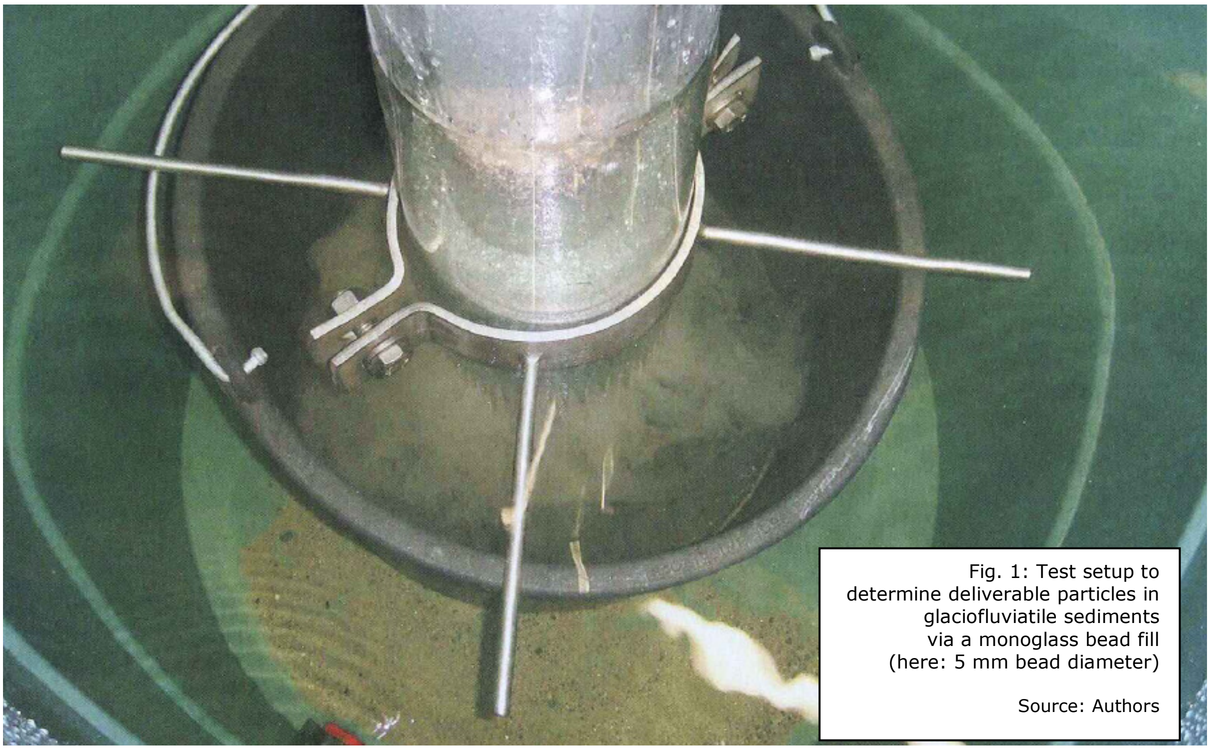


Fig. 1: Test setup to determine deliverable particles in glaciofluviatile sediments via a monoglass bead fill (here: 5 mm bead diameter)

Source: Authors

Comparison of selected material characteristics of glass beads and filter gravel for use in drinking water wells

Selected material characteristics of glass beads and filter gravel that are specific to well construction were determined within the scope of a R&D project currently underway, funded by the Federal Ministry of Economics and Technology. Initial results of these laboratory tests that are currently being performed by the project leaders are presented below.

Glass beads made of acid-proof soda-lime glass have been used as bulk materials for the "silicification" of well filters since 2007. Initial experience with glass beads as filter fills was gathered during the construction of bedrock wells in Franconia and made available to professional circles by Stiegler & Herrmann (2008). The use of glass beads in wells was first triggered as the result of knowledge gained in the development and regeneration of wells that were severely susceptible to iron clogging, as well as the autochthonous discharge of large amounts of fine grain and fine particles with the DIN filter gravels from a variety of natural mineral deposits. These fine grain components, along with the fine particles from the aquifer, were made responsible for the clogging of wells caused by undersize particles (DeZwart 2007, Treskatis 2007). At the same time, it was found that the "rough" surface and primary minerals on the gravel grains promote the agglomeration of incrustations. The first quantitative findings on the agglomeration behaviour of iron minerals to glass beads as compared with DIN filter gravels were published by Treskatis et al. (2009). These investigations provided confirmation for the practical experiences in well construction that, when glass beads are used in the well ring area, not only can the formation of fine grain pieces and fragment pieces, which are contingent on mechanical factors, be avoided, but also can a significantly lower tendency towards incrustation be expected.

