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The Influence of Fibers from Domestic Laundry Wastewater on the Clogging Process of a Filter

Jakub Nieć [1,*], Natalia Walczak [1], Marcin Spychała [1] and Zbigniew Walczak [2]

[1] Department of Hydraulic and Sanitary Engineering, Poznan University of Life Sciences, 60-637 Poznań, Poland; natalia.walczak@up.poznan.pl (N.W.); marcin.spychala@up.poznan.pl (M.S.)
[2] Department of Construction and Geoengineering, Poznan University of Life Sciences, 60-637 Poznań, Poland; zbigniew.walczak@up.poznan.pl
* Correspondence: jakub.niec@up.poznan.pl

Abstract: This study presents the impact of the size and shape of particles in laundry wastewater on the clogging process of a porous material. Clogging can be defined as a mechanical limitation of flow through porous media. The process of mechanical clogging was investigated in this study. The research was conducted in laboratory conditions in a filter column filled with glass beads whose diameter corresponded to coarse sand. The results reveal the influence of graywater quality on filter hydraulic conductivity and bed clogging, showing the impact of fiber particles in wastewater (sewage from home laundry) on the clogging process in soil. The results confirm that fiber particles significantly reduce filter permeability, particularly due to the formation of a filter cake. As analyzed in this paper, the distribution of quantitative data on particles of different sizes found in laundry wastewater indicates that they mainly accumulate in the upper layer, where particles with fiber lengths ranging from 0 to 1600 μm can be found. The average length of the fibers decreased with increasing depth. At a depth of approximately 10 cm, fibers with dimensions in the range of 0 to 100 μm were predominantly observed.

Keywords: hydraulic conductivity; gravity filtration; graywater; domestic laundry; fiber particles

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1. Introduction

Water is a natural resource that must be used wisely. Climate change affects the water cycle, for example, by changing the frequency and intensity of rainfall [1]. Therefore, actions to reduce the discharge of wastewater into the sewerage system through land retention are desirable [2]. It can be assumed that laundry wastewater is a type of graywater, and in European households, it is produced at nearly 60 L per washing cycle depending on the country and washing machines used [3,4]. Graywater is reused or disposed of by introducing it into porous media, such as soil, which can also lead to adverse effects. When liquids contaminated with suspended solids are introduced into porous media, there is often a danger of clogging, filling the spaces between soil grains with material that reduces hydraulic conductivity. Although graywater appears to be less dangerous in terms of clogging compared to domestic wastewater, for example, it is suspected and confirmed by many authors that particles that come from laundry, for example, can also pose a significant threat of intense clogging. This is because a large number of particles come from washing clothes. Additionally, fibers from washing clothes can be an important source of microplastics [5].

Filtration is "the process of separation of heterogeneous systems using porous baffles that stop one phase of these systems and other impermeable" systems [6] (Latin: filtrum—felt used in antiquity to strain impurities from liquid).

Filtration is a complex process comprising several individual processes involving the distribution of the solid–liquid phase. These processes affect the removal of particles of varying sizes.

Clogging is one of the most common effects of filtration in a porous material, especially when the medium is wastewater. Some researchers have found that clogging occurs in a relatively thin upper layer (0–15 cm in size) (for fine and medium sand, the effective sizes are 0.30 mm and 0.60 mm, respectively; for the uniformity coefficient, d60/d10, the values are 1.4 and 1.66, respectively) [7] of the filter and that clogging matter consists of inorganic and organic solids.

The clogging process causes a reduction in flow, which can be determined by the resistance factor, which is equal to the inverse of the hydraulic coefficient. Some methods of determining the hydraulic coefficient are more suitable for low-permeability soils than others [8]. For well-permeable materials, permeability should be estimated using the unsteady-state flow method.

Another factor influencing the clogging process is the soil porosity of the compacted soil, which depends on the arrangement of grains. Slichter [9] first studied the essence of this assumption in 1899 in a simple model of land with ideal spherical particles of uniform diameter (Figure 1) [10]. Błażejewski and Murat-Błażejewska [11] presented the possible ways that grains spherical as an example of ideal soil: simple cubic–cubic, orthorhombic II–II orthorhombic, body-centered cubic–rhombohedral, orthorhombic I–I orthorhombic, tetragonal sphenoidal–tetragonal, and rhombohedral hexagonal–rhombohedral arrangements.

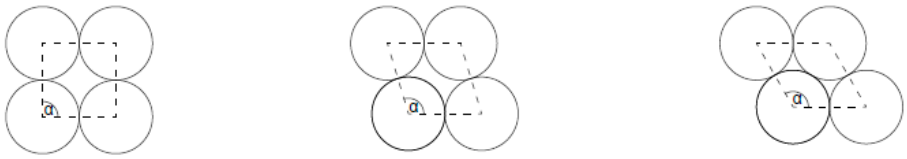

Figure 1. Various arrangements with a porous space ranging from 1500 through 900 to 500 (from left to right).

Suspended solids (SSs) are an essential feature of graywater. Jefferson et al. [12] observed a low ratio of suspended solids to turbidity in graywater. The particle size distribution in graywater from showers, baths, and hand basins ranged from 27.1 to 33.2 µm. However, the observed size of particles like hair, skin, and soap in graywater can be much higher than the range of 200–2000 µm.

