Efficiency of wastewater purification in medium sand with a lightweight expanded clay aggregate assisting layer

Marek Kalenik[1] ✉ iD, Piotr Wichowski[1] iD, Marek Chalecki[2] iD, Adam Kiczko[1] iD

[1] Warsaw University of Life Sciences – SGGW, Institute of Environmental Engineering,
Department of Hydraulics and Sanitary Engineering, Nowoursynowska 159, 02-776 Warsaw, Poland

[2] Warsaw University of Life Sciences – SGGW, Institute of Civil Engineering,
Department of Mechanics and Building Structures, Warsaw, Poland

Abstract: The objective of this experimental study was to examine whether an assisting layer of lightweight expanded clay aggregate (LECA) of the granulation 1–4 mm, introduced into a subsoil, is able to improve an efficiency of removal of total nitrogen and total phosphorus from domestic wastewater. In the investigations, an assisting 0.10 and 0.20 m thick LECA layer was applied. It has been observed that the effectiveness of removal of total suspended solids (TSS), total nitrogen and total phosphorus from wastewater as well as the level of biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) is in accordance with the Polish standards on wastewater disposal into grounds and surface water. The performed experiments showed that the effectiveness of raw wastewater purification for the medium sand soil bed with the 0.20 m thick assisting LECA layer is higher than for the 0.10 m thick assisting layer. In the medium sand soil bed with the 0.20 m thick assisting LECA layer, the removal efficiency regarding total nitrogen increased by 20.6%, total phosphorus by 5.2%, ammonium nitrogen by 8.8% and TSS by 5.3%, and reduction efficiency regarding BOD_5 increased by 1.7% and COD by 2.3% with relation to the 0.10 m thick assisting LECA layer (all percentages – in average). The results of the experiment showed that the LECA with the granulation 1–4 mm can be used to assist in removal of total nitrogen and total phosphorus from wastewater with application of infiltration drainage.

Keywords: domestic wastewater infiltration drainage, domestic wastewater purification, individual wastewater treatment plant – individual WWTP, lightweight expanded clay aggregate (LECA), soil bed

INTRODUCTION

Individual wastewater treatment plants (individual WWTP) with an infiltration drainage introduce purified wastewater into a subsoil and feed underground water, improving a water balance of rural areas where they are built. Due to that, their purification efficiency must be high in aim to avoid a pollution of the underground water with biogenic compounds and pathogens (Śliz and Bugajski, 2022). As it results from the investigations to-date (Wang, Zhu and Mao, 2021), the individual wastewater treatment plants with the infiltration drainage very well remove the pathogens (germs, viruses, parasites) from the domestic wastewater. In septic tanks, parasites' eggs are caught during

sedimentation processes; in the sand soil beds and zeolite, peat and coal assisting layers, germs and viruses are caught during filtration and absorption; earthworms efficiently eliminate pathogens as well (Wang, Zhu and Mao, 2021).

In the individual wastewater treatment plants with the infiltration drainage (Fig. 1), only a mechanical and biological purification of domestic wastewater is applied. The mechanical purification of this wastewater is realised in a septic tank – in the processes of sedimentation and flotation. During the flotation process, the wastewater is purified of mineral and organic impurities having a density lower than water's, e.g. fats. In the sedimentation process, in turn, the wastewater is purified of mineral and organic impurities having a density higher than
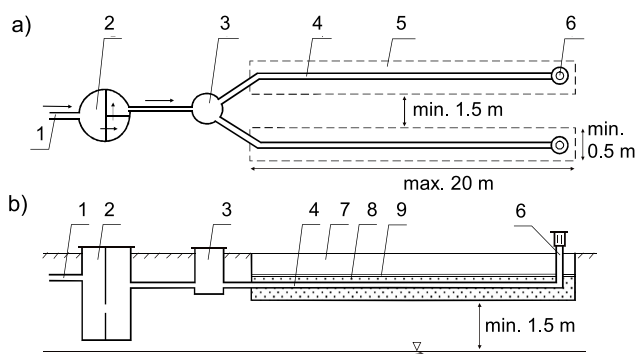
Fig. 1. Scheme of an individual wastewater treatment plants with an infiltration drainage: a) horizontal projection, b) longitudinal section; *1* = raw wastewater supply pipe, *2* = multichamber septic tank, *3* = well for dispensing wastewater, *4* = wastewater infiltration pipe, *5* = wastewater infiltration area, *6* = ventilating pipe, *7* = native soil, *8* = gravel bed infiltrating wastewater under the drainage, *9* = geotextile protecting the gravel bed; source: own elaboration

water's, e.g. sand, faeces and paper. The biological purification, however, is realised in the soil bed under the infiltration drainage. In the soil bed, it can be observed a nitrification process where nitrogen compounds are being removed from the domestic wastewater, as well as an adsorption and precipitation processes where phosphorus compounds are being removed. In the biological purification of the domestic wastewater, the aerobic bacteria and other microorganisms take part. During the filtration the domestic wastewater in the soil bed, suspensions and colloids are retained in soil pores. The wastewater filtered in the ground rises toward the terrain surface in ground capillaries, a part of it is taken by plants, other part evaporates, the rest infiltrates into underground waters.

