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A new cost effective, long life and low resistance filter cartridge for water treatment

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ABSTRACT

Filtration processes constitute the major solution among water treatments, which appear always necessary nowadays to make water suitable for human consumption or domestic uses, due to the gradual deterioration of its quality as a consequence of environmental pollution and industrial processes. In this paper a new type of filtering cartridge is presented, aimed at overcoming the main inconveniences shown by usual commercial cartridges. These drawbacks have been highlighted in a previous experimental work conducted in the Laboratory of Environmental and Maritime Hydraulics (LIDAM) of University of Salerno and aimed at evaluating the head losses produced by the most common filtration cartridges, especially under progressive clog conditions. Head losses, in fact, are particularly undesirable for low-pressure plants, where they can inhibit the normal operation of the installed apparatus. The analysis of the experimental results permitted to reveal several features of the filtration process in commercial cartridges and draw up different remarks, which led, after further laboratory tests here presented, to the design of a new economic, non-toxic, low-resistance and long life-cycle filtration cartridge, proposed and described in this paper. This cartridge, is basically made of a central element in inert cotton wrapped in a cylindrical polypropylene support, similar to the commercial one but with the core protected by elements, such as white marble pebbles, effective microorganism ceramic cylinders and granular active coal, which, while ensuring a good hydraulic permeability, is capable of stopping much of the particles suspended in the fluid before they reach the cartridge causing its clogging. The new design permits, therefore, to significantly reduce, compared with the commercial cartridges, average head losses even for high clogging degrees, and to increase, as a consequence, the life cycle of the cartridges.

1. Introduction

Progressive pollution and environment degradation, with consequent deterioration of water quality, make absolutely necessary nowadays water treatments before human and domestic consumption. Among these, filtration still represents the major solution. Almost all the domestic apparatus which make use of water are equipped with internal or installed with proper filtration elements. Increasingly efficient and innovative filtration systems have been adopted in recent years. This paper presents a new type of filtration cartridge which has been implemented in order to overcome the main disadvantages shown by commercial cartridges adopted in drinking water networks.

An experimental hydraulic study previously conducted in the Laboratory of Environmental and Maritime Hydraulics (LIDAM) of University of Salerno [1–3] on the head losses produced by the most common filtration cartridges available on the market, in fact, highlighted some inconvenient in the use of commercial cartridges, whose assessment was the starting point for the development of a new mechanical filter. Specifically, the new cartridge here proposed was designed to reduce as much as possible the head losses caused by the filter clogging and to increase, therefore, the life cycle of the cartridge. In fact, this duration depends on the quantity of substances that the cartridge retains on its outer surface and inside before reducing its filtering capacity and producing higher head losses; this occurs with a prolonged use over time, since the clogging particles leave less flow space to the fluid, thus generating the necessity to replace the cartridge.

In order to design the new cartridge, an ad-hoc experimental campaign was performed in the LIDAM Laboratory of University of Salerno, taking as reference small circuits such as the domestic ones, where flow rates are of the order of tenths of a liter or at most some liters per second. The behavior of the commercial and proposed cartridges with an increasing clogging rate was tested, at the aim of measuring head

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losses and accomplish a deeper comprehension of the physical phenomena (see also [4]).

The mechanical filters developed and tested in this work all consist of a central element in inert cotton wrapped in a cylindrical polypropylene support, similar to the one of the common commercial cartridges and with the same function: to stop the suspended particles present in the fluid to be filtered. In laboratory tests [1,4] it has been shown that filter clogging is the main cause of the head losses increase. For this reason, it was decided to properly protect this cotton core with elements which, while ensuring a good hydraulic permeability, are capable of stopping much of the particles suspended in the fluid before they reach the cartridge causing its clogging and a considerable increase in head losses. White marble pebbles, EM ceramic cylinders and granular active coal were used to protect the wadding core, first one at a time, thus making three different filtering cartridges, and then all of them properly mixed for the final filter cartridge proposed in this paper. All these materials are generally used for water treatment and, in contact with each other, form a continuous grain skeleton which is capable of incorporating in their structure particles of smaller size, without impairing the hydraulic permeability and thus avoiding the undesirable pressure drops increase.

All the tested filters exhibit different head loss trends in relation to the progressive clogging rate due to the different filtration mechanisms, but all of them guarantee, even for high clogging degree, average head losses significantly lower than those shown by the analyzed commercial cartridges. This also solves the problem of their substitution in a short time: the latter will no longer be necessary as the filters, so designed and manufactured, are able to withstand a large amount of suspended substances before they absorb their filter capacity, resulting in longer durability. In conclusion, the proposed solution, covered by a patent recently filed, represents a valid option to avoid the limitations of the commercial cartridges.

The analysis of the materials to be used for the cartridge construction is illustrated in Section 2, together with technical features and laboratory equipment. The mechanical filters here built, as well as the experimental conditions, with the modalities of the progressive filter clogging and of the head losses evaluations, are further detailed. Then the obtained results are presented in Section 3, while an attentive analysis of them and of the filtration mechanisms is reported in Section 4. The advantages of using the system compared to a generic commercial wrapped wire cartridge are discussed in Sections 4 and 5, where also remarks on the correct implementation of the mechanical filters proposed therein are reported.

A photographic report is also proposed as Ref 5, with the aim of allowing the reader to concretely view and better understand the process of filter clogging.

2. Experimental investigation: materials and methods

2.1. Materials and components

The materials used to build the proposed filters are essentially stone, ceramic, plastic and activated carbon, all of them being non-toxic, and therefore incapable of contaminating the drinking water they come into contact with [6–9]. Fine laboratory sand was also used to clog the filters. Below they are described in detail.

2.1.1. White marble pebbles

Pebbles are the largest granulometry material used to make the filters proposed here; in particular, marble cobblestones with a diameter of 10 ÷ 20 mm (Fig. 1) were chosen. The material was selected in such a way as to avoid elongated and flattened shapes which could, by compacting and disposing in a preferential direction, reduce the basic hydraulic permeability of the filter by increasing initial head losses. This type of pebbles, being made by a crusher from a calcium carbonate metamorphic rock, are not able to absorb or release any substance to the fluid they are immersed, a matter of primary importance for drinking water filters.

Fig. 1. White marble pebbles.

Fig. 2. EM ceramic cylinders.

2.1.2. EM ceramic cylinders

Another material used for the filters tested here is a special commercial ceramic shaped as small discs with diameter of 8 mm and height of 4 mm (Fig. 2), then smaller in size than the marble pebbles above described. The cylindrical shape with a ratio radius/height almost equal to one has been chosen again to avoid elongated shapes, prevent interlocking cohesion phenomena and provide a greater hydraulic permeability.

This particular type of ceramic is obtained by fermentation of Effective Microorganisms (EM) on a clay substrate (gray porous pasta ceramics) and it is a material with excellent adsorption capacity, unchanged performance over time and not polluting. Thanks to an antioxidant and regenerating effect, it is capable of eliminating methanogens and toxic pollutants formed as a result of the chemical breakdown process and tends to break down the bacterial load due to EM, or to adsorb undesirable substances due to porous ceramic [10]. Today, EM technology is an all-powerful tool for disinfection of all waters worldwide and has excellent uses in numerous fields.

2.1.3. Activated carbon grains

Another component of the new filters is granular active carbon, whose particles have the smallest size among the used materials. In particular, grains with a rounded shape and of different size (2–4 mm diameter) were used (Fig. 3), in order to avoid cohesion and poor hydraulic permeability, thus reducing the pressure losses resulting from the filtration process.

This material has long been used for the production of water treatment cartridges, since it is able to remove halogenated organic substances, such as thrihalomethane and other DBP (disinfestation products), pesticides, herbicides, triazines, chlorine and other substances that cause water alterations. It is mainly composed of

Fig. 3. Granular active carbon.

(a) (b)

Fig. 4. (a) Polymer grains; **(b)** Synthetic inert PET wool roll.

amorphous carbon, which has a highly microporous structure and a very wide specific area, and therefore is able to retain molecules of other substances inside it and, for its high adsorption capacities, it is suitable for a wide variety of treatment processes [11,12].

2.1.4. Synthetic inert cotton

Inert synthetic cotton was used to make the actual filtering septum in lieu of wire-wounded commercial cartridges. Specifically, this cotton is polyethylene terephthalate (PET) in polymer grains (Fig. 4a) suitably worked and reduced to wadding, a biologically inert and insoluble material which does not release substances, removes waste of all kinds in suspension and makes the water clear [13].

The optimum wadding has a filtration degree of 10 μm which, however, is reduced considerably with stiffening of the fibers. During the realization of the filters, therefore, special care is devoted not to compress the fibers, so as not to alter the filtering capacity and not cause an undesirable head losses increase. In the laboratory activities it was made use of rolls produced by Askoll Group, soft to the touch and white, with a height of 25 cm, so as to be able to easily wrap the wadding around a rigid support and place it inside the filter element instead of any commercial cartridge (Fig. 4b).

