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Water supply from groundwater: new solutions for a battered-and-bruised Ukraine

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ABSTRACT

We present improved technology for alternative water supplies for Ukraine during martial law and post-war reconstruction. Sugar-bonded gravel filters for well screens reduce the consumption of material and time for their transportation to the site, and avoid sanding and the formation of voids, thereby reducing hydraulic resistance. Our results facilitate on-site production of block gravel filters using sugar as a binding agent for fine-and-medium-grained sands that constitute the effective component of the filterblock. We explore the constraints on installing such a filter to depths as great as 200 m.

Key words: binders, block gravel filter, sugar, water supply, well

HIGHLIGHTS

- War has destroyed water management infrastructure and drinking water supply for millions of Ukrainians.
- Groundwater and new technological solutions offer a reliable local water supply.
- Sugar is an effective and convenient binding agent for block gravel filters.
- The scope of block-gravel well filters is established. Their performance depends on their composition, physical and mechanical properties over time, as influenced by the environment and the concentration of the binding agent.

INTRODUCTION

Political and armed conflicts disrupt water supplies (https://worldwater.org/conflict/list/). Recent decades have witnessed increasing use of water as a trigger or a weapon. Water supplies and ecosystem services have been victimised (Gleick 2019; Schillinger *et al.* 2020; Gururani *et al.* 2023; Kumar *et al.* 2024) and an alternative is needed. For example, in Somalia, where both war and drought limit access to water, roof water tanks are employed but they depend on seasonal rainfall and require filters to clean the collected water (FAO-SWALIM 2007); solar stills are used in Middle East and North Africa (MENA) countries to make brackish or polluted water potable, but at a high cost (Qi *et al.* 2019); portable filters, widely used in South Sudan and Yemen, have limited life and performance, requiring regular replacement of filter elements (Pereira & Marques 2022); humanitarian organisations everywhere distribute purification tablets for drinking water, but their effectiveness depends on the quality of the source water and they leave an unpleasant taste (UN-Water 2016; Patil *et al.* 2014).

War in Ukraine has disrupted water supplies to millions of people in the centre of Europe. The natural water shortage has been exacerbated by the destruction of hydraulic structures, water mains and pumping stations and, in 2023, the loss of almost a third (~18 km^3) of the engineered reserves of fresh water by the sabotage of the Kakhovka Reservoir (Hapich *et al.* 2024c; Mammadov *et al.* 2024), one of the world's biggest that supplied 10–12 million people and the largest irrigation scheme in Europe (Hapich & Onopriienko 2024). Replacement of these supplies requires new technological and societal paradigms within a national water resources strategy that must also confront climate change. Even before the war, surface water quality was in steep decline because of increasing evaporative demand, declining rainfall, and excessive man-made loading (Andrieiev *et al.* 2022; Chushkina *et al.* 2024). Food and water security now require investment in sustainable infrastructure, adaptive management, and international cooperation to meet domestic and transboundary challenges (Hapich *et al.* 2024a).

Wells offer a reliable alternative to surface-water supplies but require effective construction technologies, in particular for filtration of mechanical impurities (Khomenko *et al.* 2019, 2023; Ahmad *et al.* 2024; Breternitz *et al.* 2024). For wells in sediments of assorted granulometric composition (Biletskiy *et al.* 2023; Koroviaka *et al.* 2023), gravel filters are considered the most effective. But there are pros and cons (Kozhevnikov & Sudakov 2015); numerous works are devoted to the elimination of their shortcomings (Ratov *et al.* 2023a, b) but present technologies are ineffective. New technologies are needed (Ihnatov *et al.* 2023); in particular, binding materials for the production of *block gravel filters*[1] (Kozhevnikov & Sudakov 2015), as we now describe.

Our goal is to improve the technology for wells as deep as 200 m in medium-grained, fine-grained and silty sands. The idea is to make a block gravel filter with a water-based binder to hold the gravel material into a stable monolith that is installed in the well – but which will then revert to a loose structure through dissolution of the binder in the abstracted groundwater. The primary tasks are as follows: (1) substantiation of the practicability of a reversible binder for block gravel filters; (2) determination of the uniaxial compressive strength (σ_{st}) and dissolution time (t_r) of sugar-gravel composites (SGCs).