If the soil bed in such individual wastewater treatment plants is excessively burdened with sediments and colloids, a so-called filter (clogging) cake occurs (Spychała, Nieć and Pawlak, 2013; Spychała and Nieć, 2013) and the ground permeability decreases (Nieć and Spychała, 2014). Experiments show that the content of total suspended solids in the domestic wastewater under the septic tank can oscillate between 20 and 475 g·m⁻³ (Spychała and Nieć, 2013). Such high differences between the values of the TSS content in the domestic wastewater flowing out of the septic tank are related to a volume of the gathered sediment. The wastewater flowing out of the septic tank washes the sediments away. The higher is the volume of the sediment gathered in the tank, the higher is the content of TSS in the wastewater flowing out of the septic tank. Microscopic analyses showed that the filter cake formed in the ground contains mainly thread-like fibers of the toilet paper which is washed away from the septic tank by the wastewater. The toilet paper fibers biodegrade more slowly than they accumulate in the ground (Spychała and Nieć, 2013; Spychała, Nieć and Pawlak, 2013). The filter cake forms usually in poorly permeable grounds. The experiments show that the soil bed under the infiltration drainage is readily settled by earthworms which loosen the bed (make vertical and horizontal channels), improving the bed permeability (Hawkins *et al.*, 2008). The tests made in laboratories showed that if the earthworms are introduced in a clogged soil bed under the infiltration drainage, then after two weeks they increase its permeability and reduce the quantity of organic substances in the bed (Spychała and Pilc, 2011). The earthworms living in the soil

bed increase the efficiency of removal of total and ammonium nitrogen and total phosphorus (Singh *et al.*, 2018) as well.

The experiments made in the medium sand soil bed show low average efficiency of removal of the total nitrogen (22%) and total phosphorus (23%) (Kalenik and Wancerz, 2013). Other scholars (Cuyk van *et al.*, 2001; Gill *et al.*, 2009) also confirm that the efficiency of removal of the total nitrogen and total phosphorus in a well permeable ground is low. If a lot of individual wastewater treatment plants with infiltration drainages is built in a certain area, it can lead to a pollution of underground water with nitrogen and phosphorus compounds (Eveborn, Kong and Gustafsson, 2012; Heatwole and McCray, 2007). However, the accumulated phosphorus compounds in the soil bed under the infiltration drainage can be successfully used by plants with short root system (Kvarnström, Morel and Krogstad, 2004).

In aim to improve the efficiency of wastewater purification in a soil bed under an infiltration drainage for domestic wastewater, experiments were performed on permeable grounds with an assisting layer made of the opoka rock (Kalenik and Chalecki, 2021), clinoptilolite (Kalenik, 2014; Kalenik and Chalecki, 2019), chalcedonite (Kalenik and Wancerz, 2013) and dolomite (Kalenik and Cieśluk, 2009). These minerals contain ions of calcium, iron and aluminum and they are porous, thus they significantly improve the efficiency of removal of the nitrogen and phosphorus compounds from the domestic waste-water under an infiltration drainage if compared to soil beds made of a pure quartz sand.

The lightweight expanded clay aggregate (LECA), however, was applied in constructed wetlands with a vertical subsurface flow to purify rainwater (Amado, Albuquerque and Espírito Santo, 2012) and remove heavy metals from municipal rainwater (Albuquerque and Labrincha, 2008; Pla *et al.*, 2021). The LECA was also applied for a preliminary purification of surface water in a natural watercourse – in a river (Łopata *et al.*, 2017). The goal of the investigations presented hereby was to check a possibility of application of the LECA as a filtration bed for removal biogenic compounds from surface water which undergoes eutrophication evoked by them. Based on these investigations it was found that the efficiency of the applied LECA filters with regard to the removal of main pollutants from water was equal to: 5–6% for the total nitrogen, 12–16% for the total phosphorus and 17–29% for the total suspended solids (Łopata *et al.*, 2017). Laboratory tests were also performed with regard to the phosphorus sorption by LECA beds with the granulation 0–2 mm, 2–4 mm and 0–4 mm (Zhu *et al.*, 2003). In these tests, various burden of a filtration solution with phosphorus was applied. The difference in the total phosphorus sorption between these three LECA grain sizes for low concentrations of phosphorus (<15 mg·dm⁻³) was lower than for the higher concentrations of phosphorus (>15 mg·dm⁻³). The performed investigations showed that the size of the LECA grains in the applied beds affected the phosphorus sorption capacity. The finer were the grains, the higher the phosphorus sorption capacity was (Zhu *et al.*, 2003).