The wadding is capable of absorbing large amounts of water, thus increasing its surface for expansion of the interstices between the fibers: this guarantees a good hydraulic permeability and consequently modest head losses, but also causes a worsening of the ability to retain the impurities present in the fluid. During this experimental activity, then, several overlapping wadding layers were wound to the polypropylene support, in order to return a cartridge with good hydraulic permeability but at the same time with excellent ability to retain suspended particles.

2.1.5. Polypropylene slashed cylinder

A 100% pure polypropylene cylinder with rectangular windows, similar to the one of the wrapped wire commercial cartridges, from which it has been obtained, was used as a support for the PET cartridge built here (Fig. 5), forming the inner core of the synthetic wrap filter in all the filters proposed here. This element in the commercial cartridges can not be removed, so once the filter is replaced it can not be retrieved; in the proposed filters, instead, the wool is only wound to such support and therefore, when necessary, it can be easily replaced thereby allowing the cylinder to be used several times.

Fig. 6. Fine sand used to progressively clog the filters.

2.1.6. Fine sand

Fine sand was used to artificially and progressively clog the filters, both commercial and ad-hoc made. In particular, crushed sand was used, an homogeneous inorganic material consisting of calcium carbonate particles of 0.10 mm size (Fig. 6). Well weighed, the sand was added inside the cartridge holder by using water that, poured from the top, pushed down the sand progressively. For each achieved clogging degree the resulting head losses were measured.

2.2. Measurements

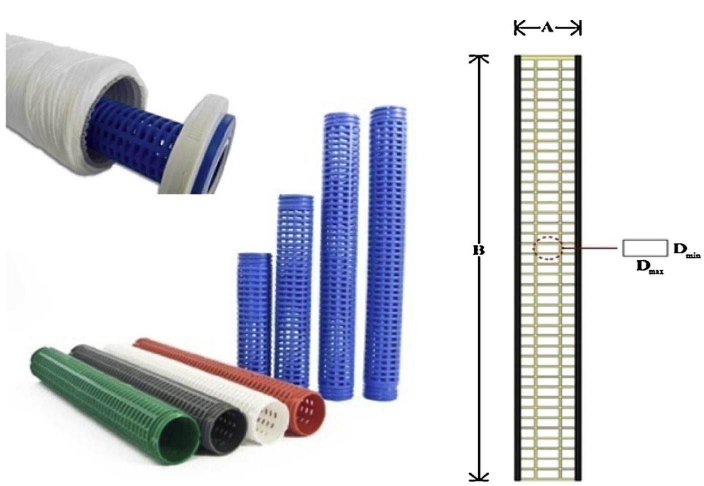
2.2.1. Measuring operations

Before carrying out the experiments, a storage tank feeding the circuit [1] is filled up to a certain level (1.50 m referred to the floor), to be kept constant during the tests in order to fix the water head upstream of the circuit; to this level refer all the measurements taken during the laboratory activity.

In different tests the upstream shut-off valve is closed in order to disconnect the filter container and each time the different cartridges, artificially clogged with quantities of sand established a priori, were inserted. Once set in position, the filter was gradually put under water pressure, by slowly opening the upstream shut-off valve. By doing so, sand was gently pushed toward the filter surface and at this point the test began setting off the pump. For each cartridge (commercial ones and proposed ones with the different clogging degrees) tests were performed for the three different circuit flow velocities, corresponding to the three fixed-curve modes set in the electronic pump. In each scenario the pressure drops produced by the cartridges were measured.

2.2.2. Measuring instruments

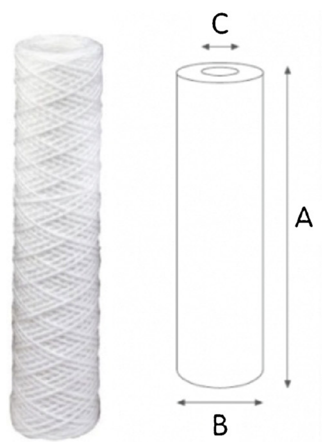
An electronic differential manometer was used to measure the pressure losses at the filter, with higher accuracy than with the liquid column gauges along the circuit [3]. Specifically, the pressure gauge is the 0–7 bar Digitron 2023 P (Fig. 7a), with 0.15% absolute accuracy,



A	30 mm
B	250 mm
D_{min}	5 mm
D.	10 mm

Fig. 5. Dimensional features and pictures of the polypropylene cylinder internal core of the cartridge.

Fig. 7. **(a)** Electronic differential manometer Digitron 2023 P; **(b)** derivations along the circuit across the filter for the connection to the manometer.



A	250 mm
B	61 mm
C	28 mm
weight	149 g

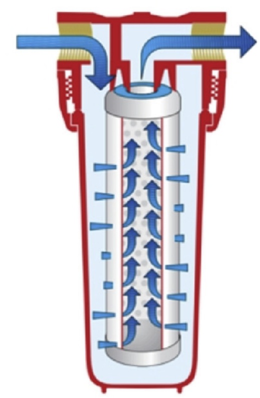


Fig. 8. Wire-wound filter cartridge with dimensional information and sketch of the water flow pattern.

connected to the circuit by joining, with plastic tubes, its two inlets with two derivations located upstream and downstream of the filter element, respectively (Fig. 7b). In this way the pressure difference between these points, which corresponds to the head loss due to the filter operation, can be evaluated. More in detail, the pressure values correspond to the ensemble average of three measures, taken in steady flow conditions. Reductions at the derivations were necessary to allow the connection between the manometer (inlets external diameter 8 mm) and the stainless steel pipes (diameter 25 mm). Piezometers were also placed upstream and downstream of the filters for independent measurements of the produced head losses below 0.2 bar.

A SF-400 balance was used to accurately measure the amount of sand to be progressively introduced into the filters to clog them. The same quantity of sand, i.e. 20 g, in fact, was added each time to guarantee an appreciable variation in head losses to be recorded at each increment.

2.3. Analyzed filtration elements

Laboratory tests started with the assessment of the head losses of commercial cartridges for several clogging rates. In particular, wire-wound cartridges have been used, as they represent the most common type used for mechanical filtration of drinking water (see also [1]).

Once evaluated the pressure losses in optimum conditions, that is at zero degree of clogging, then the cartridge has been progressively clogged, adding 20 g of sand at a time up to 300 g and evaluating for each increment the corresponding head losses. The recorded values refer to the amount of sand that actually remained trapped in the cartridge, so it was not considered the residual, although minimal, left inside the styrene acrylonitrile (SAN) resin container. The process of sedimentation and absorption of the particles suspended in the liquid by the cartridge has, in fact, very long times incompatible with the activities to be carried out; for this reason, to rapidly increase the degree of actual clogging of the cartridges, a small amount of food glue was used. This substance allowed the sand to adhere to the outer surface of the cartridge and not to deposit to the bottom of the container so as to simulate an effective clogging of the filter. Once the circuit was in operation, the glue, used only to fix the sand to the filtering septum, was shortly washed away, being it soluble in water, thus leaving only the sand deposited on the outer surface. At this point, the head losses related to the specific clogging degree were measured through the differential pressure gauge.

The results confirmed previous investigations obtained by using honey instead of food glue [1]:

Below a description of the filter elements object of the experiments is given, indicating the construction characteristics, the operating modes, the way the water flows into them, and the interior sedimentation process of the particles suspended in water.

2.3.1. Commercial wire-wound filter cartridge

Commercial wire-wound filter cartridges of the type shown in Fig. 8, with an efficiency of 80% and a filtration degree of 50 μm, were used in the laboratory tests. Fig. 8 also provides some information about dimensions and weights, as well as water flow pattern in the cartridge.

This type of cartridge is produced by wrapping a 3-mm thick wire on a slashed cylinder support, both in 100% pure polypropylene, non-toxic and therefore suitable for the treatment of drinking or domestic water.

The fluid inlet is carried out laterally, from the outer edge towards the inside of the cartridge, by depositing in the filter the still dirty water, which is thus pushed by the flow into the central duct and moves away from the filter without impurity. The honeycomb texture allows to retain most of the suspended particles, larger than the interstices, on the surface of the filtering septum. With prolonged use over time, the store of substances on the outer surface and inside the cartridge causes a decrease in the hydraulic properties of the same, leaving less transitory space to the fluid until the filtering septum is completely clogged. To this extent a considerable increase in head losses and a reduction in the filtration capacity occur [1,14–18].

Wire-wound filter cartridges fall into the category of deep filtration cartridges and are therefore not washable, so they need to be replaced in a short time, resulting in increased service costs and waste production. This, coupled with the high level of head losses also in modest clogging conditions, are the limits found in this filtering element.

