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SUBSTANTIATION OF SCHEMATIC AND STRUCTURAL SOLUTIONS OF THE MAIN ELEMENTS OF BIOGAS PLANT FOR THE DISPOSAL OF FALLEN LEAVES

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The peculiarities of biogas technology application in the falling leaves utilization plants are analyzed and the application of soil cement is proposed to create the basic elements of such plants. A new schematic and constructive solution of biogas fermenter (bioreactor) with application of soil-cement technology with a blending method for efficient functioning of technological chain of biogas fermentation of fallen leaves and other plant residues for energy supply systems has been developed. The possibility of reliable isolation of the space of the bioreactor to the excavation of the pit from the surrounding array with soil cement screen is substantiated. The corrosion resistance of the soil cement waterproof screen has been proved.

Keywords: biogas plant for the disposal of fallen leaves, pit, soil cement, waterproofing, aggressive medium, strength, coefficient of chemical resistance, soil cement waterproof screen.

ОБҐРУНТУВАННЯ СХЕМНО-КОНСТРУКТИВНИХ РІШЕНЬ ОСНОВНИХ ЕЛЕМЕНТІВ БІОГАЗОВОЇ УСТАНОВКИ УТИЛІЗАЦІЇ ОПАЛОГО ЛИСТЯ

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Проаналізовано особливості застосування біогазової технології в установках утилізації опалого листя та інших рослинних решток і запропоновано застосування ґрунтоцементу для створення основних елементів таких установок. Розроблено нове схемно-конструктивне рішення біогазового ферментатора (біореактора) опалого листя та інших рослинних решток із застосуванням ґрунтоцементної технології бурозмішувальним методом. Обґрунтовано можливість надійного ізолювання простору біореактора від навколишнього масиву ґрунтоцементним екраном до відкопування котловану. За наявності близького за глибиною водотривкого шару ґрунту екран занурюють у нього, а за його відсутності дно котловану ізолюють пошаровим укладанням литого ґрунтоцементу чи січними ґрунтоцементними елементами. Наведено результати експериментальних досліджень корозійної стійкості та міцності ґрунтоцементного водонепроникного екрану для умов використання лужних та кислотних модельних розчинів з концентрацією речовин, що можуть бути наявними в технологічному обладнанні біогазової установки. Установлено, що коефіцієнт хімічної стійкості ґрунтоцементних зразків поступово знижується при збільшенні періоду їх витримки в модельних розчинах, але він залишається в межах, що характеризують ґрунтоцемент як хімічно високостійкий. На основі результатів проведених досліджень відкривається практична можливість розроблення методів проектування та зведення основних елементів біогазової установки утилізації опалого листя із застосуванням ґрунтоцементної технології.

Ключові слова: біогазова установка утилізації опалого листя, котлован, ґрунтоцемент, водонепроникність, агресивне середовище, міцність, коефіцієнт хімічної стійкості, ґрунтоцементний водонепроникний екран.



Introduction

Burning of fallen leaves is still widespread in Ukraine in autumn and in spring – last year's grass and other plant residues, although this is prohibited by law [1]. Combustion of 1 ton of plant residues releases about 9 kg of smoke microparticles into the air [2], which contain dust, nitrogen oxides, carbon monoxide, heavy metals, dioxins – a substance that is dangerous for humans. The burning of leaves, dry grass and other plant residues, in addition to harming human health, leads to the destruction of the soil cover, smoke from fires in foggy days forms smog and hangs in the air for a long time, and much more electricity is consumed for settlements, etc.

The disposal of fallen leaves is possible by including them in the composition of composite pellets or briquettes, with their subsequent combustion or gasification in power plants for the production of heat and electricity [3], but then it is not possible to obtain fertilizers. Simply dispose of leaves and plant residues by composting. The effectiveness of aerobic composting is proven when air is added to the processing and after fermentation receive highly effective organic fertilizers. But composting does not make it possible to use this waste resource for energy purposes. More rational is the utilization of fallen leaves and plant residues by biogas technology, which allows to achieve a synergistic effect by combining the utilization and production of biogas in the same equipment – a biogas fermenter (bioreactor), in which the process of anaerobic (without oxygen access). The operation of such bioreactors makes it difficult to provide basic raw materials only for short periods in the fall and spring, but energy supply systems, such as buildings and structures that use biogas, must operate for periods determined by the daily and monthly load schedules. This necessitates the consideration of the bioreactor as a structure that will function effectively in the technological chain «accumulator of fallen leaves and other plant residues – biogas fermenter – in the substrate accumulator», etc.