MATERIALS AND METHODS

Hydrogeological conditions

Considering groundwater as an alternative water source within Ukraine, there are six artesian basins defined by geostructural features (Figure 1). Two of these (the Black Sea Artesian Basin and the fractured Ukrainian Shield) are significantly affected by the destruction of the Kakhovka dam and the drainage of the reservoir, as well as by mining enterprises (Hapich *et al.*

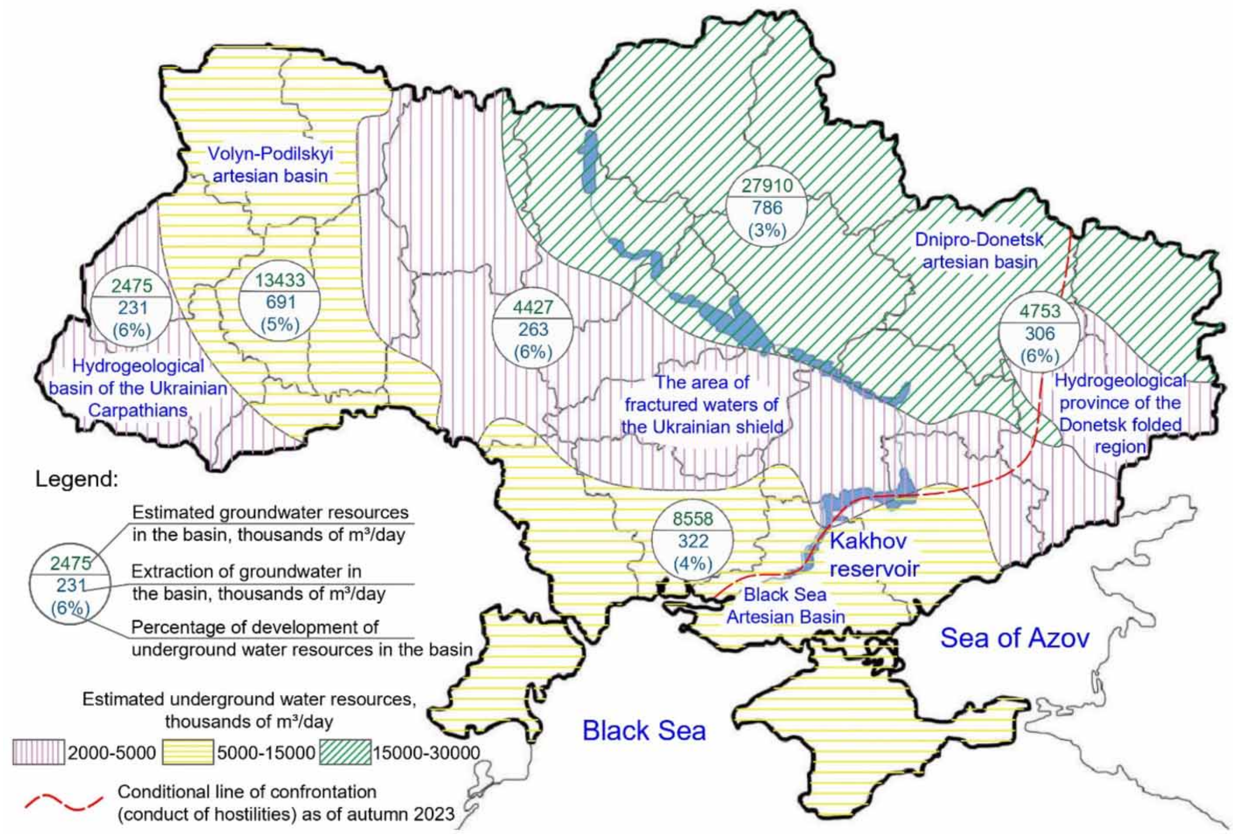

Figure 1 | Ukraine: Estimated resources and actual production of potable and technical groundwater in Ukraine (Hapich *et al.* 2024b).

[1] The term *gravel-coated screen* is in common use but *block gravel filter* is well-established in the field of hydrogeological drilling and is used in various scientific publications, state standards, and technical documents (Chudyk *et al.* 2023).

2024b). The total groundwater resources are estimated to be 3.3 km^3/year, of which 2.7 km^3/year may contain less than 1.5 g/dm^3 dissolved salts and, thus, be potable; but the total explored, operational groundwater reserves amount to only about 1 km^3/year.

Within the liberated territories of Mykolaiv and Kherson provinces, as well as Odesa province, some 330 settlements experience problematic supply and rely partly or completely on water imports. This situation can be turned around by drawing on 'non-traditional' aquifers: 18 promising areas have been identified (Borash *et al.* 2023); hydrogeological sections have been compiled and the ranges of discharge rates and drawdown during the operation of wells are given by Sadovenko *et al.* (2016), Zahrytsenko *et al.* (2018) and Sadovenko *et al.* (2024); drilling of exploratory and operational wells is now required to confirm the possibilities (Biletskiy *et al.* 2022, 2024).

Research methodology

Research was conducted in two stages. First, to determine the dependence of the uniaxial compressive strength of cubic samples of SGC on the drying time and the composition – the latter including gravel, water, and sugar (DSTU 4623-2006 2006) as an aqueous solution of 3, 6, 9, 12, and 15% sugar. Second, to determined the dependence of strength under uniaxial compression and dissolution time of cubic SGC samples of different sugar concentrations.