2.4. Built cartridge and filters

The wire-wound commercial cartridge limits were the starting point for the development of new mechanical filters designed precisely to reduce head losses even for high clogging values and increase their life time.

All the filters tested in this work consist of a central septum in PET inert wadding wrapped around a polypropylene cylindrical core, an element that, as any commercial cartridge, has to stop the suspended particles present in the fluid to be filtered. To limit and delay clogging the wadding core was properly protected and the volume involved in the filtration process was expanded (Fig. 9), occupying in the new built filters the entire interior space of the cartridge holder, and not just the central septum as for commercial cartridges. The materials described above in Section 2.1 have been used, namely white marble pebbles, EM ceramic cylinders and granular active carbon.

2.4.1. Cartridge in inert synthetic wadding

After having measured head losses for the commercial cartridge, a new filter was made by replacing in the cartridge the polypropylene wire by PET cotton or synthetic inert wadding and the head loss exhibited by different clogging degrees and for the different pump velocities were evaluated.

The wadding is wrapped around the polypropylene slashed supporting cylinder, as several layers overlapped with each other to create a spiral system capable of retaining even smaller particles. Fig. 10 shows a picture of the proposed PET cartridge compared with the

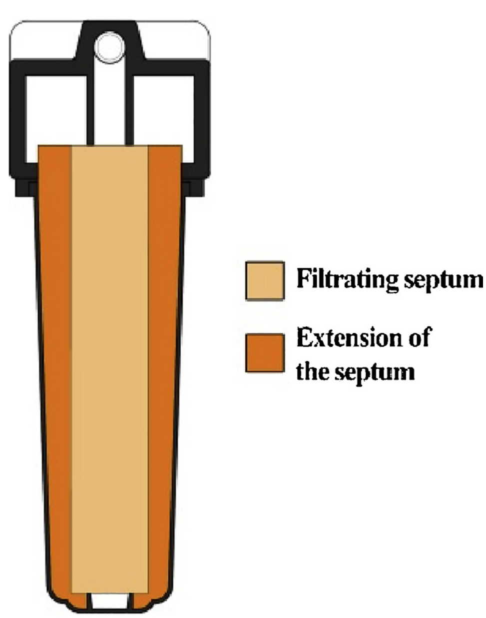


Fig. 9. Sketch of the expanded filtering septum in the new filtration system compared to the commercial ones.

classic commercial wire-wound one, also giving information on the new cartridge size and materials used to make it, while Fig. 11 contains pictures that illustrate its building process.

Once built the cartridge, head losses corresponding to a zero clog were registered. Subsequently, the filtering septum was progressively and artificially clogged, placing the sand, at a rate of 20 g at a time up to 120 g, directly between the overlapping wadding layers, and to a lesser extent on the outer surface (with honey and/or food glue to ensure effective clogging of the sand). At each increment of added sand, and thus with the progressive clogging, the corresponding head losses for each pump velocity were detected.

The cartridge was proved to be reproducible, crucial condition for the marketing of the filter cartridges proposed here, since once recreated it using the same cylinder and the same quantity of synthetic wadding, the head losses were re-evaluated under initial conditions, and the obtained values were identical to those recorded on the cartridge previously built.

2.4.2. Filter 1: inert synthetic cotton cartridge and white marble pebbles

At the aim of retaining as much sand as possible out of the cartridge, thus limiting and delaying clogging and the associated head losses, in the first proposed filter, referred to in the following as Filter 1, an outer radial layer composed of white marble pebbles (Section 2.1.1) of various sizes was added to the synthetic wadding cartridge (Section 2.4.1), randomly occupying the space between the cartridge and the SAN glass.

In the positioning of pebbles, it is important not to compress the wadding, so the pebbles would not be forcefully constrained in the glass, but just dropped little by little, freely, until they cover all the available space between the cartridge and the filter holder. This precaution is crucial, as it provides a good voids distribution and a proper settling down. Before putting the filter into service, this must be internally stable, i.e. the position of the grains must not change over time. In order to ensure this, stone elements of bigger granulometry and weight have been placed on the top. Thus, when the circuit is started, the incoming liquid flow does not cause any change in the initial state: without this technical precaution, pebbles could be compressed and constipated by the input water in the filter or washed away by the outflow. The schematic section in Fig. 12a helps to better understand the composition of the filter. Fig. 12b also shows a photo of the filter made in the laboratory and Fig. 12c reports information about the constructive features, with quantities of the used material.

Once the filter was completed and put into operation, again the head losses were first evaluated under zero clogging conditions, then the filter was clogged progressively by adding 20 g of fine sand for each increment from the top of the container and pushing it down using a small amount of water. At the end of the clogging process, the polypropylene core was recovered from the filter and reused. Also this cartridge was reproduced again and the initial head losses checked.

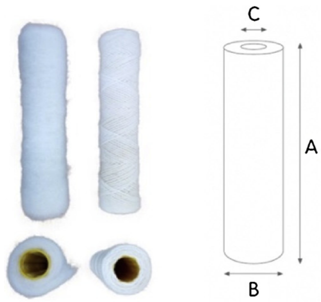
2.4.3. Filter 2: cartridge in inert synthetic wadding and EM ceramic cylinders

The PET cartridge was reproduced and the initial head losses calculated, but in this second case it was used the EM ceramic as protection of the PET filter, thus realizing the filter denoted in the following as Filter 2.

As in the previous case, the EM discs introduced in the space between the cartridge holder and the filter septum should not be compressed, but set up to occupy spontaneously the free spaces, in order to reduce interlocking cohesion phenomena, guarantee an adequate hydraulic permeability and ensure as lower head losses as possible.

Fig. 13 shows a schematic representation of the filter with: (a) indication of the constituent elements, (b) photo of the filter made in the laboratory, (c) information about components, materials and quantities for the proposed filter.

Once built the filter and evaluated the initial head losses, as for the previous filters, it was progressively clogged with fine sand, in



A	250 mm
B	60/65 mm
C	28 mm

COMPONENT	MATERIAL	QUANTITY
internal core (slashed cylinder)	100% Polypropylene	1
filter septum	synthetic inert wadding (PET)	25x40 cm / 20 g

(a) **(b)**

Fig. 10. **(a)** Front and top view of the proposed PET filter cartridge and of a wire-wound one, respectively; **(b)** dimensional information and constructive features of the PET cartridge.

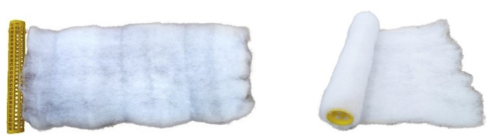


Fig. 11. Stages of the realization of a cartridge in inert synthetic wadding.

quantities of 20 g at a time, and the correspondent pressure drops were measured.

2.4.4. Filter 3: cartridge in inert synthetic wadding and granular active carbon

To build the third proposed filter, again the cartridge in inert synthetic wadding was rebuilt and the initial head losses measured to prove the perfect reproduction. In this case, the filtering septum was protected by activated carbon in grains, which, thanks to its high specific area and a very porous structure, is able to retain molecules of other substances inside it. The filter, referred in the following as Filter 3, therefore, allows, as Filter 2, both water treatment and mechanical filtration, a condition very difficult to find in standard commercial cartridges. During the fabrication of the filter, again the activated carbon should not be constipated but introduced in small quantities and piecemeal in the space between the filter cartridge and the SAN glass.

Fig. 14 shows: (a) a schematic representation of the filter element under consideration, with its different components, (b) a photo of the built filter, and (c) some information about its constructive features.

The filter was again progressively clogged with addition of 20 g of sand at a time, from the top with water permeated downwards inside the filter. In this case, the clogging process was much slower, and much more water was used than in the previous case, as the small size of the particles, and then of the voids, made the insertion of sand very difficult.

2.4.5. Sand clogging limit

During the laboratory activities, the maximum values of head losses to which the built filters should tend were sought, in the condition that all the available voids between the grains were occupied by the added sand. These values were obtained by recreating these condition by means of a specially designed filter.

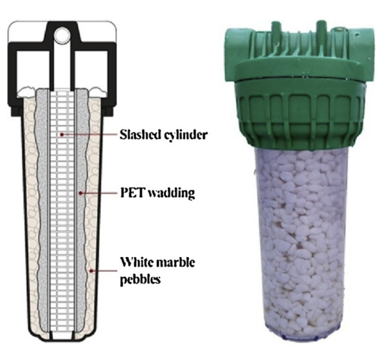
A new PET cartridge, identical to the previous ones, was then built, but in this case only fine sand was added in the space between the filter and the SAN glass (Fig. 15). It would have been very difficult to achieve this condition of all voids completely occupied by sand in the filters described above, because in them the sand is added with increasing difficulty as the clogging degree rises, due to the progressive reduction of voids and hydraulic permeability of the medium. Additionally, the reciprocal settling down of the grains to protect the cartridge creates areas where the sand could not penetrate anyway.