There is no data in the literature, however, concerning an application of the LECA for a purification of domestic wastewater in soil beds under the infiltration drainage. Due to that, the objective of the experiment presented in this study was to examine in a stand test evaluating the effectiveness of purification of wastewater in a soil bed, whether an introduction of an assisting layer of the LECA of the granulation 1-4 mm into a permeable

subsoil improves an efficiency of removal of nitrogen and phosphorus compounds from wastewater. In this aim, medium sand model soil beds with 0.10 and 0.20 thick LECA layers (Fig. 1) were used, placed under the wastewater infiltration drainage.

In the experiment, it was assumed a hypothesis that the LECA with the granulation of 1–4 mm has good absorption properties and bacteria assisting the aerobic purification of raw wastewater will efficiently immobilise on its grains' surface.

MATERIALS AND METHODS

FILTRATION MATERIALS

Medium sand soil beds with 0.10 and 0.20 thick LECA layers were used for the experiment. Granulation of the sand and LECA was determined with the sieve analysis. Granulometric tests of three samples of the medium sand and LECA were performed; their results are presented in Figure 2.
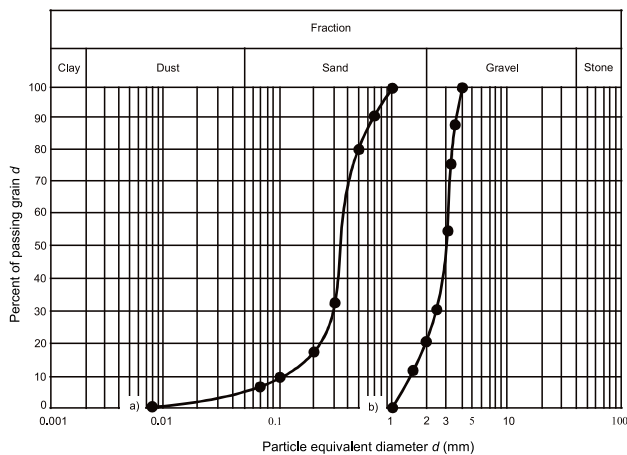
Fig. 2. Grain size distribution curve for: a) the medium sand, b) lightweight expanded clay aggregate (LECA); source: own elaboration

The 1–4 mm LECA applied in the tests (Fig. 3) is a lightweight ceramic additive made of the fired clay in the temperature ca. 1150°C in a rotary furnace where the clay of a special kind expands (Pla *et al.*, 2021). The LECA has a very porous internal structure and rough hard surface. The LECA grains have uniformly distributed small internal pores whose diameter does not exceed 1.0–1.5 mm (Łopata *et al.*, 2017). The high internal porosity (73–88%) and low density (330–430 kg·m^{-3}) of the LECA allows flowing on a water surface (Zendehzaban, Sharifnia and Hosseini, 2013). The LECA is made of swelling clays. The LECA is inflammable, chemically neutral for the natural environment, resistant against molds and other fungi, insects and rodents as well as it has good thermoinsulation and acoustic parameters (Zukri *et al.*, 2018). The LECA is also recyclable, it does not rot or thicken in soil bed over time (Huang *et al.*, 2020). The LECA is the alkali aggregate whose pH is higher than 10 (Suliman *et al.*, 2005; Ádám *et al.*, 2007).

It contains in majority the SiO_2 (58–65% of mass), Al_2O_3 (11–19% of mass), Fe_2O_3 (7–10% of mass), CaO (3–13% of mass), the remaining components (Na_2O, K_2O, MgO, TiO_2, MnO, P_2O_5, SO_3) do not exceed 2–5% of mass (Kalhori *et al.*, 2013; Sharifnia *et al.*, 2016; Shokri, 2020; Pla *et al.*, 2021).
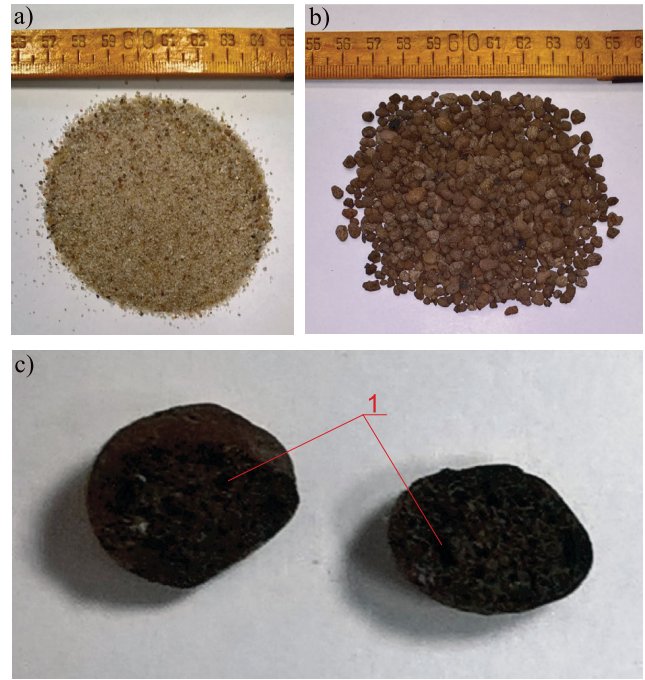
Fig. 3. Soil beds: a) general look of the medium sand grains, b) general look of the lightweight expanded clay aggregate (LECA), c) an individual LECA grain, cut in half; *1* = pores; source: own elaboration