Review of the research sources and publications

Currently, in many countries, including Ukraine, biomass is the most commonly used waste of agro-industrial and forestry facilities in biogas plants. Up to 60 varieties of biogas technologies have been developed [4]. Original technologies of anaerobic fermentation of wastes of agricultural and livestock complexes and corresponding circuit-design solutions of bioreactors for their implementation are known [5]. To maintain the optimum temperature in the bioreactor, some of the biogas produced is used, but heat pumps and renewable energy sources may also be used [6].

When developing bioreactors for the fermentation of the abovementioned wastes, it is usually considered possible to dispense with the system of accumulation and storage of raw materials in large volumes to ensure the continuous operation of the biogas fermenter. As noted above, fallen leaves, dry grass and other plant residues are accumulated over short periods in the fall and spring, which necessitates the need to address the

effective work of the bioreactor in the technological chain «fallen leaves and other plant residues – biogas fermenter – substrate accumulator».

The decomposition of the organic constituent of fallen leaves is caused by the activity of certain bacteria. The main physicochemical and structural factors affecting the process of anaerobic fermentation are: the fractional composition of the substrate, its moisture and viscosity; alkalinity, temperature and pressure in the bioreactor; intensity of mixing; fermentation time and stability of the fermentation process; structure of the fermenter tank [4, 5]. According to the technology of preparation and fermentation of raw materials distinguish liquid-phase technology (humidity of fermented organic mass – more than 85%) and solid-phase (humidity of organic mass – less than 85%).

It is advisable to use solid-phase fermentation for biogas fermentation of fallen leaves and other plant residues in order to further use biogas in energy supply systems. A simplified scheme of a solid-phase biogas plant is shown in Fig. 1 [5].

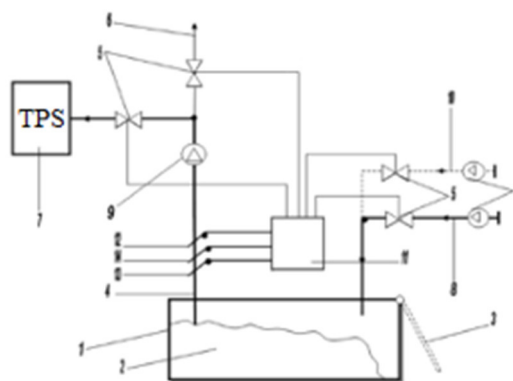


Figure 1 – Simplified scheme of solid-phase biogas plant:

- 1 – fermenter (bioreactor); 2 – biomass;
- 3 – loading-unloading hole; 4 – biogas output; 5 – valve;
- 6 – gas pipeline; 7 – power unit (TPS, CP);
- 8 – line of the exhaust gas of the power unit; 9 – fan;
- 10 – fresh air line; 11 – remote control; 12 – methane sensor
- 13 – carbon dioxide concentration sensor;
- 14 – sensor for determining the volume flow of biogas

The plant works like this. Raw material (such as biological waste, manure, sludge, fats or green mass) is placed in a hermetically sealed fermenter 1 and is usually heated and stirred. However, as a result of anaerobic processes, biogas and a digested substrate appear. Biogas is sent to power unit 7 for combined production of electricity and heat in mini-TPS units and cogeneration plant (CP). When using a gas piston internal combustion engine as a power engine, the biogas is cleaned of hydrogen sulfide (H_2S) before being fed to the engine. The work obtained in the engine is used to drive the electric generator, and the generated electricity is supplied directly to consumers or to the general electric network. The heat dissipated during engine cooling as well as exhaust gas is used for heat supply to consumers.