To recreate the clogging limit, a total of 800 g of sand was added and subsequently the head losses corresponding to the three fixed speed values of the pump were evaluated.

2.4.6. Filter 4: inert synthetic wadding cartridge, white marble pebbles, EM ceramic cylinders and granular active carbon

The fourth and last filter, referred to in the following as Filter 4, was designed based on the results obtained in the previous cases. It has been specifically sought to put in place a filter capable of displaying low head losses for both low and medium clogging values. This result was obtained by combining all the materials used to make the filters described above.

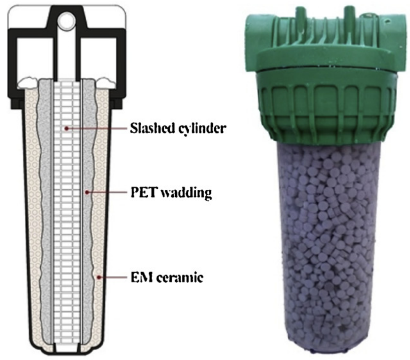
In particular, marble pebbles were used, which have a greater granulometry and hence a larger voids size than the other elements, and then they yield a greater hydraulic permeability with low head losses for a low clogging degree. Then, EM ceramic flakes and granular active carbon were also used, which, in addition to retaining the sand and preventing it from reaching the cartridge quickly, by virtue of the porous structure and its adsorptive abilities, purify the water and



COMPONENT	MATERIALS	QUANTITY
internal core (slashed cylinder)	100% Polypropylene	1
filter septum	PET wadding	25x40 cm / 20 g
filter septum protection	white marble pebbles	880 g

(a) **(b)** **(c)**

Fig. 12. Filter 1: **(a)** longitudinal section with the different components; **(b)** frontal view; **(c)** constructive features.



COMPONENT	MATERIALS	QUANTITY
internal core (slashed cylinder)	100% Polypropylene	1
filter septum	PET wadding	25x40 cm / 20 g
filter septum protection	EM ceramic	300 g

(a) (b) (c)

Fig. 13. Filter 2: **(a)** longitudinal section with the different components; **(b)** frontal view; **(c)** constructive features.

neutralize harmful molecules and smells, also improving its appearance.

Again in this case the first step was the realization of the cartridge in inert synthetic wadding. All the materials used, appropriately dosed, were previously mixed together to ensure a distribution as homogeneous as possible, to facilitate its ingrowth and maximize the ability to retain the sand to be filtered. The three mixed components were subsequently poured into the cartridge holder box, also in this case without being constipated, but allowing them to fall freely in their dedicated space. The assessment of the quantities of the various elements to be used for the filter construction was carried out in relation to the head losses that the latter would have to guarantee, in particular the amount of marble pebbles has been increased until in zero clogging conditions the head losses were conveniently low. Estimated this amount, the other elements were added later, until completely filling the space between the SAN glass and the wadding cartridge.

Fig. 16 shows: (a) the various parts of the filter, (b) a photo of the filter made in laboratory, and (c) the constructive features with the quantities of materials used to make it.

As in the previous cases, after completing the construction and putting the filter into service, it was progressively clogged, by adding 20 g of sand each time from the top and measuring for each of these increments the corresponding head losses for the three different fixed-speed curves of the pump.

3. Results of the experimental investigation

In this section the results of the laboratory tests conducted on the filter elements above described are presented. In particular, graphs with the trends of the obtained head losses for the various filters in relation to the progressively added sand are reported, for each of the three fixed-curve speeds of the electronic pump.

3.1. Commercial wrapped wire cartridge and inert synthetic wadding cartridge

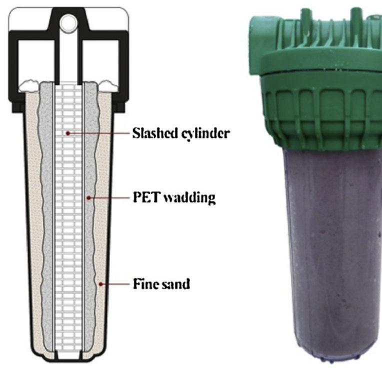
First the results of the investigations carried out on the wrapped wire commercial cartridges are presented, in terms of head losses Δp in mbar, respective to the measurements obtained both from previous experiences [1,4], in which honey was used to help clogging the filter, and from the experiments conducted in this work making use of food glue. The plot in Fig. 17 shows the trend of the results in terms of increase of head losses as the sand is progressively added, i.e. as the clogging degree increases, for the three velocities of the pump and the two experimental scenarios, also in comparison with the results obtained with the simple inert synthetic wadding cartridge.

Looking only at the results related to the commercial cartridge, it can be noticed that for low and intermediate velocities in the circuit head losses are significantly less than those exhibited for maximum velocity. In a first step, up to the first 20 g of added sand, the losses vary slightly, then the slopes of the curves increase for all the three velocities. The peak in terms of head losses is recorded at the maximum circulator velocity and for a clog degree of about 60 g of sand. In addition, the data obtained by using honey or food glue are very similar, especially for low and intermediate velocities. The only difference found in the use of these two substances is that honey, started the water flow in the circuit, washed away more quickly than food glue, thus causing more detachment of sand from the cartridge and thus slightly less actual clogging with the same added sand. This check was conducted to verify and assess whether the glue used to fix the sand on the filtering septum would affect the results and give rise to different head losses. It is proved that the head losses trend in the cartridge does not depend on the material, but only on the achieved degree of clogging and on the pump speed. Therefore, for the comparisons of the head losses in the different filters reported in the following, it was only

COMPONENT	MATERIALS	QUANTITY
internal core (slashed cylinder)	100% Polypropylene	1
filter septum	PET wadding	25x40 cm / 20 g
filter septum protection	active carbon	350 g

(a) (b) (c)

Fig. 14. Filter 3: **(a)** longitudinal section with the different components; **(b)** frontal view; **(c)** constructive features.



COMPONENT	MATERIALS	QUANTITY
internal core (slashed cylinder)	100% Polypropylene	1
filter septum	PET wadding	25x40 cm / 20 g
filter septum clogging	fine sand	800 g

(a) **(b)** **(c)**

Fig. 15. Filter for the simulation of the sand clogging limit condition: **(a)** longitudinal section with different components; **(b)** frontal view; **(c)** constructive features.

referred to the values obtained by clogging the cartridges with honey.

Comparing these results with the ones obtained with inert synthetic wadding for progressive clogging up to 120 g it can be noticed that the curves have a similar pattern. However, the cartridge made in the laboratory has in general lower head losses than a generic wound-wire cartridge, so it can be concluded that the built filtering septum is more efficient than the commercial ones.

The commercial cartridge, for example, reaches for 80 g of added fine sand and at the maximum circulating velocity a pressure loss of about 86.5 mbar, whereas the cartridge proposed here reaches this value for a higher degree of clogging, greater than 90 g. The new cartridge, therefore, requires 10 g of sand more to exhibit the same head loss.

3.2. New filters

The results obtained with Filters 1, 2 3 and 4 are reported graphically in Fig. 18, in terms of head losses for the three pump velocities, respectively, and for progressive clogging of the filter with 20 g of sand each time up to 300 g, in comparison against the ones obtained with the commercial cartridge.

For Filter 1, the head loss trend with the increase of added sand is almost linear for the three pump velocities.

For Filter 2, the trend can be tripartite for all three velocities as follows: at an initial stage, up to 120 g of added sand, the curves grow linearly; then there is an interval, between 120 and 220 g of sand, where the head losses trend is sub-horizontal, i.e. increasing the amount of sand head losses almost do not change; in the final part, between 220 and 300 g of introduced sand, there is again a linear increase in the head losses, with a greater slope than in the first segment.

As for the Filter 3 trend of head losses in relation to the increasing clogging degree, for the three different pump velocities at an initial

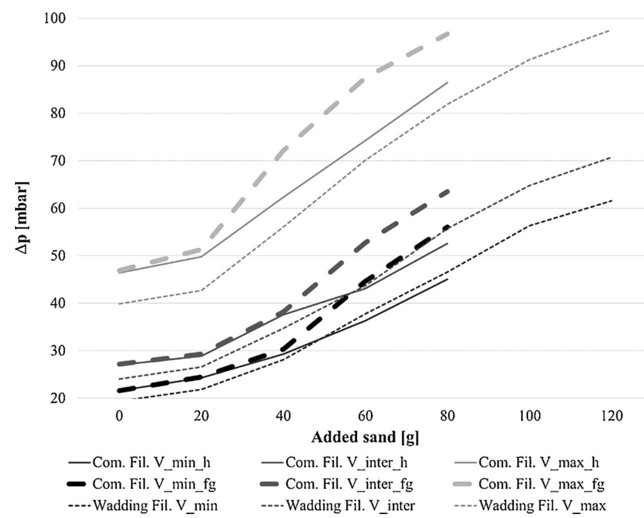
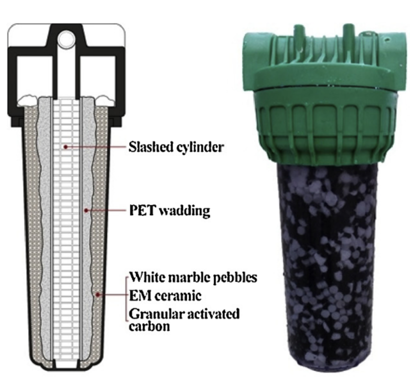


Fig. 17. Head loss increase for the commercial cartridge as the clogging degree progresses for the three circulating velocities: sand with honey (continuous line) and food glue (dashed line), respectively, also in comparison with the results of the simple synthetic wadding cartridge.

stage, approximately up to 200 g of inserted sand, head losses are little affected by the presence of sand. Subsequently, exceeding this value, there is a noticeable increase of the head losses and hence a sharp increase in the curve slope.