Sugar (sucrose) has several advantages over other binding agents:

- Strong bonding with gravel that withstands mechanical stresses
- Low environmental impact compared to artificial materials
- Non-toxic dissolution, avoiding pollution of water resources
- Phase-transition capability; the switch between solid and liquid states at specific temperature and water content.

The sugar used in the preparation of the SGC samples is food-grade, crystallised or liquid sucrose which is produced on an industrial scale. It significantly improves the filtration properties of the block gravel filter by achieving strong bonding of gravel particles and uniform pore distribution, reducing clogging risks. It dissolves completely at ambient temperatures through the filtration of groundwater, extending the operational lifespan of the gravel filter.

Rectangular cuboid samples of SGC were prepared according to DSTU B B.2.7-214 (2009) (Ukrainian standard), using medium-grained gravel with a granule diameter of 0.26–0.5 mm and crystalline sugar of particle size 0.5–1.0 mm. Five cubic samples of SGC were produced with 50 mm sides. Experiments were carried out at a room temperature of +20 °C. A hydraulic press, laboratory scales and dishes, an electronic thermometer, and an electronic stopwatch were used to measure the uniaxial compressive strength limit and dissolution time. Microsoft Excel software was used for their processing. Figure 2 presents the sequential procedure.

The cubic SGC samples were checked for any imperfection, then the limits of their compressive strength the dissolution time were determined in the Department of Oil and Gas Engineering and Drilling at Dnipro University of Technology (Table 1). For measurement of dissolution time, 50 mm cube SGC samples from Stage 2 with a sugar content in the gravel composite of 3–15% were taken; each sample was placed in a dish with water at a temperature of 15 °C, which is close to actual conditions during the operation of block gravel filters of hydrogeological wells at a depth of up to 200 m for the Dnipro region (Figure 3); and the initial and final dissolution time determined using a stopwatch. A logbook of observations was maintained during the course of the experiment.

To determine the recommended depth of equipping the water intake part of a hydrogeological well with a sugar-bound block gravel filter, a well was investigated in Vilnohirsk, Dnipropetrovsk region, under the production conditions of LLC Industrial-Geological Group Dnipro-Hydrobud.

RESULTS AND DISCUSSION

Limitations and disadvantages of gravel filters

Filters are a key element in ensuring water quality but they pose several problems: (1) filters must remove not only physical contaminants but also biological and chemical contaminants; their insufficient capacity risks public health; (2) they have a limited service-life so they need to be replaced regularly; this is problematic in remote areas and conflict zones; (3) high-quality filters can be costly; a particular problem in poor or war-torn places; (4) used filters can be a source of pollution if they are not disposed properly; their use requires some skill in their proper operation and maintenance, and inadequate training can reduce their effectiveness. So, not only it is important to implement an alternative water supply but also, to ensure that filtration systems are properly maintained.