DESCRIPTION OF A MEASURING STAND

For the experiment examining the efficiency of wastewater purification, a test stand was built in a form of a sealed transparent container (*1*) having the length of 1.20 m, width 0.20 m and height of 1.70 m (Fig. 4). The plastic container with the soil bed was built of transparent plates (*9*) enabling an observation of changes occurring in the soil bed during the wastewater filtration. The transparent plates were mounted in metal frames (*11*). A wastewater pump (*2*), started by an
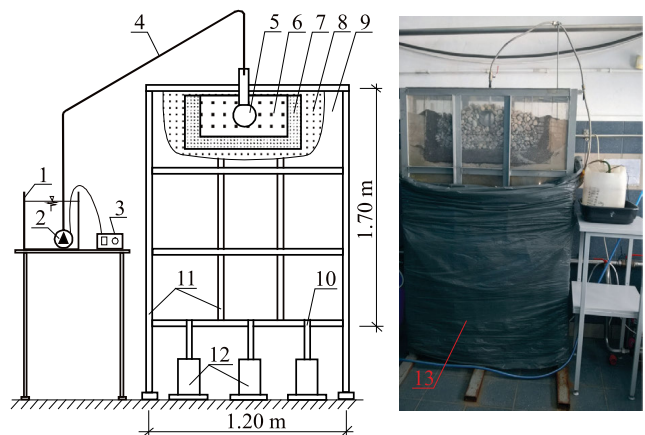
Fig. 4. Schematic diagram of the measuring stand for testing the wastewater purification efficiency of a soil bed: *1* = tank with raw wastewater, *2* = wastewater pump, *3* = electronic controller dispensing the raw wastewater, *4* = raw wastewater delivery pipe, *5* = raw wastewater drain line, *6* = raw wastewater drainage bed made of gravel, *7* = lightweight expanded clay aggregate (LECA) assisting layer, *8* = medium sand soil bed, *9* = transparent plastic plate enabling observations of changes occurring in the soil bed, *10* = raw wastewater outflow, *11* = metal frame of the tank with the soil bed, *12* = vessels collecting effluent, *13* = black film covering the measuring stand in aim to protect it from light; source: own elaboration

electronic controller (3), conveyed the raw wastewater from the tank (1) through a delivery pipe (4) to a raw wastewater drain line (5) of 100 mm in diameter, placed in a bed layer (6) made of stones with the diameter 20–40 mm. The drainage bed layer (6) for the raw wastewater had the dimensions: length 0.50 m, width 0.20 m, height 0.20 m. The raw wastewater flowed from the raw wastewater drain line (5) to the stone drainage bed layer (6) through an outlet of 8 mm in diameter in the bottom of the drainage pipe. Then, after passing the gravel drainage layer (6), the wastewater was evenly distributed onto the whole surface of a LECA assisting layer (7). After the filtration of the raw wastewater through the LECA assisting layer (7), the wastewater soaked through a medium sand soil bed (8). The infiltration bed (6) was ventilated by the raw wastewater drain line (5).

The experiment was carried out with use of the medium sand soil bed and the assisting LECA layer, having the thickness 0.10 or 0.20 m and granulation 1–4 mm. The thickness of the sand soil bed was 1.40 and 1.30 m, respectively. Three openings (10) were drilled in the bottom of the measuring stand to enable outflow of the wastewater to the collecting vessels (12). The tank was filled with the medium sand in layers, each having the thickness 0.10 m, and then they were compacted (the degree of compaction of the medium sand was not determined). The layer-by-layer compaction gives the best results.

The traser tests were performed as well and the drainage time of the wastewater through the sand soil bed was determined, equal to 15 hours.

METHODS OF INVESTIGATIONS

According to Polish recommendations, the wastewater infiltration drainages are being designed through a selection of a wastewater daily dose referred to a given soil category having a defined permeability and to a drainage pipeline length (Tabernacki et al., 1990). On the other hand, according to the recommendations of CEN/TR 12566-2:2005 (European Committee for Standardization, 2005), the wastewater daily dose is being selected based on a given soil type and its Darcy's filtration coefficient or a standardised permeability coefficient referred to a wastewater infiltration area. Regarding the experimental investigations of efficiency of wastewater purification in soil beds with the assisting LECA layer, the daily wastewater dose was assumed according to the Polish recommendations. Due to that, the hydraulic load of the drainage line for the domestic wastewater is related to a 1 m long line and for the medium sand it is equal to 15 $dm^3 \cdot m^{-1} \cdot day^{-1}$ (Tabernacki et al., 1990). In the measuring stand for examining the efficiency of wastewater purification (Fig. 4), the drain line was 0.20 m long. For this length of the wastewater drain line (5), the daily raw wastewater dose was equal to 3 $dm^3 \cdot day^{-1}$. This daily dose was supplied by the wastewater pump (2) to the drain line (5) at 8 a.m., 4 p.m. and 12 p.m. in three equal, 1 dm^3 partial doses.