In comparison with the head losses exhibited by the commercial filter, the benefit in terms of pressure drops and then of durability is remarkable for the three filters. It can be noticed, for example, how Filter 1 shows the same 73.2 mbar head loss that the commercial filter



COMPONENT	MATERIALS	QUANTITY
internal core (slashed cylinder)	100% Polypropylene	1
filter septum	PET wadding	25x40 cm / 20 g
filter septum protection	pebbles	500 g
	EM ceramic	110 g
	active carbon	90 g

(a) **(b)** **(c)**

Fig. 16. Filter 4: **(a)** longitudinal section with various components; **(b)** front view; **(c)** constructive features.

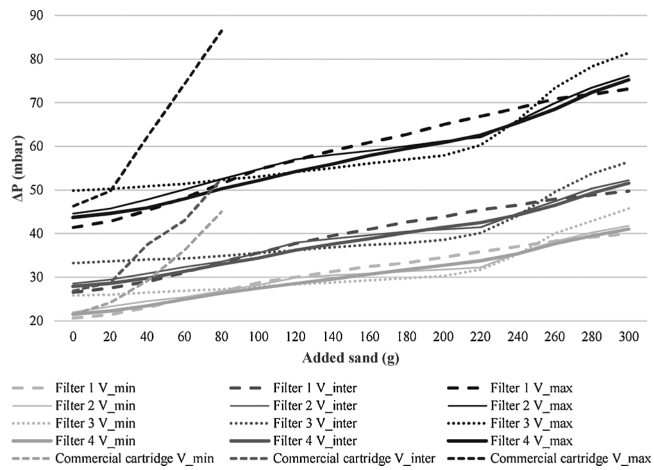


Fig. 18. Comparison of the head losses exhibited by the new Filters 1–4 with those of the commercial cartridge for increasing sand clogging rates.

manifests for maximum speed at 60 g of clogging, only at 300 g of added sand. This means that the commercial filter should be replaced much earlier, since for low clogging values it shows great losses, whereas the proposed filters are also efficient at high levels of clogging, so they ensure a longer duration in time.

The comparison with the simple wadding cartridge (Fig. 18), where the commercial filter is only wrapped with wadding, shows the advantage of protecting the cartridge with marble, ceramic or carbon material, again proved by lower head losses and longer life time. In fact, for example, at the maximum speed, where head losses are higher, Filter 1 achieves the same head losses that the wadding cartridge reaches for 80 g at about 300 g of added sand.

Summarizing, the three filters are realized starting from the same cartridge in synthetic wadding and then protecting it with materials of different nature and size.

The filter made with pebbles (Filter 1), material with the biggest granulometry among the used ones, guarantees minimal head losses at both initial and maximum clogging conditions, but exhibits maximum head losses in the central zone of the chart, so for an average clogging degree, precisely for values between 120 and 260 g of added sand.

The filter made with activated carbon (Filter 3), i.e. with the material, among those used, with the smaller grain size, returns inverted results: minimum head losses in the central zone, for added sand values between 120 and 240 g, and maximum head losses at clogging degrees zero and maximum, i.e. in the initial and final zones of the chart.

The filter made using the EM ceramic filter (Filter 2), intermediate size component among the used materials, both in the initial and final phase exhibits pressure losses higher than Filter 1 and smaller than Filter 3, whereas in the center of the graph it shows pressure losses higher than Filter 3 and lower than Filter 1.

Finally, Filter 4, made by combining the various granular elements, for low clogging values produces very small head losses, greater only to those related to Filter 1, and for average clogging values it has head losses higher only respect to Filter 3 but lower than those of Filter 2 and much smaller respect to Filter 1. Filter 4 tends to the minimum values in terms of head losses, both for a low and a medium degree of clogging. Finally, the head losses found for 300 g of added sand are still very small and greater only respect to the filter made with marble pebbles: this suggests the use of a greater amount of such elements for the realization of the final version of Filter 4. The smaller the size of the material (moving from Filter 1 to Filter 3), the higher the head losses for low values of added sand. The advantage in using smaller grains becomes evident for high values of filter clogging, particularly at about 80/100 g of sand introduced, where Filter 3 returns the lowest values of head losses with the progressive clogging, up to a considerable degree of clogging, corresponding to approximately 240/260 g of added sand. However, the results obtained by adding such amounts of sand are interesting for analyzing the various filtration mechanisms, but represent little significant data, since a filter would be cleaned or replaced before reaching such high clogging values. Manufacturers of drinking water filter cartridges, in fact, recommend replacing cartridges, on average, after three months of use.

Table 1
Head losses for the three pump speeds, respectively, and the maximum clogging filter.

Fine sand [g]	ΔP [mbar]		
	Minimum velocity	Intermediate velocity	Maximum velocity
800	52.1	65.4	90.3

Filter 3 can be considered, therefore, advantageous, since it causes low head losses for low and medium clogging values, conditions which really occur in the life cycle of the cartridge.

Table 1 shows the experimental data in terms of head losses, for the three velocity values, related to the filter made to simulate the condition of maximum clogging by sand (Section 2.4.5), i.e. in which the introduced sand occupies all the voids present between the interstices of the materials used to protect the cartridge.

It is noted how Filter 3 is the filter which shows the head loss values closest to the ones reported in Table 1, since it is the one, among the proposed filters, which gives the smaller void size.

Finally, the head losses trends for Filter 4 show that in this case there are no stalemate areas for head losses, but the trends are almost linear with a steady slope, and the variations in head losses are well distributed from the lowest clogging values up to the highest ones.

Filter 4, compared to a generic commercial wire-wound cartridge, once again allowed to obtain sparing pressure losses also with a high degree of clogging, with a consequent benefit in terms of durability.

Comparing the head losses trends of Filter 4 with the ones of Filter 3, it can be seen that the mix of materials selected for the realization of the final filter, which contains a big amount of marble pebbles, allowed to significantly lower the values of the head losses at the initial and final stage of the graph. However, this caused a slight rise (still acceptable) in the head losses in the central zone, where instead Filter 3, made only with activated carbon grains, retains better the added sand, so as to prevent it from reaching the cartridge and return, therefore, reduced head losses.

In comparison with Filter 2, the trend of Filter 4 does not deviate significantly; only for the maximum velocity Filter 4 exhibits for low clogging values less pressure drops. The pressure drops are very similar, because in Filter 4 the mixing of the different elements creates a grain skeleton very similar to that of Filter 2, made with material of intermediate granulometry between pebbles and active carbon grains. However, the general trend of the curves is not the same. In fact, Filter 2 shows the tripartite pattern described above, hence initial increase in head losses, sub-horizontal central phase, and final stage with losses linear raise. The pressure loss trend of Filter 4 is, instead, rather linear.

Finally, the comparison of the head loss trends for Filter 4 and Filter 1 highlights that the curves are for both linear and increasing; Filter 4, however, exhibits lower gradients and, therefore, lower increments in head losses as the clogging level increases.

In conclusion, Filter 4 appears very effective because, for any clogging rate, it exhibits overall pressure losses lower compared to the other proposed filters. Combining properly the various components in Filter 4 led, therefore, to satisfactory results, because the advantage of the more coarse fraction for low clogging degrees and the advantage of the finest elements for intermediate clogging degrees are merged.

4. Discussion of the results

4.1. Analysis of the head losses trends

The different behaviors of the filters can be explained by observing from the transparent walls of the filter container (see the photographic documentation in Ref [5]] the evolution of the process. In Filter 1, for example, the pebbles showed a poor ability to retain the sand and then to protect the filter. In the clogging process they place themselves in the space between the cartridge and the filter holder with very low gear, leaving many empty spaces that are immediately filled with sand. The sand, even adding the least amount of water, immediately deposited on the glass bottom and quickly clogged the cartridge. This phenomenon, starting from the bottom where the sand deposited initially, proceeded with parallel levels towards the top, until all the interstices were occupied by the introduced grains. As a consequence, the introduced sand produces an increase in head losses. However, since the pebbles do not hold properly the sand, they return a very permeable solid skeleton and then permit to keep head losses relatively low.