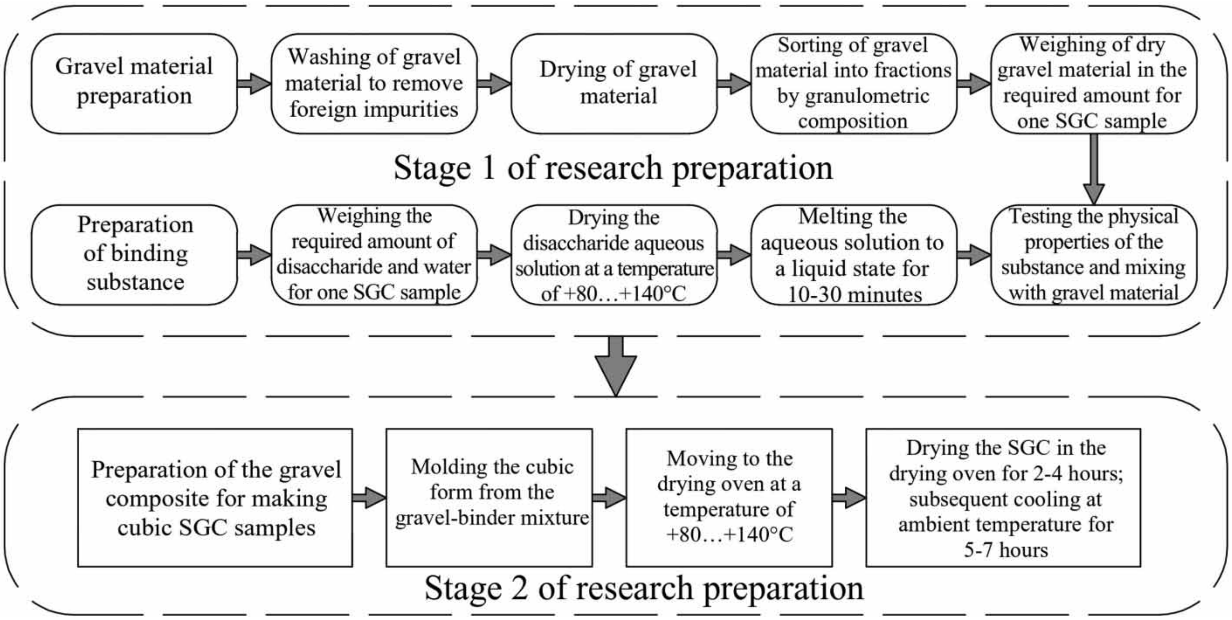

Figure 2 | Methodology and sequence for preparing research and cubic samples of SGC.

Table 1 | Procedure for determining the strength and solubility of cubic samples of SGC

Methodology for determining the strength limit of cubic samples of SGC	Methodology for determining the dissolution time of cubic samples of SGC
Stage 1: – Production of cubic SGC samples – Exposure of samples at ambient temperature (5–7 h) Stage 2: – Installation of cubic samples in the press – Increasing the load to failure of cubic samples – Ascertaining the maximum load of SGC cubic samples. Stage 3: – Calculation of strength limit for uniaxial compression of cubic SGC samples – Determination of the average value of the strength limit for uniaxial compression of cubic SGC samples.	Stage 1: – Preparation of cubic SGC samples for testing – Measuring mass of samples before immersion in water – Immersion of samples. Stage 2: – Recording initial dissolution time of cubic SGC samples – Recording the final dissolution time of samples; – Measuring the mass of SGC samples after dissolving the sugar.

Fine-medium-grained sandy aquifers demand a well which includes a gravel filter that ensures the specified flow rate (i.e. low hydraulic resistance), and resistance to destruction and corrosion (Ratov *et al.* 2023a, b). Gravel filters are classified according to whether they are fabricated in the well or on the surface (Kondrat & Dremlyukh 2014; Kozhevnikov & Sudakov 2015) (Figure 4).

Block gravel filters can be fabricated either way from gravel particles mixed with a binder. The following binders have been used: sulfite-alcohol, cement, BF glue, bitumen, bakelite varnish, liquid glass, rubber glue, etc. and, more recently: polyurethane, aqueous gelatin solution, phenolic resin, polyethelene, polyester, epoxy resin, etc. (Kozhevnikov & Sudakov 2015).

No more binder should be used than necessary to maintain the required porosity. In practice, block gravel filters have lower permeability and higher hydraulic resistance compared to loose fill of the same mechanical composition; the introduction of a binder decreases the effective porosity and the size of the pores in the gravel block, either by completely blocking the filtration channels with glue, or narrowing them. Therefore, the application of block gravel filters has been limited although they have received general recognition and continual development on account of the high permeability of gravel compared to the sand of the productive layer; absence of dead-end pores; unlimited filtering surface; any form of cavern gravel filling; small gradient

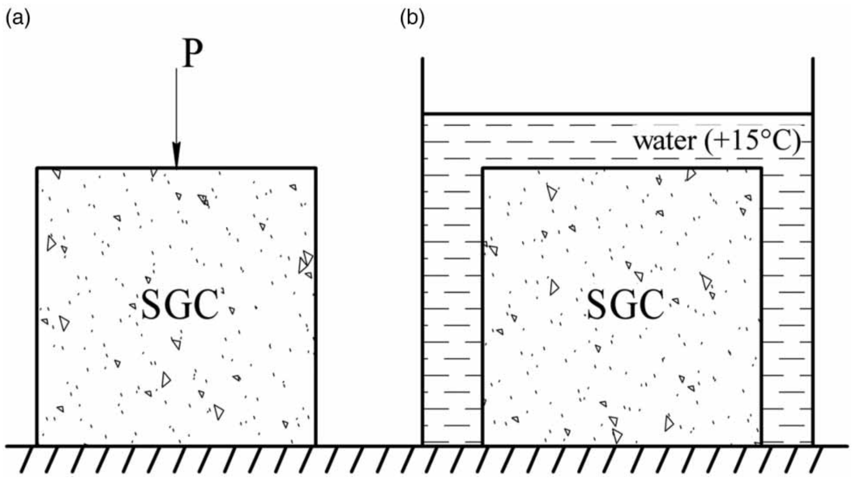

Figure 3 | Schemes of determination of the strength (a) and solubility (b) of cubic SGC samples.