For the experiment, it was prepared a model wastewater made according to the standard PN-C-04616/10:1987 (Polski Komitet Normalizacyjny, 1987) of distilled water and the following compounds: grey soap – 50 $g \cdot m^{-3}$, potassium chloride – 7 $g \cdot m^{-3}$, soluble starch – 50 $g \cdot m^{-3}$, enriched dry broth – 150 $g \cdot m^{-3}$, sodium chloride – 30 $g \cdot m^{-3}$, peptone – 50 $g \cdot m^{-3}$, urea – 30 $g \cdot m^{-3}$, crystalline calcium chloride – 7 $g \cdot m^{-3}$, anhydrous sodium acetate – 10 $g \cdot m^{-3}$, magnesium sulfate – 50 $g \cdot m^{-3}$.

For the wastewater, both raw and purified, following indicators were determined: total nitrogen, ammonium nitrogen, nitrate nitrogen, nitrite nitrogen, total phosphorus, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), pH value. The individual indicators were determined once a week with consideration of the wastewater filtration time of the medium sand soil bed with the 0.10 or 0.20 m thick LECA assisting layer. For the raw and purified wastewater, it was performed 16 series of physical and chemical analyses in total.

The synthetic wastewater was prepared once a week. The temperature in the laboratory during the experiment was equal to 16°C. During the tests, the measuring stand for evaluation of the efficiency of wastewater purification in soil bed (Fig. 4) was covered by a black film (13) to protect the tested soil beds from the white light. Following indicators: the total nitrogen, total phosphorus, ammonium nitrogen, nitrate nitrogen, nitrite nitrogen were determined with use colorimetric methods (the spectrophotometer HACH); the pH value – by the electrometric method (the HANNA pH-meter). The BOD_5 was determined by the electrochemical method (the BZT OxiTop measuring set), COD – by titration with potassium dichromate. The TSS content was determined in weighing, using filters with pores of the 0.7 mm diameter. A statistical analysis was performed as well in aim to check if the differences between average values of the results (Tab. 1) for the wastewater purified in the medium sand soil bed with the 0.10 and 0.20 m thick LECA assisting layers are statistically significant.

RESULTS AND DISCUSSION

The experiment did not encompass investigations of the medium sand soil bed itself because it is known from the literature (Cuyk van et al., 2001; Gill et al., 2009; Kalenik and Wancerz, 2013) that the removal efficiency of total nitrogen and total phosphorus for such bed is low.

The height of the soil bed in the measuring stand (Fig. 4) was equal to 1.5 m, according to the Decree (Rozporządzenie…, 2019). It is the required height between the domestic wastewater infiltration level and the groundwater level of underground water.

The formation of biologically active layer in the medium sand soil bed with the LECA layer lasted 11 weeks. This time was determined on the basis of results of control tests of the total nitrogen and total phosphorus only. The control tests of the total nitrogen and total phosphorus were made in the tenth and eleventh week in aim to check whether the concentration values in a given measurement were comparable to the values from the previous measurement, i.e. whether they were stable. During the performed experiment, the 2.0–2.5 cm thick soil under the drainage layer changed its colour from pale to dark what indicates that a biological film arose in the soil which was a bed for bacteria and other microorganisms. This process is known and very well described in the literature (Cuyk van et al., 2001; Beal, Gardner and Menzies, 2005). During the experiment, the medium sand was wet, but the model wastewater did not stagnate in the soil bed during the filtration.

Table 1 contains average values of the contamination indicators of raw and purified wastewater in the medium sand soil bed with the assisting LECA layer having the two thicknesses –

Table 1. Average values of the indicators for the raw wastewater and wastewater purified in the medium sand with the 0.10 and 0.20 m thick lightweight expanded clay aggregate's (LECA's) assisting layer