Graywater also includes fibrous particles, which Spychala et al. [13], according to OECD 110 [14], defined as water-insoluble particles wherein the ratio of length-to-diameter is greater than or equal to three and wherein the particles have a diameter of less than or equal to 100 µm. It is recommended that particle fibers be measured using a microscope. Virtually all have a diameter much wider than the range of 0.05 to 5000 µm (the upper value is visible to the naked eye), and all fiber types can be detected using a microscope. Particles less than 10 µm in size are recommended for testing using electron microscopy.

Particle properties related to shape, density, and some other features can influence both the sieving (filtration) and sedimentation processes, especially their dynamics (velocity).

Particle (including synthetic fibers contained in graywater) migration is influenced by many factors, such as particle properties (hydrophobicity, tendency to have an agglomerate formation, or a large specific surface area), medium properties (e.g., pore structure), hydraulic conditions, and the water's physicochemical properties [15].

Many features can impact the filtration and clogging processes. Some are related to fiber origination or material, including the degree of cross-sectional swelling, the specific gravity, width, cellulose/lignin content, wicking, texture, etc.

Particle shape is one of the most critical factors for filter media [16,17]. For spherical filter media particles, one crucial parameter is the particle's spatial distribution [11].

Many authors [15,18] emphasize that one of the main sources of microplastics in the environment is graywater from textile washing (grinding and wear of textiles), posing a potential threat to ecological systems and human health.

Some researchers suggest that particles originating from laundry graywater (synthetic fibers) are one of the main contents of marine sediments. This is confirmed by the similar fiber content in wastewater and marine sediments (78% polyester, 9% polyamide, 7% polypropylene, and 5% acrylic) [19,20]. Washing machine effluent contains approx. 120 (blankets) to 300 fibers (fleece) for every kg of washed fabric [21]. Over 1900 fibers from a single garment are released into graywater during a single wash cycle [5]. Some parts of fibers are released from improperly disposing hygiene products into wastewater [22]. As a result of regular use or tumble drying, textile fibers and dust are also released into the air [23].

Even though previous studies have used natural or reference materials, there is a lack of data, especially mathematical data (modeling descriptions), for intermediate/mixed conditions, e.g., processes cannot be averaged for cross-section filters when there are privileged flow paths in the filter material.

This study aimed to assess the influence of the size and shape of particles in laundry wastewater on the clogging process of highly permeable material.

2. Methodology

The relationship between the shape of the soil grains and the filtration process is an important issue, mainly due to the geometry of the particles and the structure of their surfaces; these factors determine the size and shape of the pore spaces, which determine the flow conditions of the filtering water. Among the factors that determine the behavior of a porous material are the grain size, mineral composition, and the shape and configuration of the particle surfaces. Total porosity considers the total pore space of the soil. It depends largely on the uniformity of the soil grain size. Therefore, evenly graded soils have a much higher porosity than differently graded soils because smaller particles fill the pore spaces between larger particles. In this study, glass balls with a 1.5 mm diameter were used. The glass balls have a density of about 2.50 g/cm^3 and offer good chemical resistance. Depending on their arrangement, they can form a maximum pore space size ranging from 500 through 900 to 1500 µm. Three possible configurations were analyzed and are presented in Figure 1.

Research was conducted on laundry wastewater collected from a four-person household. Clothes were washed daily, and the distribution of materials was about 85% cotton, 24% polyester, and 1% additives such as elastane and viscose. The standard washing cycle was carried out in a temperature range of 45 °C to 60 °C, predominating at 45 °C in a 2012 front-loading washing machine [24].

According to the scheme presented in Figure 2, the wastewater was first filtered through a strainer with diameters equal to 1.0, 0.125, and 0.071 mm.

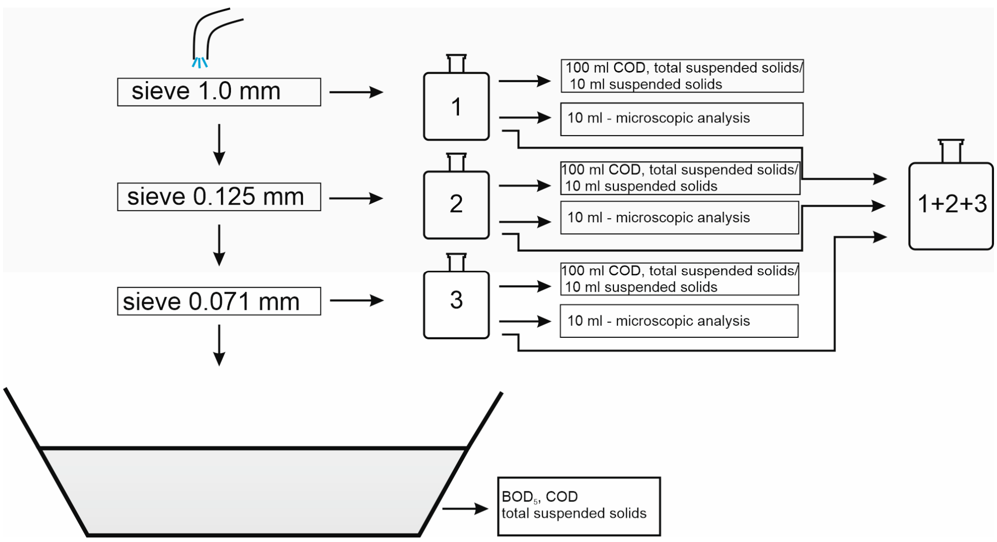

Figure 2. The first stage of laundry wastewater fractional.