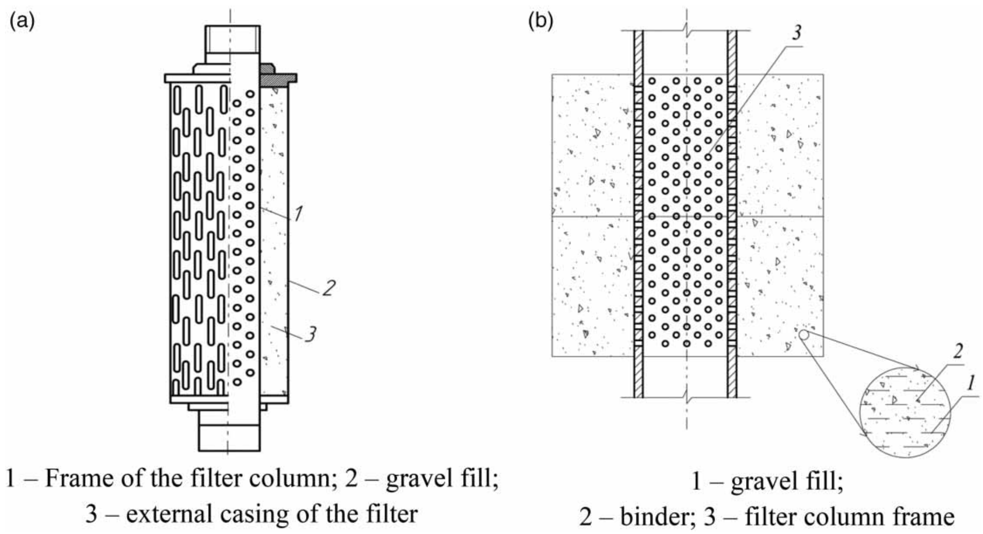

Figure 4 | Gravel filters of hydrogeological wells: (a) casing gravel filter and (b) block gravel filter.

of hydraulic resistance across the filter thickness and low intensity of clogging; low resistance of the filter frame, due to a possible increase in the size of the holes by 6–10 times; simplicity of construction; uniform length and thickness; the possibility of prompt removal of the filter for replacement.

Most methods of manufacturing block gravel filters have significant disadvantages: insoluble binders form dead-end pores, reducing productivity; corrosion of steel columns; acid treatments destroy filters made of BF glue; transportation and installation often leads to damage; depth of use is limited and production is difficult. Therefore, it is necessary to seek other binders that must be inert to gravel, strong during transportation, inert to well fluid, acquire the rheological properties of water under the influence of hydrodynamic conditions and high temperatures, environmentally friendly, accessible and inexpensive.

New solutions for production of block gravel filters

For decades, the authors have undertaken the development of technologies for making and installing reversible block gravel filters. During this time, several procedures were substantiated for hydrogeological wells in fine-grained sands up to 200 ms deep in by fine-grained sands, in which gelatin and sodium silicate were used as water-based reversible binders (Kozhevnikov & Sudakov 2015). The new ecological, humanitarian, and technological situation in the liberated and frontline territories of

Ukraine demands drilling and equipping productive horizons at a depth of 200 m and deeper (Bazaluk *et al.* 2021). This requires new technololgies for the manufacturing and equipping of productive horizons with block filters (Kozhevnikov & Sudakov 2015):

- Blocks installed on filter pipes (columns) must maintain sufficient strength for transportation.
- Binders must be soluble the well fluid.
- The dissolution time of the binder in the gravel block must be fully controlled.
- In the process of development of hydrogeological wells, binders must be completely removed from the gravel filling.
- The design of gravel filters should provide the lowest hydraulic resistance to water abstraction.

Essentially, filters must be durable, functional, environmentally friendly and cost-effective. During the delivery and descent of block gravel filters into the well, the filter element is subjected to load and hydrodynamic influence. Common sugar (sucrose) presents itself as a suitable binder and the chosen criteria for compliance with the requirements set for the binding agents of gravel block filters are: strength limit for uniaxial compression ($\sigma_{ст}$) and dissolution time of SGCs in water (t_p).

Based on our previous studies, binder concentrations of 3, 6, 9, 12, and 15% were used to experimentally select the optimal conditions for the manufacture of a block gravel filter.

At the first stage of the study, it was found that water reduces the physical characteristics of the sugar, it was not possible to determine the strength characteristics of the cubic SGC samples. SGC samples are unstable and viscous, which complicates the process of forming them into cubes SGC (Figure 5(a) and 5(b)). Therefore, we decided to bypass the first stage of preparing cubic SGC samples with the addition of water, but these shortcomings can be countered during further research.

At the second stage, we managed to make cubic samples of SGC with 50 mm sides (Figure 6(a) and 6(b)). During the heating of the sugar with gravel, the sugar melts (caramelises) forming a gel that covers the gravel particles and, upon cooling, ensures strong adhesion of the gravel particles as a monolith.