Currently, the city of Kyiv is considering building a pilot biogas complex for the processing of fallen leaves, dry grass and other plant waste using a similar technology for biogas and fertilizer production (for information, up to 120.000 tonnes of waste mentioned above are generated in Kyiv) [7]. Among the main ways of intensification of the fermentation process by increasing the level of decomposition of organic mass of fallen leaves, we can create and maintain stable preset temperature conditions of fermentation and ensure the qualitative mixing of biomass, which will ensure a uniform distribution of temperature in biomass, and prevent its delamination in the reactor [5]. The analysis has shown that the main elements of the technological chain of biogas fermentation of fallen leaves and other plant residues: storage for fallen leaves; biogas fermenter (bioreactor); fertilizer accumulator (spent substrate), – it is advisable to develop with the use of schematic and structural solutions based on soil cement technology [8 – 15]. Soil cement is a mixture of soil, cement, and water from which soil cement elements are made by blending technology without soil extraction.

Definition of unsolved aspects of the problem

Thus, the advantage of biogas reactors mainly that are mainly used nowadays, coated with steel over concrete is the durability, no need for formwork, reduced erection and installation time, but the main disadvantage of such bioreactors is their high cost. Therefore, the use of soil-cement technology for the construction of biogas reactors designed for the fermentation of fallen leaves and other plant residues will largely preserve the advantages of steel-coated reactor structures, but will reduce their cost. This generalization is made on the basis of research and development, including the author's, with the application of soil-cement technology by the blending method.

Problem statement

For the purpose of the work, it was accepted – substantiation of schematically-constructive decisions with application of soil-cement technology with a miscible method for ensuring efficient functioning of technological chain of biogas fermentation of fallen leaves and other plant residues at the power supply systems.

Basic material and results

Storage for fallen leaves and other plant residues

For temporary storage of fallen leaves and branches in Kremenchug, specially dedicated places are practiced, and fallen leaves from private sector homes can be taken away along with the total mass of solid household waste (SHW) if these leaves are packed in plastic bags [16]. In 2018, a leaf improvement facility was created in Brovary to store fallen leaves, mowing products and vegetation residues, which will be collected in city-wide territories for further composting [17]. This object is a trench dug by the excavator in the soil (Fig. 2).



Figure 2 – The object for fallen leaves storing "Lystivnyk"

Storage of leaves in objects of this type does not satisfy the conditions of preservation of its organic mass, since storage will be accompanied by the process of aerobic fermentation of organic matter, which will significantly reduce the potential of fallen leaves for biogas production in the subsequent process of anaerobic fermentation.

Therefore, the authors propose to use satisfactory conditions for storage of fallen leaves and other plant wastes constructed using soil cement technology [8 – 15]. Such construction will be different from the construction of slurry barns made of soil cement, similar to the scheme design [15], with additional equipment: roof and equipment for loading and unloading of fallen leaves.

Biogas fermenter (bioreactor)

From the analysis of design solutions of known biogas plants, the basic requirements to the typical design of the bioreactor (methane tank) are formulated: to ensure uniform mixing of the mass, in the state of fermentation, with a speed not exceeding 0.5 m/s; create a uniform temperature field in the bioreactor using a combination of different types of heat exchangers; provide a special device in the design to prevent crust formation and clogging of the discharge pipe. Cylindrical reactors are preferably used in operating biogas plants. In bioreactors of such construction with some efficiency it is possible to mix the substrate, unload the spent substrate, remove biogas and destroy the surface crust [5].

In the construction of the reactors concrete, reinforced concrete, steel sheet, fiberglass are used. The reactor vessel shall be heat-insulated and corrosion-resistant and the enclosure of the fermentation chamber shall be sealed to prevent air access. General view of the reactors of the cylindrical structure of the biogas plant Zorg Biogas [18, 19] are shown in fig. 3. Such a biogas plant reactor consists of high quality coated steel panels using enamel high temperature sintering technology. This coating is durable, resistant to chemical effects, both internal and external corrosion and dynamic action.

A patented variant of a circuit design for an anaerobic biogas reactor, the housing of which can be made from soil cement in a blending method [20], is presented in Fig. 4.