The particle shape and size were analyzed after each filtration. Particular attention was paid to the number of filamentous particles [13]. The measurements also included qualitative analyses of the chemical oxygen demand (COD_{Cr}), biological oxygen demand (BOD_5), total solids (TSs), total suspended solids (TSSs), and volatile suspended solids (VSSs). All parameters are expressed in mg/L. The retained particles on the sieves were rinsed and mixed with distilled water to avoid influencing the hydraulic conductivity of the colloids contained in wastewater [25]. Image investigations were conducted to analyze the samples [26] after filtration (trapped on sieves), and the results are presented in Figure 3.

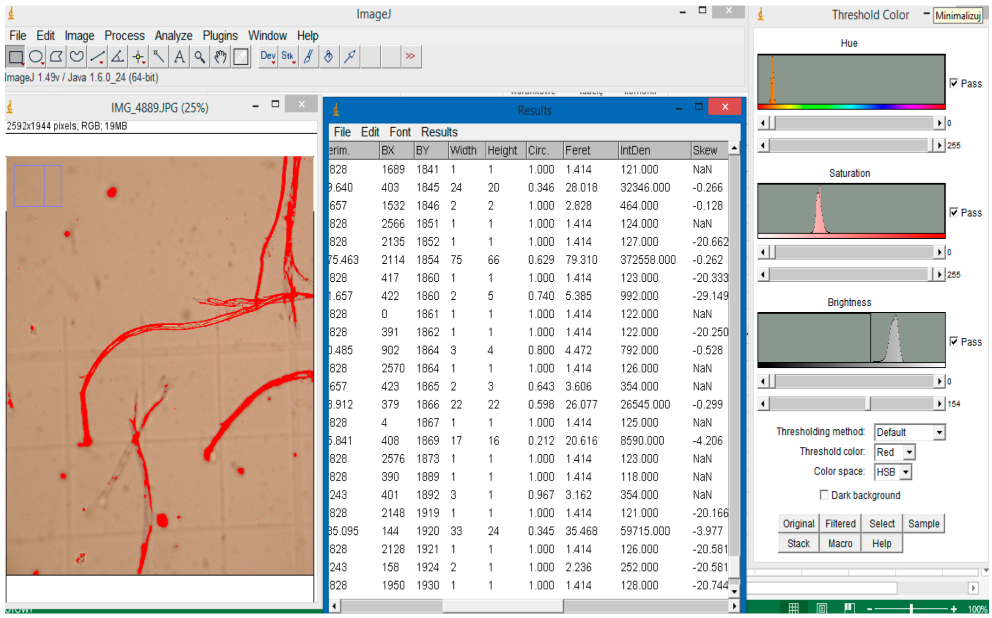

Figure 3. Print screen from image analysis.

The following samples were collected before and after rinsing and were measured. All washed particles from the three sieves were mixed, and a 300 mL sample was obtained and divided into three equal doses of 100 mL. The entire dose was dispensed onto the column in three portions. These samples were used to check the influence of laundry wastewater (trapped on sieves—mainly fibrous particles) on porous material permeability. The clogging process was determined as a hydraulic conductivity change. Hydraulic conductivity was measured in a transparent pipe-filled porous material (filter) made of glass balls. The used material was homogeneous to avoid influencing the variable arrangements and is similar to coarse sand with a diameter of 1.5 mm. Homogeneous filter material in the form of glass beads was used to simulate the most optimal material for filters to treat various types of wastewater. In order to prevent clogging, the grain size of the filter material (for example, gravel) should be as homogeneous as possible because the greater the heterogeneity of the filter material's ground grain size, the greater the danger and the greater the dynamics of the clogging process. The balls were randomly placed, which did not preclude the creation of preferential flow during migration. Glass filter media, such as cullet, are commonly used to treat wastewater and drinking water and to clean swimming pool water [27].

The 10 cm high filter was divided into pieces 2 cm in height (scheme Figure 4) and was installed in the transparent pipe with a 4.0 cm diameter and 40 cm height.

Solids in laundry wastewater are estimated to have an influence on the clogging process due to hydraulic conductivity (HC) changes. Hydraulic conductivity measurements were carried out using the falling head method (from 40 cm to 15 cm above the filter), which is appropriate for permeable soil [5]. The results were obtained by solving Equation (1) [28]:

$$K_{us} = 2.3\frac{l}{t}\log\left(\frac{H_0}{H_t}\right) \tag{1}$$

where K_{us}—the permeability estimated using unsteady-state flow, m/s; l—the thickness of the filtration layer, m; t—the time it takes for the water surface level to fall from H_0 to H_t, s; H_0—the height of the water level at the start of the measurement, m; and H_t—the height of the water level at the end of the measurement, m.

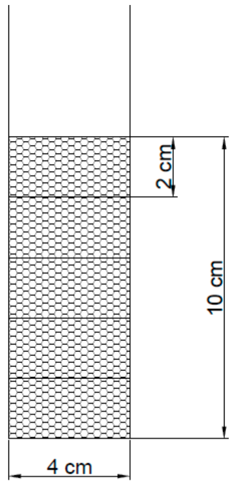

Figure 4. Filter scheme.

After adding suspended solids to the column, measurements of falling water (measurements of HC) were taken after adding distilled water to the H_0 level (40 cm above the filter surface). The falling head test was repeated three times after adding a total of 100, 200, and 300 mL of laundry wastewater with suspension.