Indicator (unit)	Raw wastewater				Purified wastewater				Acc. to Rozporzą-dzenie… [2019]
	12 week	13 week	14 week	15 week	12 week	13 week	14 week	15 week	
Assisting LECA layer, thickness 0.10 m									
TSS (g·m^{-3})	134.6	137.3	135.9	134.5	40.7	41.0	41.4	40.8	50
BOD_5 (g O$_2$·m^{-3})	193.9	195.7	194.6	192.9	4.6	4.4	4.5	4.3	40
COD (g O$_2$·m^{-3})	302.4	304.4	302.7	303.3	20.3	20.8	19.7	19.4	150
Total nitrogen (g N·m^{-3})	37.5	38.4	37.3	36.8	25.7	25.2	24.8	24.4	30
Ammonium nitrogen (g N-NH$_4$·m^{-3})	0.91	0.88	0.78	0.86	0.13	0.12	0.11	0.12	–
Nitrate nitrogen (g N-NO$_3$·m^{-3})	0.82	0.89	0.78	0.83	2.81	2.77	2.74	2.76	–
Nitrite nitrogen (g N-NO$_2$·m^{-3})	0.027	0.025	0.026	0.026	0.009	0.007	0.007	0.008	–
Total phosphorus (g P·m^{-3})	1.39	1.37	1.35	1.34	0.11	0.13	0.11	0.10	5
Reaction, pH	7.35	7.38	7.36	7.35	7.48	7.45	7.44	7.47	–
Assisting LECA layer; thickness 0.20 m									
TSS (g·m^{-3})	133.9	135.5	134.2	133.5	32.4	34.2	33.8	33.5	50
BOD_5 (g O$_2$·m^{-3})	197.5	196.5	194.8	195.5	1.3	1.2	1.0	1.4	40
COD (g O$_2$·m^{-3})	305.4	299.3	306.5	303.7	13.2	13.4	12.7	13.3	150
Total nitrogen (g N·m^{-3})	38.4	36.5	37.6	38.1	18.2	17.8	16.9	16.7	30
Ammonium nitrogen (g N-NH$_4$·m^{-3})	0.89	0.84	0.87	0.85	0.06	0.03	0.04	0.05	–
Nitrate nitrogen (g N-NO$_3$·m^{-3})	0.87	0.85	0.84	0.86	2.49	2.47	2.38	2.42	–
Nitrite nitrogen (g N-NO$_2$·m^{-3})	0.030	0.028	0.027	0.029	0.006	0.005	0.004	0.005	–
Total phosphorus (g P·m^{-3})	1.35	1.38	1.36	1.37	0.05	0.05	0.03	0.04	5
Reaction, pH	7.34	7.30	7.37	7.58	7.63	7.65	7.64	7.67	–

Explanations: TSS = total suspended solids; BOD_5 = five-day biochemical oxygen demand, COD = chemical oxygen demand.
Source: own study.

0.10 and 0.20 m. The analysis of the experiment results allows to state that after the drainage of the model wastewater through the sand soil bed with the assisting LECA layer the following indicators reduced their values: total nitrogen, ammonium nitrogen, total phosphorus, BOD_5, COD and TSS. The nitrates content and pH value in the purified wastewater increased, whereas the nitrite nitrogen occurred at trace level.

The average TSS removal efficiency in the medium sand with the 0.10 m thick LECA layer amounted 69.8% and with the soil bed with the 0.20 m thick LECA layer – 75.1%. Attention is drawn by a high TSS retention efficiency of the investigated soil beds. High quantity of TSS being introduced to a soil bed causes its fast clogging and formation of a filter cake (Spychała and Nieć, 2013) which reduces the permeability of the soil bed, hence limits the life of an infiltration drainage purification plant. Odours coming out through drainage vent chimneys is a sign that the soil bed are clogged. It proves that the soil bed permeability has drastically decreased, the wastewater is retained in the drainage bed and oxygen cannot reach inside it. Due to this fact, oxygen-free conditions arise in the infiltration drainage and the rotting wastewater emits odour. In the experiment being presented, the wastewater did not stagnate and the bed did not emit odours.

The average efficiency of the BOD_5 and COD reduction in the sand bed with the 0.10 thick LECA layer was high and amounted 97.7% and 93.4% respectively. In the soil bed with the 0.20 m thick layer, however, it was even higher and amounted 99.4% and 95.7% respectively. A laboratory experiment concerning efficiency of wastewater purification in a sand-gravel bed, performed by other scholars (Chmielowski and Ślizowski, 2008), also presented high efficiency of the BOD_5 and COD reduction in the domestic wastewater – the respective values amounted there 97.9% for BOD_5 and 85.2% for COD.

The average total nitrogen removal efficiency in the soil bed with the 0.10 m thick LECA layer amounted 33.3% and with the 0.20 m thick layer – 53.9%. The application of the LECA assisting layer significantly improved the average total nitrogen removal efficiency related to the bed consisting only of medium sand where the average total nitrogen removal efficiency amounted 22% (Kalenik and Wancerz, 2013).

The ammonium nitrogen removal efficiency in the sand soil bed with the 0.10 m thick LECA layer amounted 86.0% in average and in the soil bed with the 0.10 m layer – 94.8%. As Sharifnia et al. (2016) claim, such high removal efficiency of ammonium ions in the LECA is achieved due to high content of SiO_2 in its structure. Other scholars (Wąsik and Chmielowski, 2017) also obtained high ammonium nitrogen removal efficiency in well permeable soil – it amounted 66.74%. Kalenik and Chalecki (2021) proved in an experiment that in a medium sand soil bed with a 0.10 m thick opoka assisting layer the ammonium nitrogen removal efficiency was also high and amounted 86.6% in average,

whereas in the soil bed with the 0.20 m thick opoka layer – 94.9% in average. The ammonium nitrogen removal efficiency in well permeable soils with an assisting LECA, opoka or clinoptilolite layer (Kalenik and Chalecki, 2019) is comparable because all these beds contain the calcium ions and have high specific surface area resulting from a high porosity. The results of investigations made by Sharifnia et al. (2016) also confirm that the LECA is a good absorbent for removal of the ammonium ions.