a



b

Figure 3 – Reactors of cylindrical structure of biogas plant Zorg Biogas:

a – in the process of installation;
b – during operation

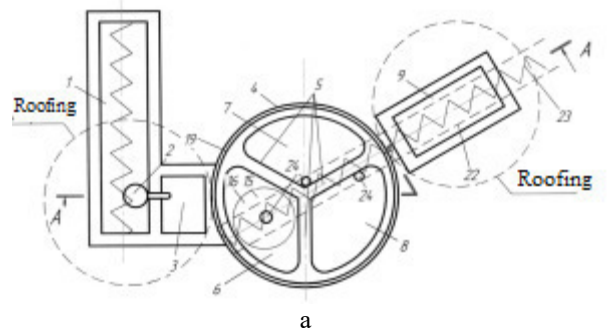
An anaerobic bioreactor for the production of biogas and organic substrate contains a cylindrical tank body with a vertical baffle, a mixer, mechanisms and hydraulic locks for biomass supply and output, a biomass heater, a gas cap gas holder with control and automatic control, valves, and a gas outlet pipe. The housing is constructed of modified soil cement according to the drilling technology of the manufacture of soil cement elements. The housing is a bicameral chamber, three-chamber and has three internal vertical partitions located relative to each other at an angle of 120°, and is made integral and monolithic, with reinforcing reinforcement cages if necessary.

The basic elements of the plant: 1 – receiving tank for waste of biological origin; 2 – pump; 3 – capacity dispenser; 4 – a bioreactor housed in housing 4. The walls and bottoms of tanks 1 and 3 are formed from soil cement.

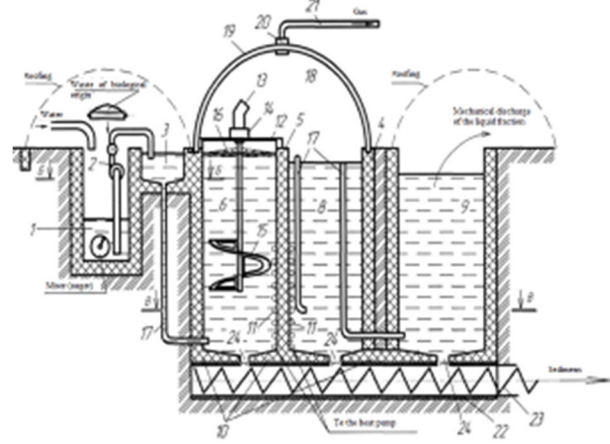
The anaerobic bioreactor for the production of biogas and organic substrate consists of a cylindrical housing 4 in shape (Fig. 4) with three internal vertical partitions 5, located relative to each other at an angle of 120° and forming three chambers for anaerobic fermentation, respectively 6, 7 and 8. Outside the bioreactor is a collector of fermented mass 9 created by the walls and bottom of soil cement. The shell of cylindrical shape 4, the three internal partitions 5 and the common bottom 10 (Fig. 6) are made in the «monolithic» version – as 10 integral with the soil cement. On the surface of the internal partitions 5, heat exchangers 11 are provided from a polymer pipe with a connection to a heat pump (not shown in Fig. 4). In the fermentation chamber 6 through the beam 12 is installed biomass mixer,

including a hydraulic motor 13, a gearbox 14 with a vertically arranged shaft, in the lower part of which is fixed short-base single-screw auger 15, and in the upper part is fixed trapezoidal framework 16 for the destruction of the surface crust. Partitions 5 provide openings for by-pass pipes 17.

The accumulation of gas and its initial temporary storage takes place in the cavity of the gas holder 18, formed by the gas cap 19, which is tightly and hermetically installed in the grooves of the soil cement walls of the housing 4. The top of the cap 19, which is made of dark-colored material 20 to further heat the bioreactor from the sun's rays, has controls and automatic controls 20 and a gas outlet 21.



a



b

Figure 4 – Bioreactor plant installation with loading pump unit and bioreactor:

a – top view; b – cross-section;

- 1 – receiving capacity; 2 – pump; 3 – capacity dispenser; 4 – the housing of the bioreactor;
- 5 – partitions; 6, 7, 8 – fermentation chambers;
- 9 – the collection of the mixed mass; 10 – bottom;
- 11 – heat exchangers; 12 – mixer traverse;
- 13 – electric motor; 14 – gearbox; 15 – single screw;
- 16 – a framework for the destruction of the surface crust; 17 – openings for by-pass pipes;
- 18 – gas storage; 19 – gas cap holder;
- 20 – controls and automatic controls;
- 21 – outlet gas pipe; 22 is a sludge discharge pipe;
- 23 – long-screw auger

In the lower part of the bioreactor, a reinforced concrete pipe 22 is provided with a long-base screw 23 installed in it, by means of bearing support, to withdraw sediment (substrate).