In Filter 2, unlike Filter 1, clogging does not proceed from the bottom up, but horizontally, by level. The introduced sand has, therefore, a different preferential direction and is no longer able to reach the bottom, but moves towards the edges, particularly toward the outer edge or to the interface between the cartridge holder and the ceramic discs, migrating later towards the filtering septum. The outer edge of the filter appears to have a greater amount of voids than the wadding-discs interface, which is almost without voids. In fact, being the wadding soft, it fits very well to the surface of the discs. Initial head losses can be attributed, therefore, to the minimum amount of sand that, moving horizontally into the space between the cartridge and the holder pushed by the current, instead of reaching the outer edge, reaches the cartridge. The stalemate phase, on the other hand, corresponds to the time when the introduced sand fills the voids between the discs, i.e. the space between the cartridge and the holder. Finally, in the third stage the interstices between the particles are saturated, and therefore additional added sand creates pressures on the wadding cartridge that will be reached from other sand, with a consequent increase in head losses.

The Filter 3 trend can be explained by the fact that it shows, from the first grams of added sand, a greater resistance than the other filters previously proposed, since the active carbon grains retain the sand very well and do not let it flow to the cartridge. In the first phase, therefore, the head losses do not have large variations when sand is added, because it does not reach the cartridge, but it remains trapped between the grains and in part migrates towards the outer edge or towards the cartridge holder-granular carbon interface. Thus, as for Filter 2, the outer area is the one with more voids, due to the low adhesion between grains and the smooth surface of the cartridge holder; it is, therefore, the region where water migrates more easily. In the final part of the curve, after the 260 g of added sand, all the interstices are saturated and the migration of sand forced by the circulating water towards the cartridge begins, resulting in increased head losses generated by the filter.

The comparison of Filter 2 with Filter 1 shows that, as the size of the material used for the cartridge protection is smaller than in Filter 1, the losses in Filter 2 are initially larger, because at 0 g of added sand smaller pieces leave less voids, resulting in increased water resistance. However, in the interval between about 120–260 g, Filter 2 produces significantly lower head losses than Filter 1, whereas in the final segment the head losses of Filter 2 are again higher. This behavior can be explained by the greater ability of the ceramic to retain the sand respect to the marble pebbles: larger volumes of water were needed even to introduce the minimum amount of fine sand, due to the smaller dimensions of the ceramic elements, which guarantees a better distribution and a smaller size of the voids. This, in response to a slight increase in initial head losses due to the lower hydraulic permeability of the medium, returns a filter capable of more effectively retaining the suspended particles. EM ceramic discs constitute a more effective protection for the central filtration septum, since it is clogged with sand in times longer than those required for the previous filter, with consequent lower head losses. Filter 2 has also the ability to combine mechanical filtration and water treatment, two conditions that are typically carried out by different products.

During this experience, it was noted as well that, by compressing the wadding, the head losses increased.

In comparison with Filter 2, Filter 3 manifests higher head losses initially, in no-clogging conditions. In fact, the small-sized grains make water passage more difficult, as they leave less voids. However, activated carbon grains recreate many overlapping radial layers in the interposed area between the cartridge and the SAN container, thus blocking very well the permeation of the sand and preventing it from reaching the cartridge. As a result, in the middle part of the chart, the filter has lower losses than those of the filter made with ceramic discs, which retains less sand. Finally, appreciable head losses for Filter 3 are only reached at a high degree of clogging, due to the smaller amount of voids, compared to the other materials. The differences in head losses with Filter 1 are, instead, very marked. Specifically, under zero clogging conditions, without any sand addition, Filter 1 has very little head losses compared to Filter 3. This gap is decreasing, with higher losses for Filter 1, until the first 80/100 g of added sand; after this value, in fact, it is the activated carbon filter that shows lower head losses, up to 240/260 g of added sand. Therefore, the advantage of using larger cobs extends to about 80 g of sand introduced into the filter, as the benefit derived from the higher water permeability is counteracted by the rapid clogging of the cartridge. The advantage in using activated carbon is, instead, evident by average clogging values up to 260 g of added sand; after this value, the interstices are already saturated and, therefore, there are considerable increases in head losses, i.e. Filter 3 exhibits greater head losses than Filter 1, due, as before, to the lower presence of voids, i.e. to the lower hydraulic permeability of the medium.

4.2. Identified filtration mechanisms

From the experimental evidences, correlations were found between the head losses trends showed by the filters for the different clogging degrees and the constructive characteristics of the filters themselves, which determines a different way of depositing sand inside the filter and thus a different clogging mechanisms for the filters.

First of all, the water flow that reaches and passes through a filtering septum splits into smaller flows so that it can cross the fibers of which the septum is made. The suspended particles, therefore, undergo a number of changes in direction until they are trapped, depending on the type of filter (Fig. 19). In the specific case, to model the filtration process reference is made to the sieve mechanism [13].

This type of mechanism occurs when the diameter of the suspended materials is greater than the distance between the fibers and, therefore, the particles fail to cross the septum. The larger particles deposit on the first layers of the filter element, while the minutest ones can pass to the innermost layers. The spongy structure, result of the building process of the wadding used for the PET cartridge, allows the bulk of particles suspended in water to be retained on the filtering surface, although the cartridge can only retain particles larger than the minimum size of its interstices.

With prolonged use over time, accumulation of suspended particles will cause a decrease in the hydraulic properties of the cartridge, leaving less transitory space to the fluid, until the filtering septum is completely clogged by the solid particles extracted from the liquid. At this point, as shown by the experimental results, there is a considerable increase in head losses.

Besides the filtering mechanism, it is important to define also the way in which the different filters reach the maximum clogging, observing the manner in which the sand added from time to time is deposited inside (Fig. 20).

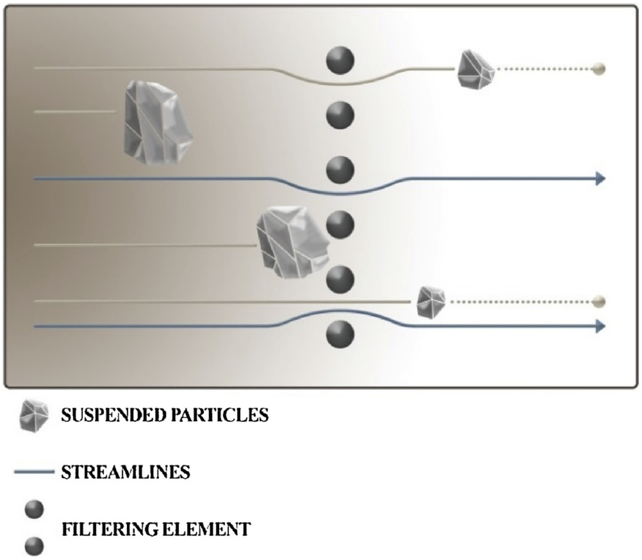


Fig. 19. Sketch of the sieve filtering mechanism.

The identified mechanisms are mainly three (Fig. 21): the first (Filtration Mechanism 1 - FM1) concerns the filter made using white marble pebbles; the second (Filtration Mechanism 2 – FM2), with appropriate variations, refers to the filter made with EM ceramic and to the one with granular activated carbon; the third (Filtration Mechanism 3 – FM3) occurs in the final filter, made by combining all the granular elements.

In the first detected mechanism FM1, which interests Filter 1, the filter clogging proceeds from the bottom upwards. Specifically, given the high permeability of the skeleton formed by the marble grains, for the large size of the voids, the sand, flowing from the top, where it is introduced, does not encounter any obstacle and proceeds undisturbed to the bottom of the glass. The pictures show a progressive increase in the clogging degree for horizontal planes [5]. Thus, the cartridge is poorly protected, as sand comes to it from the first quantities introduced. The described mechanism is associated with an almost linear and growing trend of the head losses as the clogging increases. The use of a highly permeable material such as marble pebbles, therefore, gives poor protection against the filtering clogging and a consequent immediate increase in pressure drops; however, it is also able to guarantee at the initial stage the minimum detected head losses.

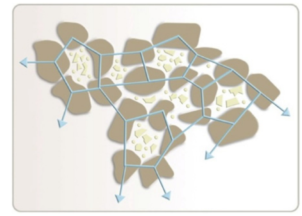


Fig. 21. Image showing the filtration process in any granular material.

In the second mechanism, FM2, occurring both in Filter 2 and Filter 3 (Fig. 21b), the clogging proceeds, instead, from the outer edge to the inside, then starting from the cartridge glass until it reaches the PET filtration septum.