After sintering in the drying oven (+80 to +140 °C), cooling of the cubic SGC samples along with the 50 × 50 mm mould lasted for 7 h at the ambient temperature of +20 °C. The cubic samples were then compressed using a hydraulic press to evaluate the strength of the cubic SGC sample under uniaxial compression ($\sigma_{ст}$). Figure 7 depicts the dependence of the strength limit according to the sugar content, i.e. depending on the quantity of gel-like particles binding the gravel. These results indicate that the cubic SGC samples are sttrong and stiff enough for making block gravel filters and stonger than other soluble binders used to date.

Figure 8 illustrates the determination of solubility time indicators of cubic SGC samples which showed that the average time of initial dissolution of cubic SGC samples is half as long as the average time for complete dissolution. Water reacts quickly with the SGC so, after flushing the well, the sugar will be completely removed. This has virtually no impact on microbial proliferation or the quality of water resources Figure 9 shows the dependence of the time of solubility of cubic

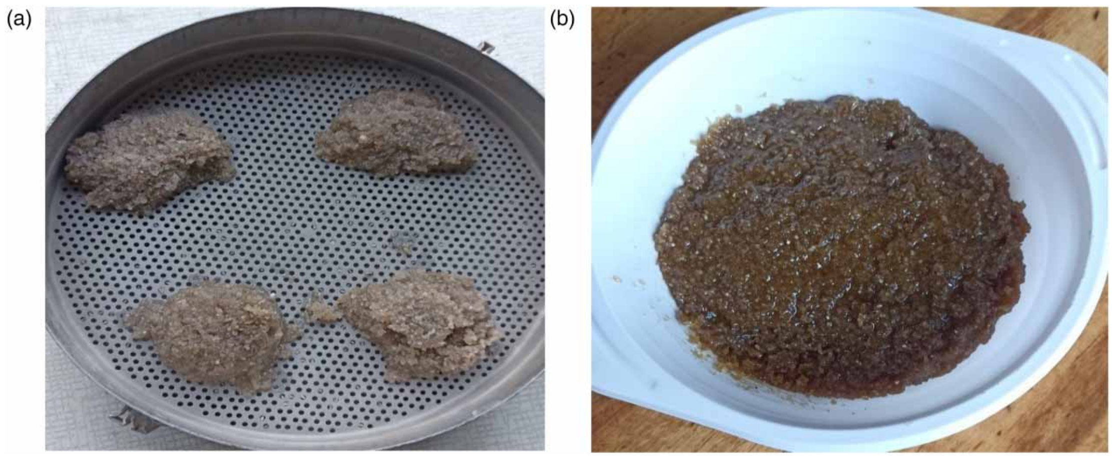

Figure 5 | The first composition at the first stage of the study: (a) aqueous solution of sugar mixed with gravel and (b) aqueous solution of sugar with gravel after heat treatment.

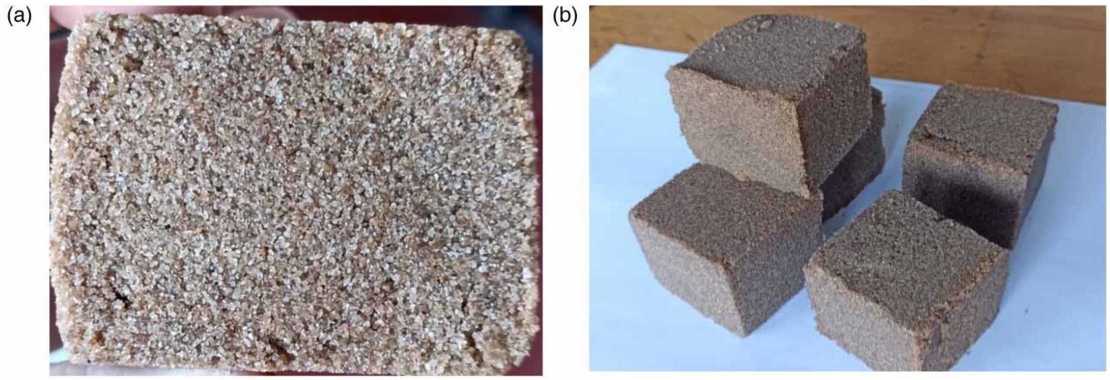

Figure 6 | General appearance of the second composition (at the second stage of the study): (a) texture of a cubic SGC sample and (b) experimental cubic samples of SGC.