In this case, the bottom surface 10 of the body 4 of the bioreactor in the fermentation chambers 6, 7, 8 and 25 of the fermented mass collector 9 has internal slopes to the openings with installed water locks 24, through which, periodically and in a certain sequence, the precipitate (substrate) enters the internal the cavity of the pipe 22 with the screw 23.

To create a holistic and sealed housing structure with partitions and a bottom with a diameter of a cement element of 0.5 m, they are arranged along the axis so that the distance between 30 centers of neighboring elements is 0.4 m.

Storage for substrate and composting

In the bioreactor, in the process of anaerobic fermentation, not all the mass of fallen leaves will be fermented. Therefore, to obtain high-quality organic fertilizers, it is necessary to provide not only the storage of the solid mass of the substrate separated after the bioreactor, but also its composting by the use of aerobic fermentation technology.

The simplest solution for composting [5] is to store the spent fallen leaf substrate in an open area when fencing or in a compost pit.

But in these cases, it is almost impossible to provide the conditions necessary to obtain a high quality compost, because: 1) the material must be stirred after 3 – 6 months or 1 – 4 times for the entire cycle to ensure sufficient oxygen access to all layers; 2) the humidity of the material should be kept at the level of 50 – 60% (composted material to the touch should be as «well squeezed towel»). Such conditions can be ensured in the structures of the substrate accumulator and composter, made similarly to the slurry barn for toxic drilling waste and oil and gas wells operation [15].

Such substrate storage and composting structures consist of a ditch and waterproofing, which is made of soil cement (soil cement elements), made by mixing technology without soil extraction, and additional equipment (pump for supplying water, loading and mixing devices).

Study of soil cement parameters as bioreactor structures material

Chemical constituents of substances formed during anaerobic fermentation in a bioreactor, in contact with soil cement, cause II and III types of soil cement corrosion [8]. The second type of corrosion are the processes that develop under the action of water, which contains substances that react with cement. The reaction products formed therefrom are carried out by water or released at the reaction site in the form of amorphous masses which do not have astringent properties. The second type is, for example, the corrosion processes associated with the action on the concrete of various acids and salts. The third type includes the combined processes of corrosion caused by exchange reactions with components of cement stone. The products of such reactions crystallize in pores and capillaries and cause the destruction of cement stone. The processes of corrosion caused by the deposition in the pores of stone salts, which are released from the evaporating solutions and saturate the soil cement, are included to the same kind. Usually, several

aggressive factors are affected by soil cement structures at the same time, but one of them is the main process that causes the corrosion of the second kind [8].

The work [8] presents the results of our experimental studies on the determination of chemical corrosion resistance of soil cement for alkaline and acidic model solutions with concentrations of substances of III and IV environmental hazards, which may be present in the technological equipment of the biogas plant.

The corrosion resistance of building materials is their ability to resist the processes of destruction occurring in materials when exposed to external aggressive factors [8].

The resistance of soil cement to the influence of the corrosive environment is estimated by the coefficient of chemical resistance K_r – is the ratio of the compressive strength of specimens that have been exposed to such an environment R_a , to the compression strength of the control specimens stored in the water R_w

$$K_r = R_a / R_w . \quad (1)$$

By the value of K_r distinguishes: materials of high resistance ($K_r > 0.8$), resistant ($K_c = 0.5 – 0.8$), relatively resistant materials ($K_c = 0.3 – 0.5$) and non-resistant materials ($K_c < 0.3$).

To test the soil cement for chemical resistance, laboratory tests were carried out for which cylindrical specimens were made of height $h = 15$ cm and $d = 15$ cm in diameter, consisting of soil (sandy clay), Portland cement of the M400 brand in the amount of 20% by weight of dry soil and tap water. On the second day after molding, the samples were removed from the molds and stored until tested in water for 28 days (strength gain time). These samples were divided into five groups of 30 samples and placed in a container of chemical solutions of the most aggressive components of drilling mud, and for comparison - in a tank of water for further studies of soil cement for corrosion resistance:

- I group – tap water (H_2O);
- II group – 2.8% caustic soda solution (NaOH);
- III group – 4.0% soda ash solution (Na_2CO_3);
- IV group – 15.0% potassium chloride solution (KCl);
- V group – 50.0% an aqueous solution containing plant residues (model bioreactor medium (BioR), pH less than 7 (acidic medium [5, 6]).