The sand added from time to time, flowing through the interstices of the granular material pushed by the circulating water, proceeds to the direction which has the least resistance to transit, that is, the one in which the presence of voids is higher, in the specific case to the filter container outer walls, which are smooth and regular and, therefore, unable to adapt to the shape of the granular elements. The spongy texture of the filtering septum, on the other hand, perfectly adheres to the shapes of the material placed in the protection of the same, returning a small amount of voids and creating a zone less permeable than the outer edge. Thus, two distinct zones are created: one interior, at the interface between the spongy material and the grain skeleton, characterized by a low presence of voids, and one outside, close to the PET glass and made of the granular elements, characterized by a high hydraulic permeability. The two zones are respectively separated from EM ceramic cylinders in the case of Filter 2 and from granular active carbon in the case of Filter 3.

The grain skeleton formed from Filter 2 presents, given the larger dimensions of the particles, a greater presence of voids and therefore the sand, proceeding from the outer edge towards the cartridge, is only partly stopped, depositing in the interstices of the solid skeleton of the

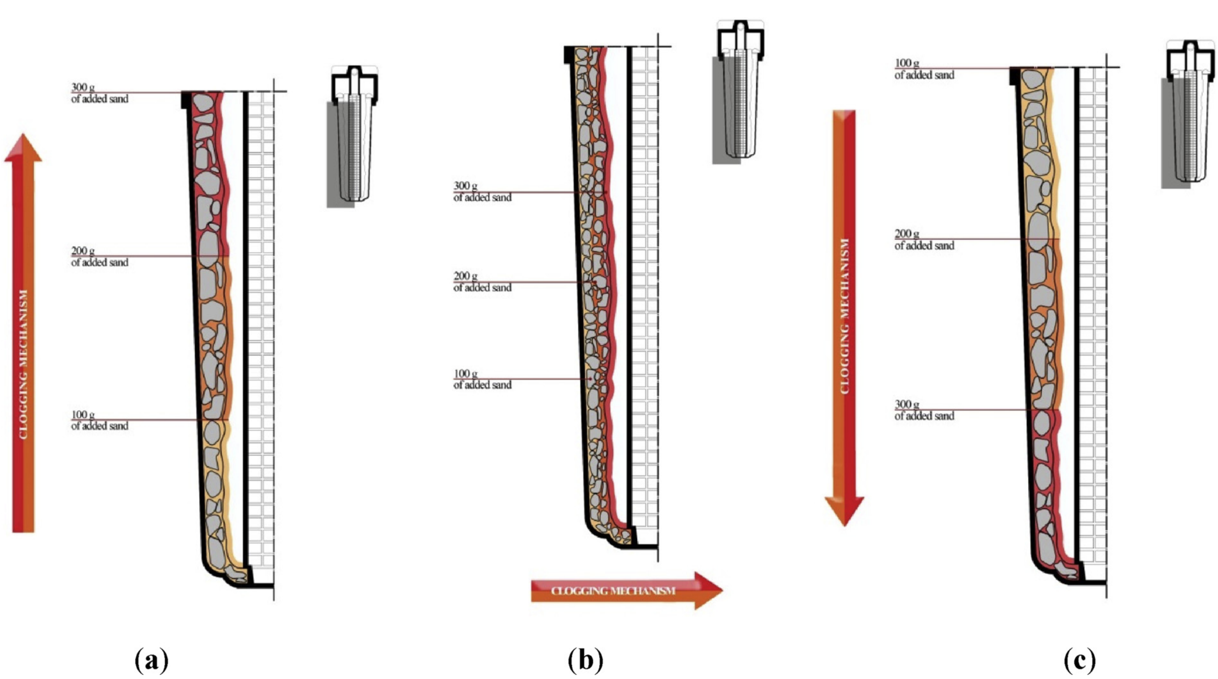


Fig. 20. Image showing the different clogging mechanisms: a) FM1 (Filter 1); b) FM2 (Filters 2 and 3); c) FM3 (Filter 4).

granular material, whereas the other part goes to the cartridge, thus being responsible for the head losses detected at the initial stage of the clogging process. By keeping adding sand, there is a slight increase in pressure losses, as in this second phase the sifted sand is saturating the voids between the grains and therefore can not reach the cartridge. In the final part of the process, there is a considerable increase in head losses, corresponding to the progressive clog of the cartridge. The mechanism just described is associated with the tripartite graph described in Section 3.

The activated carbon, even smaller in size than the EM ceramic, stops almost totally the incoming sand not allowing it to reach the septum, and it is able therefore to prevent the increase of pressure losses. This second just described clogging mode is associated with a pressure trend distinguished by a low-slope starting segment, characterized by a modest increase in head losses, and from a high-slope end section where, on the contrary, there is a sudden increase of the drops.

The third identified mechanism FM3 affects filter 4 (Fig. 21c). It is completely analogous to the first presented with respect to Filter 1, but the direction must be inverted because the sand introduced from time to time in this case saturates the voids between the interstices of the solid skeleton by proceeding from top to bottom. This is due to the less permeability of the medium, which retains the sand by preventing it from flowing deep into the filter. The sand progressively added from the top of the SAN holder by the inlet water flow, exerting pressure on the underlying layers, pushes more and more deeper the sand already deposited between the interstices of the skeleton reaching the bottom of the glass, condition corresponding to the maximum clogging of the filter.

5. New cartridge design

5.1. Technical precautions for the correct implementation of mechanical filters

After the analysis of the experimental results, some remarks can be pointed out regarding the technical implementation of the proposed cartridges. In fact, these filters are only effective if equipped with some specifications such as: internal stability, open porosity, rounded shape of the materials placed as protection for the filters, adequate hydraulic permeability, non-cementing components, adequate grain settling, and so on.

All the material used in combination with the inert synthetic PET wadding for the realization of the various filters, as said before, are able to incorporate in their granular structure smaller particles without impairing the hydraulic permeability. A property that guided the search and the choice of such materials used to protect the filtering septum is the porosity (Fig. 21), generally defined as the ratio between the volume of voids, or pores, and the total volume of the material.

Depending on the size and distribution of pores, the mechanism responsible for the diffusion of matter changes, together with the characteristics and phenomena associated with it. In fact, in this case what affects the filtration process is not the porosity of the single element, related to its adsorption capacity, but the porosity of the solid skeleton, formed by aggregation of various grains of different materials but considered as a whole medium [19,20]. The suspended particles can move transported by the fluid in the adjacent pores if they are sufficiently small, i.e. if the narrow gorges connecting two or more interstices of the main skeleton are larger than the embedded particles. The re-created skeleton must be permeable only to the fluid to be treated, i.e. water in the specific case, but not to the suspended particles, which must be appropriately retained in order not to reach the filtering septum. The different granular materials, of different dimensions, when combined return a solid skeleton having different sizes of the voids too (Fig. 22).

The permeability of the skeleton, which unlike porosity is a vector, represents its ability to be crossed by fluids, is affected by factors related to the characteristics, essentially to the microscopic structure (for example, curvature and pore size), of the porous medium and appears as a constant of proportionality in the Darcy's law between the pressure gradient and the discharge [14,21]. Porosity and permeability are, therefore, two properties that, although correlated, are distinct and not to be confused, since a single carbon grain is, for example, porous and non-permeable; the solid skeleton formed by the aggregation of more grains of the same material is, instead, porous and permeable (Fig. 23) [19,22].

The design and building of the filters is essential to ensure an adequate permeability of the solid grain skeleton.

A granular filter, such as the one created in the proposed cartridges, has to be also internally stable in order to be efficient, i.e. its structure must not undergo variations in time, settlements or reciprocal displacements between grains that may vary the distribution and size of the voids. This condition has been guaranteed by the use of large-scale stone material which, placed in correspondence with the filter element ring, inhibits, by exercising a slight pressure on the underlying elements, the reciprocal movements between the grains, thus ensuring the stability required for the solid skeleton. However, it is also necessary to avoid the so-called cohesion by "interlocking", a phenomenon linked to the elongated form of the particles, preferring rounded grains, in order to favor hydraulic permeability and to avoid the arrangement of grains in parallel filaments.

Finally, another required property is that the different used granular materials must be non-cementing, i.e. not soluble in water. Cementation is, in fact, one of the mechanisms occurring together with the sedimentation and consists in the precipitation of substances, brought to solution from the circulating waters, to the pores of the sediment. The process of lithification, that is of transformation of an inconsistent sediment into a coherent or high-consistency one, can occur with mechanical actions (reduction of pores, generally occupied by water or air, by means of mechanical compression, resulting in a reduction in volume) and chemical reactions (further reduction in volume as interstitial waters determines the precipitation of the substances contained in sediment pores).

Each filter made using grain material, and therefore also the proposed filters, exhibits a "clogging limit", a condition analogous to that rebuilt in the laboratory, in which the pores of the coarsest material are gradually occluded by the particles of the finer material to a level that prevents hydraulic efficiency. To this extent it is necessary to clean it, if possible, or to replace it immediately.