The last step of the measurement was partitioning the columns and determining the content of accumulated dry residue at different depths of the filter. Images of the division are shown in Figure 5.

Figure 5. The partitioning of columns with accumulated VSSs at different depths. 1a represents the highest filter level (the inlet to the filter), and 5a represents the lowest (the outflow from the filter).

At the end of the research, statistical analyses were conducted.

3. Results

More than 150 L of laundry wastewater was used for the measurements. The quality of the laundry wastewater was measured after straining, and the results of the repetitions with standard statistical measures are presented in Table 1. The values of the wastewater quality indicators were determined in accordance with standards (for COD: PN-ISO 6060 [29]; for TSS: PN-EN 872 [30]). Water quality was measured by the water utility and verified in accordance with the law.

Table 1. The quality of laundry wastewater after filtration through sieves (the results are presented as the mean and standard deviation).

Parameter	Test No. 1 (4 April)	Test No. 2 (28 April)	Test No. 3 (24 May)
Chemical oxygen demand (COD_{Cr})	607.67 ± 2.52	698.33 ± 7.64	1088.33 ± 2.89
Biological oxygen demand (BOD_5)	300.0 ± 0	323.33 ± 5.77	513.33 ± 11.55
Total solids (TSs)	375.20 ± 12.08	351.87 ± 31.766	775.73 ± 2.66
Volatile suspended solids (VSSs)	227.47 ± 14.84	185.60 ± 17.24	529.60 ± 81.44
Total suspended solids (TSSs)	147.73 ± 2.89	166.27 ± 15.77	246.13 ± 82.56

Figure 6 presents the fiber length distribution after filtering through a sieve with diameters equal to 1.0, 0.125, and 0.071 mm.

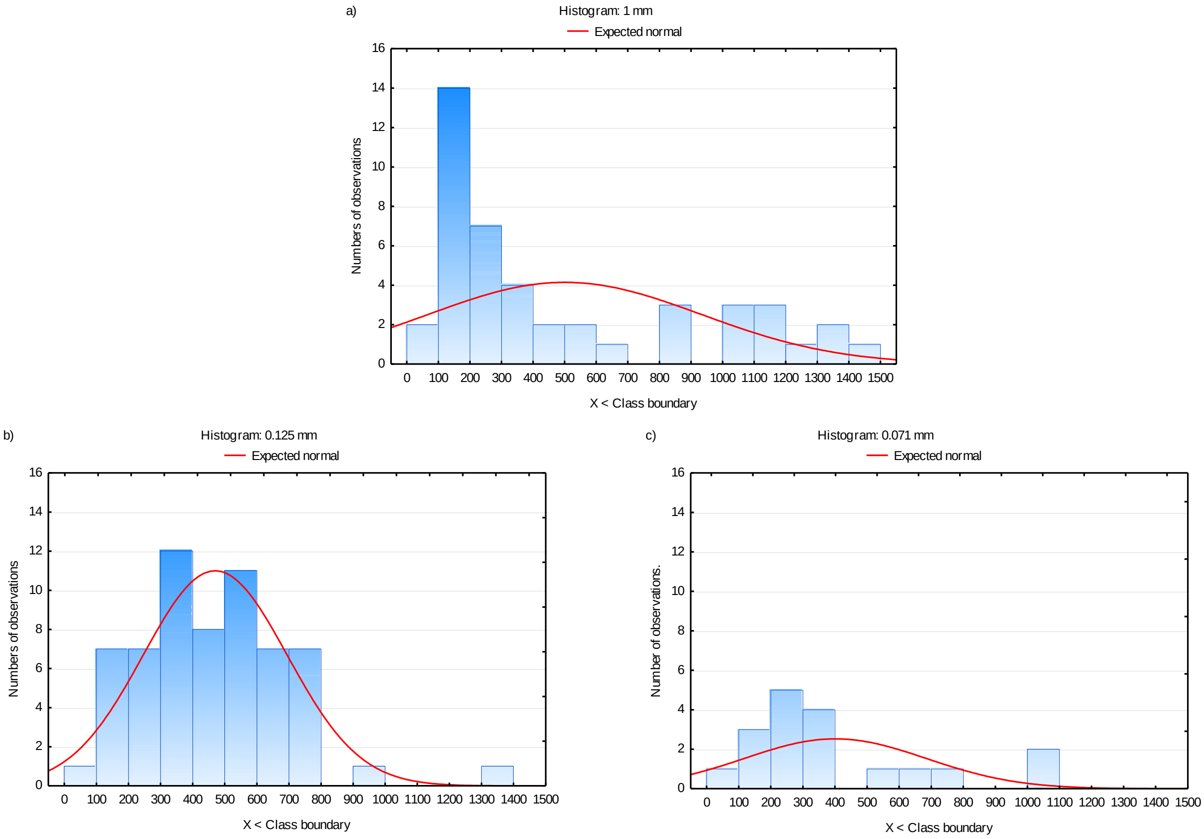

Figure 6. Distribution of fiber lengths deposited in laundry wastewater after filtration with (**a**) 1 mm, (**b**) 0.125 mm, and (**c**) 0.071 mm diameter sieves.

Analyzing the histograms of the numbers revealed that most fibers (50%) were collected with meshes with a diameter of 0.125 mm, followed by sieves with diameters of 1 mm (36%) and 0.071 mm (14%). In Figure 7, the distribution of fiber lengths is presented with a standard statistical value.