Determination of strength is to measure the minimum effort that destroys specially designed test specimens under static load. The maximum effort made during the test was considered to be a destructive load. According to the tests, the compressive strength R was determined. Before the tests, the density of soil cement ρ and its humidity W were determined, according to which the density of the skeleton was calculated ρ_d . Each determination of material parameters was carried out in 6-fold repetition.

The tests resulted in an average compressive strength of soil cement specimens of a certain time and medium. The coefficient of variation v was determined for each characteristic.

The results of the test part are summarized in Table 1. For static analysis of the strength values of soil cement specimens, data were taken from Table. 1.

Table 1 – Averaged results of studies of the physical and mechanical characteristics of soil cement specimens (cylinders h = 15 cm, d = 15 cm) with different holding time in chemical solutions and water for 365 days

Medium	$W, \%$ (v)	$\rho_d, t/m^3$ (v)	R, MPa (v)	K_r
H ₂ O	37 (0.05)	1.33 (0.03)	5.52 (0.06)	1.00
NaOH	35 (0.07)	1.37 (0.05)	5.37 (0.08)	0.97
Na ₂ CO ₃	36 (0.06)	1.38 (0.04)	5.21 (0.07)	0.94
KCl	37 (0.08)	1.56 (0.03)	4.96 (0.08)	0.90
Biomass 50%	38 (0.06)	1.35 (0.04)	5.03 (0.06)	0.91
H ₂ O	35 (0.04)	1.41 (0.04)	6.43 (0.08)	1.00
NaOH	34 (0.08)	1.44 (0.02)	6.19 (0.07)	0.96
Na ₂ CO ₃	32 (0.09)	1.46 (0.04)	5.95 (0.09)	0.93
KCl	30 (0.09)	1.37 (0.05)	5.77 (0.08)	0.90
Biomass 50%	34 (0.07)	1.39 (0.07)	5.60 (0.11)	0.87

v – coefficient of variation

The graphs show a slow gradual decrease in the coefficient of chemical resistance of the soil cement, depending on the period of holding in an aggressive environment. However, in this case, the coefficient of chemical resistance of the material K_r remains within the limits characterizing soil cement as chemically highly resistant.

The results of laboratory studies allow us to predict the high efficiency and sufficient reliability of the use of soil-cement technology by blending method in biogas plants for the disposal of fallen leaves and other plant residues.

Conclusions

Thus, the presented research results indicate the solution of the scientific problem of developing

schematic and structural solutions of the main elements of a biogas plant for the disposal of fallen leaves, a new design of a biogas fermenter (bioreactor), which involves the use of soil cement waterproof screen, on the basis of which can be developed methods of designing and erection of biogas plants by soil cement, boring and mixing technology. In particular, the following is established.

1. The most significant disadvantage of existing designs of bioreactors is: insufficient cost-effectiveness, due to use of concrete, reinforced concrete, steel sheet, fiberglass. Clay and film waterproofing coatings of bioreactors are also unreliable because some of their waste is not recovered for a long period and such screens lose their properties due to destruction. Clay and film waterproofing coatings of bioreactors are also unreliable because some of their waste is not recovered for a long period and such screens lose their properties due to destruction.

2. The space of the bioreactor before excavation can be reliably isolated from the surrounding array by arranging the soil cement screen of the given dimensions. If there is a waterproof layer of soil close to the depth, the screen is immersed in it. When there is no waterproofing, the bottom of the pit is insulated by layer-by-layer laying of cast soil cement or secant soil cement elements, since soil cement has a high water resistance much greater than concrete.

3. The results of experimental studies of corrosion resistance and durability of soil cement waterproof screen for conditions of alkaline and acidic model solutions use with concentration of substances that may be available in the technological equipment of biogas plant for the disposal of fallen leaves are analyzed.

4. The chemical resistance coefficient of the soil cement K_r was experimentally evaluated, which assesses the material's resistance to the influence of the chemical environment. This figure is slowly decreasing depending on the aging time of the soil cement in the aggressive environment. At the same time, it remains within $K_r > 0.8$, characterizing the soil cement as being chemically highly resistant.

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