A nitrate nitrogen content in the purified wastewater after filtration through the soil bed with the 0.10 m thick LECA layer increased 3 times in average and after filtration through the soil bed with the 0.20 m thick layer – only 2 times. High nitrate nitrogen content in the wastewater filtered in the soil bed proves that the nitrification process runs very well at the LECA. It means that nitrifying bacteria are well immobilised on the LECA which is very porous and coarseness. On the other hand, the nitrification process in the pure sand soil bed is very slow (Cuyk van et al., 2007; Gill et al., 2009), because it depends on the soil pH, ventilation and the total nitrogen content. Sand consists mainly of quartz grains and is a loose mineral fraction. It results from microscopic observations that the sand grain surface is not porous and it is smooth and slippery to a very large extent (Mycielska-Dowgiałło and Woronko, 1998). Due to that, it is very hard to settle for nitrification bacteria.

After filtration of raw wastewater through the sand soil bed with the 0.10 m thick LECA layer, the pH reaction increased by 1.4% in average, whereas after filtration through the sand soil bed with the 0.20 m thick LECA layer – by 3.4%.

The phosphorus from domestic wastewater can be removed from soil bed by plants or in adsorption and precipitation processes which depend on the sorption capacity, pH value and redox potential of a soil bed, presence of ions of iron, aluminum and calcium in the soil bed as well as on the native phosphorus content in the bed. In the alkaline soil beds, the phosphorus adsorption processes occur thanks to the calcium compounds, with which the phosphorus creates permanent mineral combinations. However, in the soil beds having light acid or neutral reaction, the adsorption process occurs thanks to the iron and aluminum compounds which adsorb the phosphorus in form of insoluble complex compounds. Experiments showed that the average total phosphorus removal efficiency for the soil bed with the 0.10 m thick assisting LECA layer amounted 91.7% and for the soil bed with the 0.20 m thick layer – 96.9%. Ádám et al. (2007) also obtained the high phosphorus removal efficiency in a well permeable soil bed with an assisting LECA layer. They showed that the phosphorus removal efficiency with a LECA layer amounted 90.0% in average. The application of the LECA assisting layer in the medium sand soil bed significantly improved the total phosphorus removal efficiency. The bed consisting only of medium sand has the total phosphorus removal efficiency amounting 23% in average (Kalenik and Wancerz, 2013). The results of the experiment showed (Tab. 1) that the LECA with granulation 1–4 mm, characterised by high porosity and coarseness as well as containing calcium, iron and aluminum, is an efficient adsorbent of total phosphorus.

The results of the investigations also showed that the raw wastewater purification efficiency in the sand soil bed with the assisting LECA layer satisfies the Polish requirements concerning introduction of wastewater into the grounds and surface water (Rozporządzenie…, 2019) – Table 1.

A statistical analysis was also carried out in aim to investigate whether the differences of average values (Tab. 1) in the results for the raw wastewater purified in the medium sand soil bed with the 0.10 and 0.20 m thick LECA assisting layers are statistically significant (Tab. 2, 3). Firstly, the normality of distribution was checked with use of the Shapiro–Wilk test and then the homogeneity of variance with use of the Levene test. Using the Statistica software, calculations of normality of distribution and homogeneity of variance were made; their results are presented in Table 2. An analysis of this table allows to state that in both tests for individual groups of the examined indicators the values of calculated probability p_{cal} are greater than the assumed significance level $a = 0.05$. It means that the conditions of normal distribution and homogeneity of variance in the investigated groups are satisfied. Then, using the Statistica software as well, the t-Student test was performed for two populations. It was formulated a zero hypothesis (H_0: $n_1 = n_2$), according to which the differences between the average values are statistically equal to each other, and an alternative hypothesis (H_1: $n_1 \neq n_2$), according to which these differences are statistically different. Results of the calculations of the t-Student statistics value $|t_{cal}|$ are shown in Table 3.

