grain size distribution PA5.

Elapsed time, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,65	2,52	2,75	2,85	2,69	2,58
	Overflow	0,98	1,78	1,68	2,26	1,95	2,00
	Effluent	1,67	0,74	1,07	0,59	0,74	0,58
PM concentration, [m] (g/L)	Influent	5,71	5,71	5,71	5,71	5,71	5,71
	Overflow	5,71	5,71	5,71	5,71	5,71	5,71
	Effluent	2,3	2	2,1	1,6	1,7	1,5
Particle mass, m (g)	Influent	15,13	29,53	45,23	61,50	76,86	91,59
	Overflow	5,62	15,78	25,40	38,32	49,45	60,85
	Effluent	3,83	5,31	7,55	8,49	9,75	10,63
Total mass, M (g)	Influent	2500	2375	2595	2690	2540	2430
	Overflow	928	1678	1588	2134	1839	1882
	Effluent	1597	719	1023	512	684	557
Strained particle mass, ms (g)		5,68	8,43	12,28	14,69	17,66	20,12
Particle mass separation efficiency, η (%)		59,72	64,97	63,22	71,98	70,23	73,73

Mass + Container (g)	Influent (t-1)	34040	31540	29165	26570	23885	21345
	Influent (t)	31540	29165	26570	23885	21345	18915
	Overflow	11838	12588	12498	13044	12749	12792
	Effluent	1824	946	1250	739	911	784
Volume calibrated, Vc (L)	Influent	1					
	Effluent	1,67	0,74	1,07	0,59	0,74	0,58
Mass calibrated, Mc (g)	Influent	943					
	Effluent	1597	719	1023	512	684	557
Density, ρ (g/L)	Influent	943					
	Effluent	958,65	970,40	959,34	871,67	924,85	953,68
Container's mass (g)	Influent	3698					
	Overflow	10910					
	Effluent	227					

Filtration Test 8-4

Summary of the experimental results obtained from the execution of the test 8-4, which corresponds with the clogged specimen with grain size distribution PA8.

Elapsed time, t (min)		5	10	10	20	25	30
Volume, V (L)	Influent	2,50	2,19	2,58	2,70	2,37	2,61
	Overflow	0,90	0,69	1,03	1,19	2,08	2,41
	Effluent	1,60	1,50	1,55	1,51	0,29	0,20
PM concentration, [m] (g/L)	Influent	5,7	5,7	5,7	5,7	5,7	5,7
	Overflow	5,7	5,7	5,7	5,7	5,7	5,7
	Effluent	2,6	2,2	2,5	2,6	2,06	1,5
Particle mass, m (g)	Influent	14,27	26,73	41,42	56,83	70,33	85,20
	Overflow	5,15	9,06	14,92	21,72	33,56	47,29
	Effluent	4,16	7,46	11,33	15,26	15,86	16,16
Total mass, M (g)	Influent	2410	2105	2485	2600	2280	2515
	Overflow	870	660	990	1150	2000	2320
	Effluent	1563	1448	1603	1473	243	153
Strained particle mass, ms (g)		4,96	10,21	15,17	19,85	20,90	21,74
Particle mass separation efficiency, η (%)		54,39	61,40	56,14	54,39	63,70	73,68

Mass + Container (g)	Influent (t-1)	38130	35720	33615	31130	28530	26250
	Influent (t)	35720	33615	31130	285230	26250	23735
	Overflow	11780	12440	13430	14580	16580	18900
	Effluent	1790	1675	1830	1700	470	380
Volume calibrated, Vc (L)	Influent	1					
	Effluent	1,60	1,50	1,55	1,51	0,29	0,20
Mass calibrated, Mc (g)	Influent	963					
	Effluent	1563	1448	1603	1473	243	153
Density, ρ (g/L)	Influent	963					
	Effluent	976,88	965,33	1034,19	975,50	837,93	765,00
Container's mass (g)	Influent	3698					
	Overflow	10910					
	Effluent	227					

Eidesstattliche Versicherung

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Development of Hydraulic Properties in PU-Bonded Pavement

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*Nichtzutreffendes bitte streichen

Belehrung:

§ 156 StGB: Falsche Versicherung an Eides Statt

Wer vor einer zur Abnahme einer Versicherung an Eides Statt zuständigen Behörde eine solche Versicherung falsch abgibt oder unter Berufung auf eine solche Versicherung falsch aussagt, wird mit Freiheitsstrafe bis zu drei Jahren oder mit Geldstrafe bestraft.

§ 161 StGB: Fahrlässiger Falscheid; fahrlässige falsche Versicherung an Eides Statt

(1) Wenn eine der in den §§ 154 bis 156 bezeichneten Handlungen aus Fahrlässigkeit begangen worden ist, so tritt Freiheitsstrafe bis zu einem Jahr oder Geldstrafe ein.

(2) Straflosigkeit tritt ein, wenn der Täter die falsche Angabe rechtzeitig berichtigt. Die Vorschriften des § 158 Abs. 2 und 3 gelten entsprechend.

Die vorstehende Belehrung habe ich zur Kenntnis genommen:

Aachen, 28.07.2017

Ort, Datum

Unterschrift