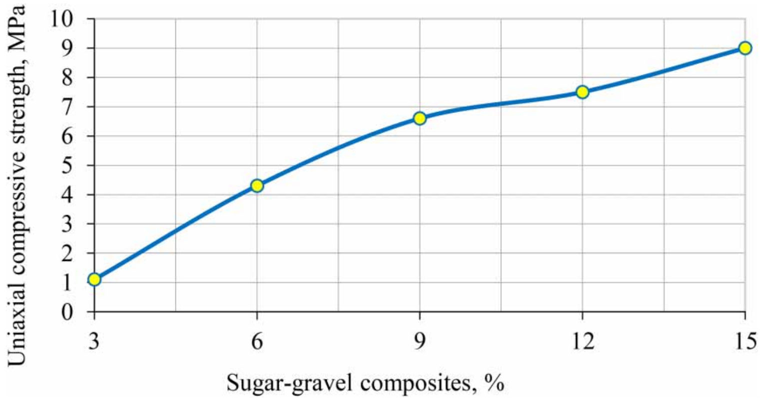

Figure 7 | Average values of dependence of strength limit of cubic SGC samples on sugar content.

SGC samples and the theoretical depth of transport of the block gravel filter from the watertable in the well, on the content of sugar.

Time-study data of hoisting and lowering operations under the conditions of LLC Industrial-Geological Group Dnipro-Hydrobud obtained during the drilling of hydrogeological wells at the Vilnohirsk site established that the temperature of the well fluid ranges from +12 to +15 °C at a depth of up to 200 m. Time to lower the filter column to a depth of 100 m is about 30 min. So, the recommended maximum depth for equipping the water intake section of a hydrogeological well with a sugar-based block gravel filter cold well waters, with a transportation speed of 3.33 m per min from the water table, will be:

- with a 3% mass concentration of sugar in the block gravel filter – up to 10 m;
- with a 6% sugar – up to 18 m;
- with a 9% sugar – up to 25 m;
- with a 12% sugar – up to 43 m;
- with a 15% sugar – up to 80 m.

If the temperature of the water is higher than +15 °C, then such a block gravel filter will collapse faster, as a result of which there will not be enough time for its transportation along the well column. This is an issue for further study. Moreover, we need to investigate changes in its physical and mechanical properties of the block filter under field conditions (e.g., accidental wetting, increased environmental humidity), ensuring the airtightness of its packaging, and examining appropriate storage conditions.