The mean fiber length deposited on each of the three sieves (with mesh diameters equal to 1, 0.125, and 0.071 mm) was similar, with values equal to 500, 482, and 400 µm, respectively. The first sieve also retained the most fibers with a wide range of fiber lengths.

After the hydraulic conductivity tests were completed, a clogging layer, including a filter cake, could be observed (Figure 8).

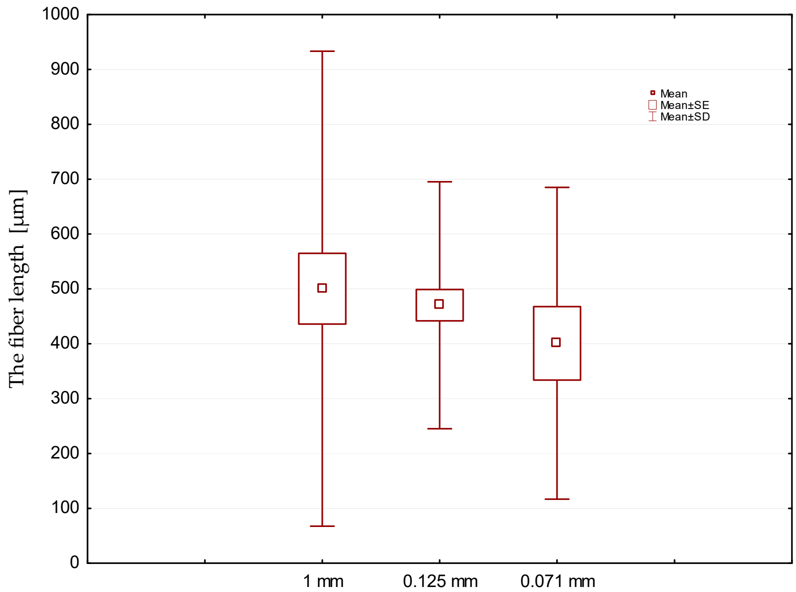

Figure 7. The fiber length distribution after filtration.

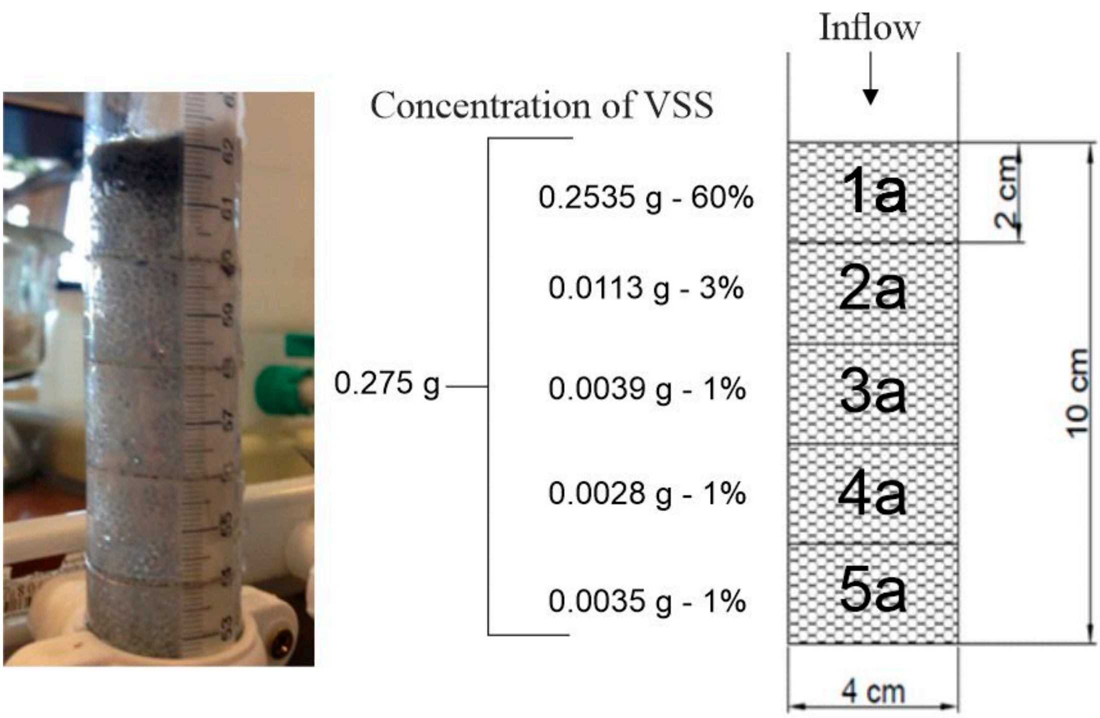

Figure 8. The filter column after the HC tests (**left**); a schematic with VSS accumulation (**right**).

Measurements of VSS accumulation were conducted after dividing the column used in test Nos. 1, 2, and 3 into five equal parts (with each being 2 cm high). The results of the VSS accumulation at different heights are presented in Table 2, and with basic statistical measures are presented in Figure 9.

Wang et al. [31] also observed that most of the filamentous particles (fibers) were captured in the surface layer of the sand column.

When pouring glass beads, they should have a loose arrangement (Figure 1—left), but this did not apply to the entire volume of the filter; there were random single deviations from this arrangement. These anomalies were rather unusual pores of intermediate size for the systems presented in Figure 1.