The use of materials with the aforementioned properties and the steps to be taken in implementation, described in this section, are necessary conditions for making mechanical filters, such as those proposed, capable of yielding moderate head losses even at high degrees of clogging and much longer lasting than normal cartridges.

5.2. Advantages and properties of the new proposed filters

In Fig. 24 an axonometric explosion of the proposed system and a detailed image of the container designed to accommodate granular elements are reported.

The main advantage of this new designed and built cartridge is that it is capable of ensuring low head losses. This last aspect is not to be underestimated, for example in the case of dwellings on the top of a building, in which the input pressure may not be sufficient for the operation of the various water appliances if the filter element has a great impact on the plant. The new filter here proposed can guarantee reduced pressure losses in all working conditions, thus avoiding this inconvenience, even in the presence of waters with many suspended elements or dissolved substances. In fact, it is demonstrated to provide average head losses significantly lower than those shown by the analyzed commercial cartridges, even for high levels of clogging. This also resolves the problem of a substitution in a short time: the filter so designed and manufactured is able to withstand a large amount of

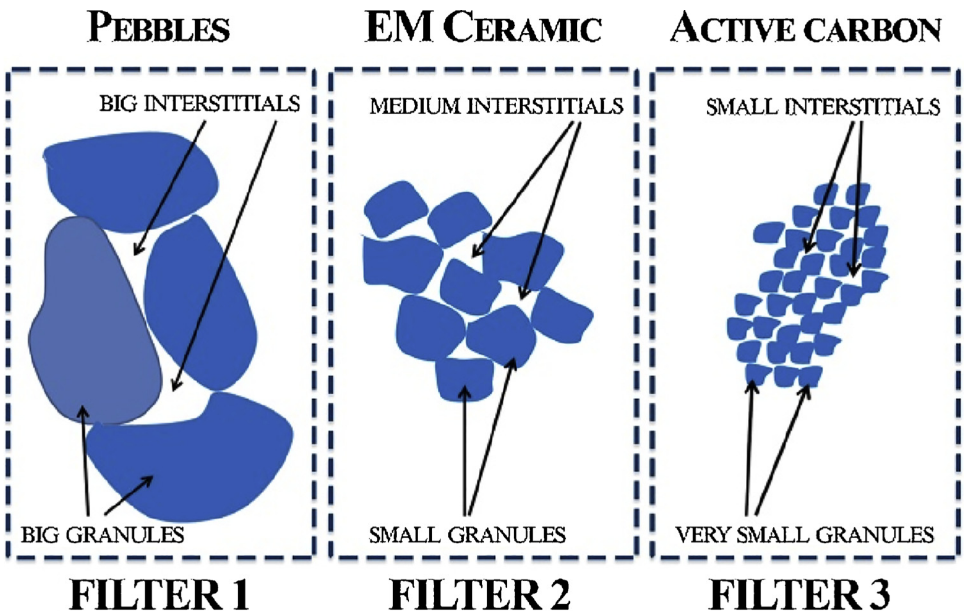


Fig. 22. Different grain and voids size of the different solid materials combined in the new filters.

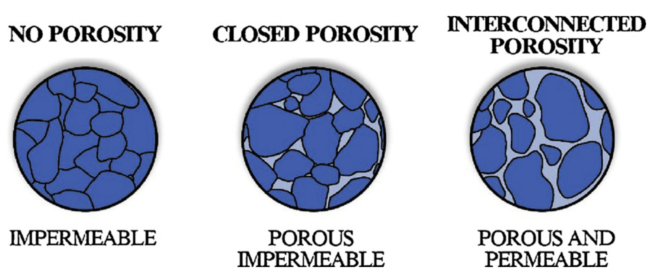


Fig. 23. Relationship between porosity and permeability in a granular material.

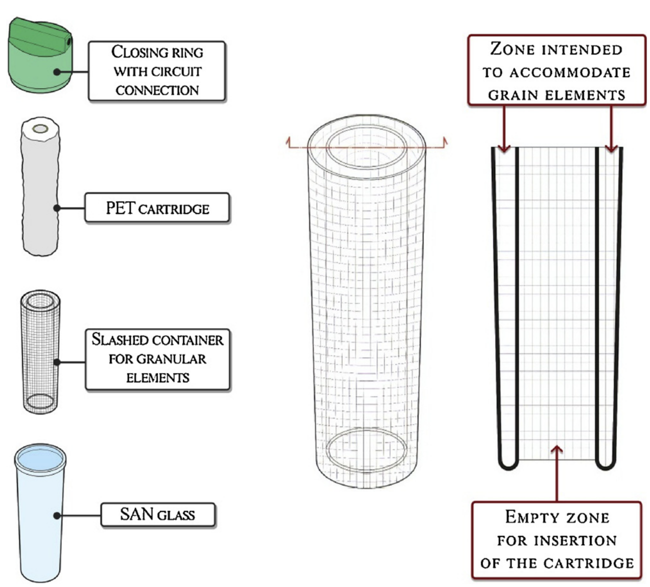


Fig. 24. Assonometric view of the designed filter, indicating the different components.

suspended particles before annulling its filtering capacity, so high clogging values are reached in longer operating times and, as a result, the filter lasts longer.

To this feature it has to be added the combined action of mechanical filtration and water treatment, difficult to find on the market, as the various currently available products act selectively by resolving the proposed issues individually.

Another noteworthy factor is the advantage in economic terms, which concerns both the individual materials used for the various filters, and the management of the filter itself. Concerning the former, 1 kg of white pebble actually sells for just 080 Eur, the activated carbon grains range from 6 to 10 Eur per kg, while EM ceramic cylinders, despite featuring the highest price - $50 \div 60$Eur per kg-, have the advantage to be reused for up to 10 years. About the latter aspect, the modified cartridge can be used for period up to one order of magnitude longer respect to the commercial products, i.e. featuring a lifecycle of 5–6 years depending on the progressive clogging of the outer region of the filter. The reduced cost of the various components with reference to this time horizon makes the filters very economical. Additionally, the long-lasting life and efficiency make the replacement not required in short periods, with a further benefit in terms of labor and costs. The proposed filters are also ecologically compatible: in fact, being composed of natural elements, they are simple to dispose of in the case in which they have to be replaced.

Lastly, the new cartridge has an excellent chemical compatibility with foods, drinks, drinking water and chemical solvents and, therefore, it shows a great versatility and can be used extensively. The proposed solution not only solves the before mentioned limitations of the commercial cartridges, but also present additional properties and benefits which justify its selection.

All these advantages are summarized in Table 2.

The only disadvantage found is the implementation, as this is more articulate and demanding than a simple replacement of a generic commercial cartridge. However, this problem may be easily solved by

Table 2
Summary of the advantages of the novel cartridge.

Main benefits
low head losses
durability
combined mechanical filtration and water treatment
economic advantage
efficiency
ecological compatibility
chemical compatibility
versatility

using a specially designed plastic slashed holder of the type similar to that used for the commercial cartridge support, suitably shaped so as to fit perfectly inside the SAN glass and leave a special vacuum in the center, useful for receiving any filter cartridge or septum. By introducing the grain elements inside this container, it would be possible to guarantee the internal stability required for the solid skeleton for optimum operation of the filter and, at the same time, a quicker and easier installation. The container was not used during laboratory tests, it was designed later and has as its sole purpose to simplify the process of making the filtering cartridge as reproducible as possible. In this way, the same simplicity and immediacy in the implementation of the commercially available cartridges would be reproduced, since the realization of the filter would reduce to insert in the interior of this special container the various pre-packaged and ready-to-use elements.

6. Conclusions and future perspectives

The experimental activity carried out in this work permitted to draw up some useful remarks on the filtering cartridges, aimed at proposing innovative long-lasting in time and economic systems capable of ensuring low head losses, significantly lower than those produced by commercial cartridges, even in high clogging conditions. The experiments, in fact, led to the design of a versatile cartridge and the selection of a proper combination of various granular materials for the proper protection of the filter from the clogging effects. This benefit of inducing low pressure drops may be particularly relevant in low pressure plants, and allows for longer operating times of the cartridge.

The proposed filtering cartridge also presents advantages in economic terms, both for the reduced cost of the materials and various components and for the long-lasting life and efficiency, which make the replacement not required in short periods.

It is also ecologically compatible: in fact, it is composed of natural elements, simple to dispose of when they have to be replaced.

To this feature it has to be added the combined action of mechanical filtration and water treatment, difficult to find on the market in a single filter cartridge.

The new cartridge has also an excellent chemical compatibility with foods, drinks, drinking water and chemical solvents and, therefore, it has a great versatility and can be used extensively.

The proposed solution, covered by a recently filed patent, not only solves the limitations of the commercial cartridges, but also present additional benefits which justify its use.

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