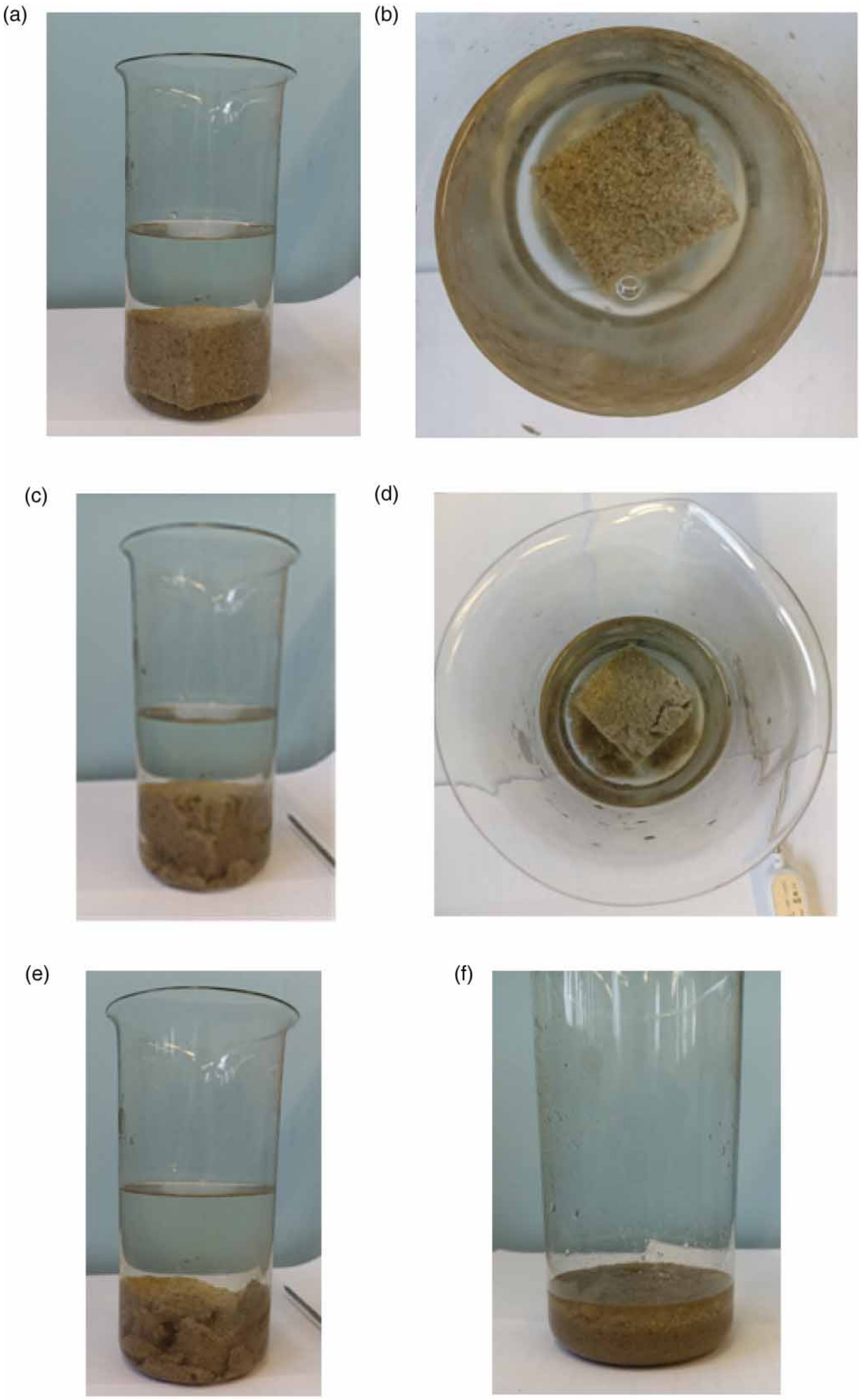

Figure 8 | Laboratory studies of the dissolution of a cubic SGC sample (15% sugar): (a, b) the beginning, (c, d) after 25 min of exposure in water, (e) after 35 min of exposure, and (f) after 45 min.

CONCLUSIONS

Common sugar (sucrose) can be used as a binding agent for block gravel filters in hydrogeological wells but it is important to consider:

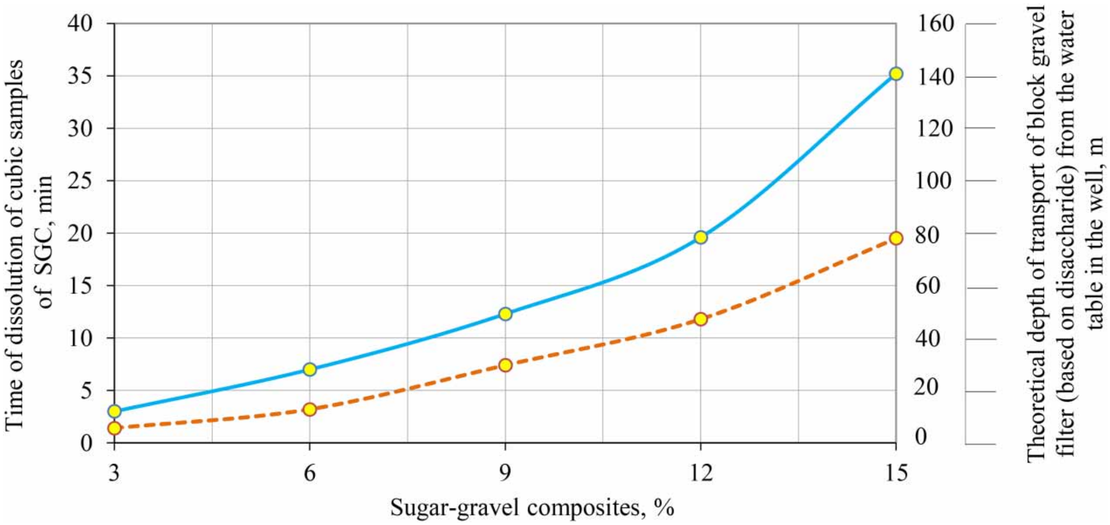

Figure 9 | Dependence of indicators of dissolution time of cubic SGC samples on sugar content: solid line – end of dissolution time of cubic SGC samples; dotted line – beginning of dissolution time of cubic SGC samples.

- the dissolution time of the sugar in water;
- the temperature of the well fluid;
- the speed of transport of the filter along the wellbore;
- the mass concentration of sugar in the block gravel filter.

Some of the shortcomings of sugar-bonded block gravel composite may be alleviated in the following ways:

- Increase the drying time of the cubic SGC samples in the drying oven;
- Increase the sugar concentration, in field conditions use a sugar content of 9–15%;
- Installing the block gravel filter in cold well water at a transport speed through the borehole exceeding 3.33 m/min.

The outcome is an ecologically safe technology for ensuring the proper quality of water for the needs of the country including the reintegration of occupied territories, and for other countries in the world. The research results can also be used in the oil and gas industry, the energy industry (shale gas and coal mine methane extraction), in the extraction of strategic raw materials (rare earth metals, uranium) by leaching methods, in the field of housing and communal services, etc. The research is ongoing.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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