Table 2. The VSS distribution at different depths (accumulation) in the glass filter.

Column Depth	Accumulation of VSS					
[cm]	Test No. 1		Test No. 2		Test No. 3	
0–2	0.2535	59.8%	0.2477	59.4%	0.3040	93.54%
2–4	0.0113	2.7%	0.0185	4.4%	0.0115	3.54%
4–6	0.0039	0.9%	0.0038	0.9%	0.0029	0.89%
6–8	0.0028	0.7%	0.0027	0.6%	0.0005	0.15%
8–10 (bottom)	0.0035	0.8%	0.0026	0.6%	0.0001	0.03%
Total	0.2750	64.9%	0.2753	66.0%	0.3190	97%

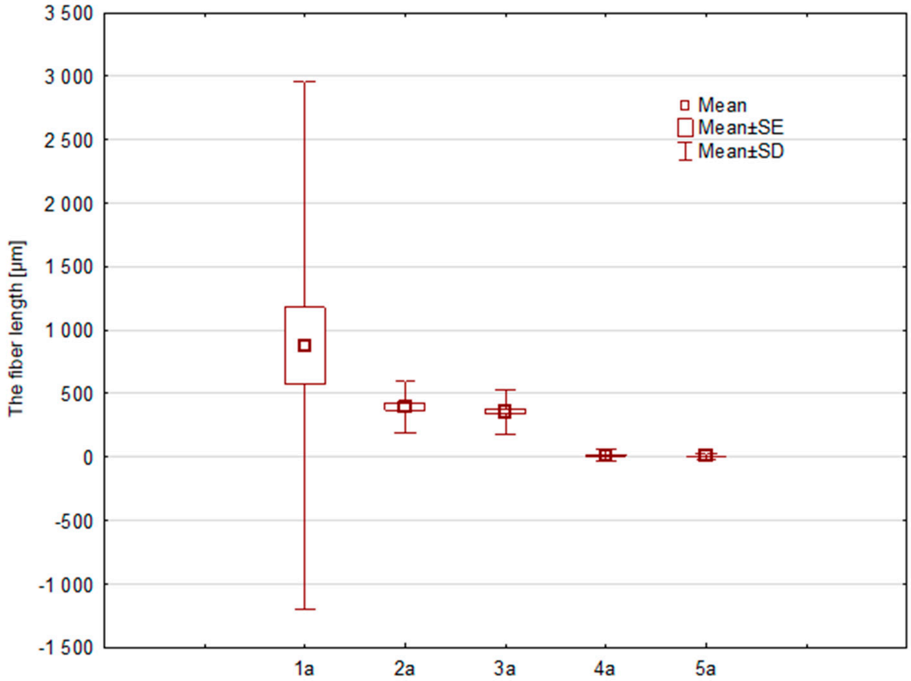

Figure 9. VSS accumulation at different depths.

The next step was to count the accumulated fibrous particles in each part of the filter. The results are presented in the histograms in Figure 10, which are arranged from the highest filter level to the lowest.

We observed that smaller particles tended to enter the deeper layers of the filter (Figure 10). A similar trend was observed by Ochoa et al. [32] in their research; at a depth of 50 cm, the share of larger particles (0.075–0.032) among the accumulated ones (apart from particles in the range of 0.032–0.0045) was still significant (several percent). However, at a depth of 100 cm and especially at 150 cm, this value was negligible (a few percent).

Research shows that accumulating suspended solids in laundry wastewater significantly reduces hydraulic conductivity by up to two to three orders of magnitude. Harold et al. [33] analyzed, using an unsaturated flow model combined with a reactive transport model, the clogging of intermittent sand filter systems. Their findings indicated that the components critical to the reliability of the ISF operation were chemical oxygen demand and total suspended solids. Additionally, they developed a mathematical model to estimate the rate of bacterial growth on the bed surface and the estimated time to filter plugging at specific pollutant loads. The abundance tables indicate that particles ranging from 300 to 600 µm in length, on average, accumulated in the upper layer, while in the third survey, most accumulated particles ranged from 100 to 700 µm in length.