For the formulated alternative hypothesis, it was determined a critical region $|t_{cal}| \geq t_{a=0.05}$ and, for $v = n_1 + n_2 - 2 = 6$ degrees

Table 2. Results of calculations of the Shapiro–Wilk and Levene statistics for the medium sand soil bed with the assisting lightweight expanded clay aggregate's (LECA's) layer of thickness 0.10 and 0.20 m; the differences of average values are significant with probability $p > 0.05$

Indicator	Thickness (m)	Probability value (p_{cal}) obtained in the test of	
		Shapiro–Wilk	Levene
Total dissolved solids	0.10	0.53808	0.248281
	0.20	0.57460	
Five-day biochemical oxygen demand	0.10	0.97188	0.65974
	0.20	0.84997	
Chemical oxygen demand	0.10	0.80354	0.10956
	0.20	0.24012	
Total nitrogen	0.10	0.97508	0.31443
	0.20	0.45670	
Ammonium nitrogen	0.10	0.68296	0.26657
	0.20	0.97188	
Nitrate nitrogen	0.10	0.73354	0.17231
	0.20	0.72615	
Nitrite nitrogen	0.10	0.97188	0.26657
	0.20	0.68296	
Total phosphorus	0.10	0.40639	0.77956
	0.20	0.27245	
Reaction	0.10	0.71428	0.65974
	0.20	0.84997	

Source: own study.

Table 3. Results of calculations of the *t*-Student statistics for the medium sand soil bed with the assisting lightweight expanded clay aggregate's (LECA's) layer of thickness 0.10 and 0.20 m; the differences of average values are significant with probability $p > 0.05$

Indicator	Thickness (m)	Average	Standard deviation	Obtained *t*-Student statistics value $|t_{cal}|$	Obtained probability value (p_{cal})
Total dissolved solids	0.10	40.975	0.309	23.917	0.000160
	0.20	33.475	0.772		
Five-day biochemical oxygen demand	0.10	4.450	0.129	25.800	0.000127
	0.20	1.225	0.171		
Chemical oxygen demand	0.10	20.050	0,624	24.653	0.000146
	0.20	13.150	0,311		
Total nitrogen	0.10	25.025	0.556	68.771	0.00000677
	0.20	17.400	0.716		
Ammonium nitrogen	0.10	0.120	0.00816	15.000	0.000643
	0.20	0.045	0.0129		
Nitrate nitrogen	0.10	2.770	0.0294	25.562	0.000131
	0.20	2.440	0.0497		
Nitrite nitrogen	0.10	0.00750	0.00129	5.000	0.0154
	0.20	0.00500	0.000816		
Total phosphorus	0.10	0.1125	0.0126	12.124	0.00121
	0.20	0.0425	0.00957		
Reaction	0.10	7.460	0.0183	14.999	0.000643
	0.20	7.648	0.0171		

Explanation: *t*-Student statistics value read from the tables for $p = 0.05$ and $\nu = 6$, $t_{a=0.05} = 2.447$.
Source: own study.

of freedom and an assumed 5% significance level (risk of error, $a = 0.05$), the critical value $t_{a=0.05} = 2.447$ was read from the *t*-Student distribution tables. Analysis of Table 3 allows to state that $|t_{cal}| \geq t_{a=0.05}$, i.e. the zero hypothesis must be rejected and a conclusion formulated that the differences between the mean values of the indicators for the wastewater purified in the medium sand soil bed with 0.10 and 0.20 thick LECA layers are indeed statistically different. This is also confirmed by the calculated probability value $|p_{cal}|$, which is lower than the assumed significance level 0.05.

The analysis of results of the experimental investigations of efficiency of wastewater purification in soil beds with the assisting LECA layer, presented in the paper, confirmed the assumed hypothesis that the LECA has good absorption properties and bacteria assisting the aerobic purification of raw wastewater will efficiently immobilise on its grains' surface because the nitrification process went very fast in the tested soil beds what shows that the nitrifying bacteria are well immobilised on the LECA with the granulation of 1–4 mm.

CONCLUSIONS

The experiment showed that the medium sand soil bed with the layer of lightweight expanded clay aggregate (LECA) with granulation 1–4 mm and thickness 0.20 m presented a better effectiveness of removing impurities from raw wastewater than the medium sand soil bed with the LECA layer with the same granulation and the thickness 0.10 m. In the soil bed with the

0.20 m thick LECA layer, the effectiveness of removal of total nitrogen increased by 20.6%, total phosphorus by 5.2%, ammonia nitrogen by 8.8% and TSS by 5.3% as well as the effectiveness of reduction of BOD_5 increased by 1.7% and COD by 2.3% in relation to the 0.10 m thick assisting LECA layer (all percentages – in average). According to the experiment, the removal efficiency regarding the total nitrogen, total phosphorus, ammonium nitrogen and TSS as well as reduction efficiency regarding BOD_5 and COD fulfilled the Polish recommendations concerning purified wastewater disposal into grounds and surface water. Hence, the light expanded clay aggregate with granulation 1–4 mm can be used in a soil bed under an infiltration drainage to removal of total nitrogen and total phosphorus from domestic wastewater. However, very good effectiveness of the TSS removal from the raw wastewater in the investigated medium sand soil beds with LECA assisting layer can lead to their fast clogging. Due to that, in individual wastewater treatment plants with infiltration drainages for domestic wastewater, an application of multi-chamber tanks is recommended instead of one-chamber ones or prefabricated treatment units for septic tank effluent.

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