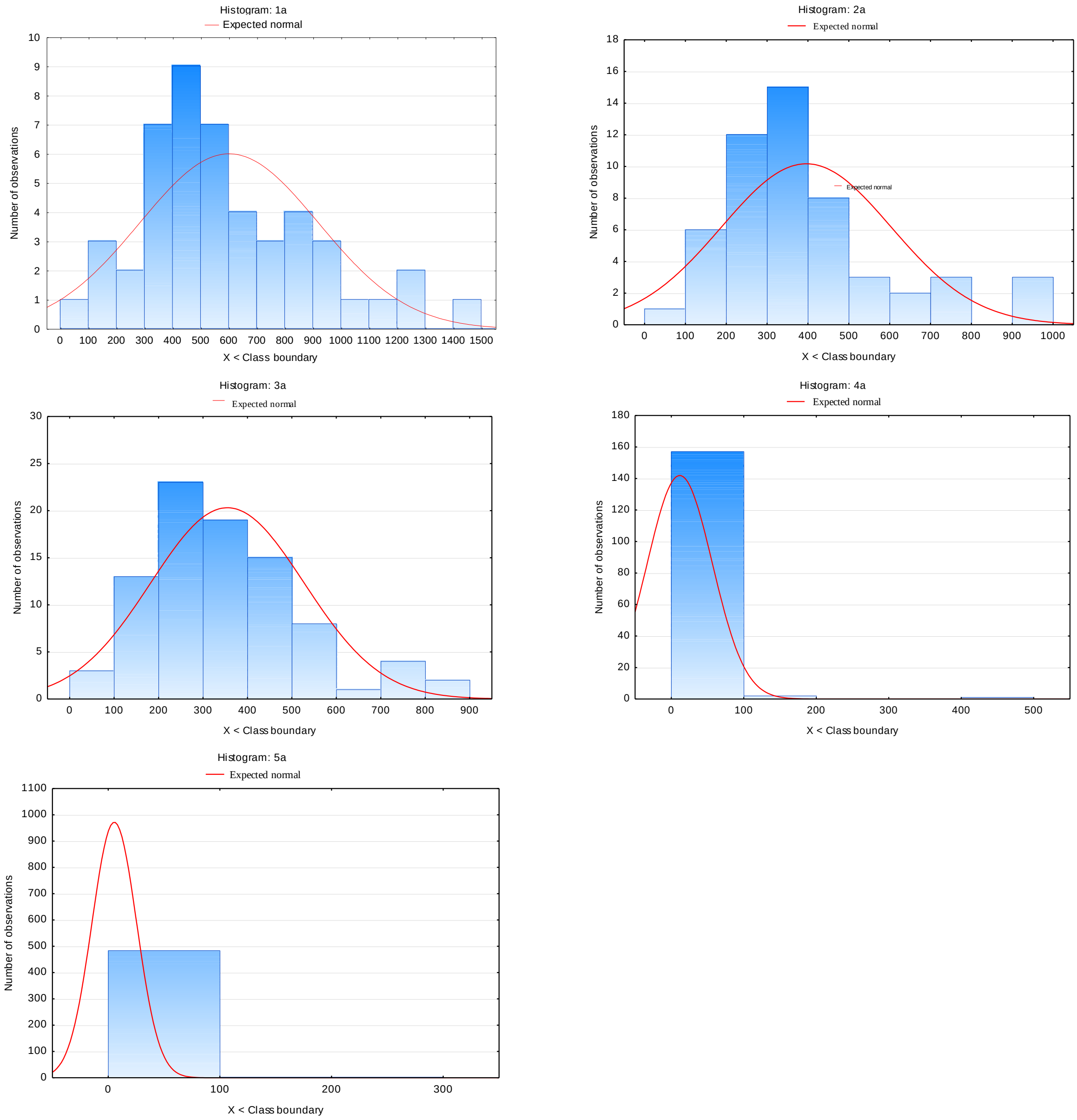

Figure 10. The number of accumulated fiber particles in different parts of the column (the class boundary represents the length of the fiber).

The accumulation of solids in columns during the clogging process was shown to reduce hydraulic conductivity. Figure 11 presents the hydraulic conductivity for three measurements in the transparent pipe, which was measured after every dose (100, 200, and 300 mL).

Despite the similar quality of graywater, the relation between the accumulation of VSS in the filter and hydraulic conductivity was quite different.

Considering the above difference in the results for HC, the hypothesis that only the filter cake on the filter surface is responsible for the low permeable coefficient (HC) value was tested. To this end, tests were carried out only for the upper layer with the filter cake after dismantling the column in test No. 3. The results are shown in Table 3.

The measurements of hydraulic conductivity show that the first layer has a value almost two orders higher (63.45 $\pm$ 2.39 m/d) than the whole filter with a 10 cm height (0.53 $\pm$ 0.02 m/d).

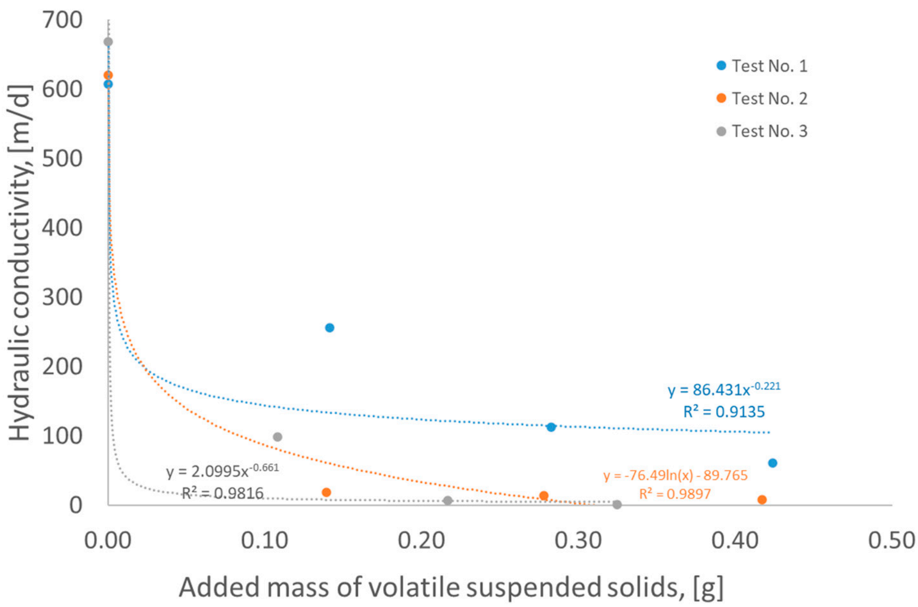

Figure 11. The influence of fiber dose on hydraulic conductivity.

Table 3. A comparison of HC results. The test was conducted in the hole column and only for the upper layer.

No	Column from Test No. 3	Hydraulic Conductivity *K* [m/d]
1	Column with filter cake and 10 cm height	0.53 ± 0.014
2	Column with filter cake and 2 cm height (only upper layer)	63.45 ± 1.950

The discharge of graywater into the soil is a potential cause of clogging. It is related to solids in graywater, mainly filamentous particles in washing machine outflow. Many sources in the literature demonstrate that laundering produces a relatively high amount of solids. Some crucial data related to washing machine graywater show the emission of about 0.0012 wt% at separation using a 200 µm filter [34,35], with polyester fleece fabrics being one of the fibers emitting the most fleece [36]. Several important factors also affect the amount of solids released from the washing cycle; one of the more crucial ones is the use of detergents and softeners, where up to 20% of the washing powder used in these products includes zeolites [37]. It is important to note that using softeners reduces the volume of microfibers by about 35% [25].

Winter and Goetz [38] analyzed the impact of sewage composition on the soil clogging phenomena of vertical flow constructed wetlands. They indicate that the content of suspended solids, especially particles > 50 µm, is considered to play a key role in clogging. Spychała et al. [39] indicate that organic matter deposits changed significantly with sand filter depth. The largest deposit was observed in the top layer of 4.0 cm depth.

Ground (sand/gravel) filters in the context of suspended solids that originated from laundry graywater can be considered in two aspects. Filters intend to remove suspended solids as pre-treatment filters before another device or receiver, and filters also collect domestic or graywater for mechanical and biological treatments and/or discharge (ground filters). In both cases, the amount of retained suspensions and the impact of this process on the hydraulic properties of the filter are important.

It is very likely that soon there will be a need or even a legally required treatment/pre-treatment of graywater, especially laundry graywater. In developing countries, laundry equipment is standard. Purification of this wastewater, at least mechanically, is not standard even in developed countries. The need for at least the mechanical treatment of laundry graywater results from two key reasons: limiting the emission of microplastics into the environment and preventing the ground infiltration systems (infiltration drainage) from clogging. Even if there is a collective (communal) or individual sewage treatment plant upstream of the receiver, it may not be effective in removing suspended solids (filaments) from laundry graywater, for example, due to their low susceptibility to settling or the formation of homogeneous or heterogeneous agglomerates, including those with colloids (also originating from laundry graywater).

The authors believe that the pre-treatment of laundry graywater using filters, including sand or gravel filters, is technologically and economically justified. The described study showed that a filter/bed containing a mineral aggregate or other material (e.g., granulate) with comparable geometric, hydraulic, strength, and durability properties can significantly capture this type of suspension. However, due to the problem of clogging and possible cleaning, one of the most important factors (apart from the dimensions and shapes of the filter particles) is its uniformity, which can be determined, especially in the case of aggregates, by the uniformity coefficient.

4. Conclusions

This study involved three laboratory experiments. The results reveal the relationship between wastewater quality and solid phase density in the filter and their influence on lowering hydraulic conductivity in the filtration column and bed clogging. This research shows the impact of wastewater (sewage from laundry cycles) on the clogging process in soil. The abundance tables showing fibrous particles found in laundry wastewater indicate that they accumulate mainly in the upper layer, where particles with fiber lengths ranging from 0 to 1600 µm can be found. On average, shorter fibers were identified with an increasing depth. At a depth of about 10 cm, fibers with dimensions of 0÷100 µm were mainly found.

In this study, it was impossible to indicate which parameter (e.g., effluent quality, fiber particle count, or total suspended solids) has a decisive influence on the clogging process. We found that not only does the upper layer of the filter (where more particles accumulate) restrict the flow, but also the accumulation of smaller particles in deeper layers will affect the flow. Contaminant migration may be caused by privileged flow paths, which were seen in the experiments and are common, especially in undistributed soils. For this reason, the accumulation of particles was also observed at different filter depths in other studies [31]. As a result, the size and shape of particles may play a greater role in clogging processes than particle concentration.

The spatial distribution of glass balls is predictable, and it causes the size (length) of a single pore to be at least 500 µm. The size of pores determines the size of particles that can move with the flow direction. It is worth mentioning that the fibers derived from common clothes, totaling more than 90%, have a length of less than 500 µm, with half of them having a length of <100 µm [36].

Despite using the same laundry detergents in the exact dosage, we can see differences in wastewater quality and a consistent amount of fibers.

High-concentration fibers increase the risk of clogging, especially in the top layer of porous materials, well-permeable materials, and materials with a high porosity similar to coarse sand. It should be remembered that in addition to fibers, colloidal particles are also present in laundry wastewater, which can further increase clogging [26].

Graywater drainage into the ground is beneficial, but further research is needed to ensure that the effluent does not cause the drainage system to fail. Appropriate legislation can help reduce soil contamination and consequently reduce soil clogging. France is the leader in this regard; as of 2020, new washing machines with fiber-reducing filters are required to be sold from 2025 onwards [18].

Elongated particles from washed clothes, especially fibrous particles, are characterized by significant specificity. Their very elongated shape and high flexibility are favored, allowing them to pass through the pores of a filtration membrane or thin separation layer; however, in filters—due to the tortuosity of the pore—this may not occur.

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