Aside from the agglomeration behaviour towards incrustations, mechanical stability, wear resistance, roundness of the fill grains, and chemical resistance (e.g. against regenerants according to DVGW worksheet W 130) are important parameters in well construction, especially for a well's hydraulic productivity.

Object of study and methodology
Materials examined for testing purposes were four commercially available filter gravels used in well construction, in grain size fractions according to DIN 4924 (1 to 2 mm up to 8 to 12 mm) and glass beads (acid-polished and matt) in granulation spectra 1.25 to 1.65 mm and up to a maximum size of 12 mm. The following physical properties were examined in bench scale tests:

- roundness,
- specific weight,
- fill weight,
- grading,
- breaking load during static stress,
- breaking properties during static stress,
- breaking properties during dynamic stress,
- abrasion resistance,
- surface relief,
- surface profile,
- peak-to-valley heights,
- specific surface,
- chemical resistance to pH-controlled regenerants.

The methods and boundary conditions used to determine these material properties are summarised in table 1. As of now, initial results are available from comparative measurements of these physical parameters for the following gravel and glass bead fractions:

- Filter gravel: 1 to 2 mm and 1.4 to 2.2 mm as the main products used in comparison, as well as 2.0 to 3.15 mm, 5.6 to 8.0 mm, and 8.0 to 12.0 mm for selected tests
- Glass beads: 1.25 to 1.65 mm as products used in comparison with the filter gravels listed above, and 1.50 mm, 2.85 to 3.45 mm, 3.00 mm, 5.00 to 6.00 mm, and 12 mm for selected tests.

Parameters no. 5 to 7 affect the clogging properties of the fill body and, together with parameter no. 4, the amount of the undersize grains from the aquifer or from the bulk material itself that can be desanded or that promotes clogging. The formation of undersize grain particles within the bulk material was one of the reasons for looking for alternatives for fragment-forming filter gravels that are conducive to clogging.

Parameters no. 9 to 12 affect the microbiological and chemical incrustation properties of a fill inside a well.

Parameter no. 12 is also of importance in selecting the fill goods in drinking water wells. According to Houben & Treskatis (2003), small inner surfaces on the fill goods reduce primary agglomeration of the incrustation products, thereby delaying the "iron clogging" of wells. Furthermore, this parameter affects the results obtained with the regenerant and its sustainability regarding the dissolving process and repeated iron clogging.

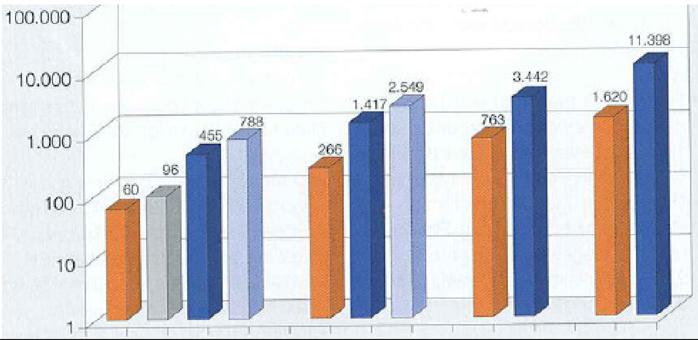
Results
The laboratory tests comparing the two types of materials and various grain sizes yielded the following results:

- Parameter no. 1: The specific weight of the commercially available quartz filter gravel is between 2.615 and 2.655 kg/dm^3, depending on quartz content. Specific weights of 2.503 kg/dm^3 are measured for glass beads.
- Parameter no. 2: The fill weight for grade 2 mm quartz filter gravel is 1.599 to 1.615 kg/dm^3 and 1.585 kg/dm^3 for a glass bead of comparable size.
- Parameter no. 3: The roundness of glass beads was determined to be 0.97 according to the formula listed in table 1. The quotient b/(l x 3) comes to 0.73 to 0.78 for quartz gravel in the optimal case.
- Parameter no. 4: Grading was determined for several glaciofluviatile sediments from the Lake Constance area by means of digital image analysis, in order to determine the grain size that can pass through the fill mass, when filter gravel and glass beads are most densely stacked. This ➢

allows the fitting of grain sizes in the embankment and the well's desanding capability to be improved, and makes it possible to directly determine the grain from the aquifer that is able to pass. Additional experiments are currently being done regarding this in bench scale tests. Figure 1 shows a test set-up to quantitatively determine the grain that is able to pass through from the sediment via a glass bead fill with a defined ball diameter.

Average breaking load depending on filter type

Average
breaking load [N]



A B C D E F G H I J K

A = Filter gravel no. 1 (1.4-2.2 mm); B = filter gravel no. 2 (1-2 mm); C = glass bead type S (1.25-1.65 mm) part no.: 4505 #923033; D = glass bead type S (1.50+-0.2) part no.: 4505-A #820029-1; E = filter gravel no. 3 (2.0-3.15 mm); F = glass bead type S (2.85-3.45 mm) part no.: 4511 #920032; G = glass bead type S (3.00+-0.3) part no.: 4511-A #820022); H = filter gravel no. 4 (5.6-8 mm); I = glass bead type S (5-6 mm); J = filter gravel no. 5 (8-12 mm); K = glass bead type M (12 mm) part no.: 5018-99-24 #855057-20

Filter type

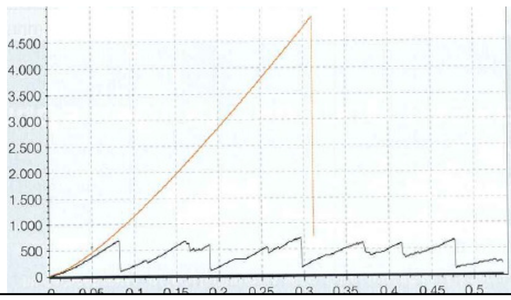
Inspection lot n=20;
Machine type inspect table 20kN (Hege-Hegewald & Peschke)
Test velocity: from 0 ≤ 50 mm/min

Breaking load determination: at 90 % -> Fmax.
Tester: Michael Danhof

Fig. 2: Magnitudes of breaking load of filter gravel and glass beads at different granulation and bead sizes and mixtures at static load handling.
Source: Authors

Comparison of breaking characteristics filter gravel no. 4 (5.6-8 mm) glass bead 4515R (5-6 mm)

Force [N]



Path [mm]

____ Filter gravel no. 4 (5.6-8 mm) Glass bead 4515R #953059 (5-6 mm)

Fig. 3: Load curves for filter gravel (here: 5.6 to 8 mm) and glass beads (here: 5.6 to 8 mm) as a function of the path of the testing stamp. In the case shown here, the glass bead can only be deformed by 0.3 mm, the gravel grain of the same size only by 0.09 mm before it breaks up into smaller pieces for the first time. Source: Authors

- Parameter no. 5: The breaking load at static load for the filter gravels showed an increase in load handling of ca. 60 N up to 1.620 N maximum, in parallel with the increase in grain size (Fig. 2). Glass beads showed an analogous increase in load handling with sphere size. The breaking load here rose from 455 N to > 11,000 N.
- Parameter no. 6: the breaking characteristics of filter gravel and glass beads differ significantly. Filter gravel breaks into smaller fractions at lower loads which then continue to break into even smaller pieces during further loading. The load curves for filter gravel (here: 5.6 to 8 mm) and glass beads (here: 5.6 to 8 mm) as a function of the path of the test stamp (= deformation length) are shown in Fig. 3. The curve for filter gravel shows load handling up to ca. 700 N. The grain breaks and the load is distributed out to several grains which themselves also break once the break threshold has been exceeded. This results in a saw tooth curve of the load handling-deformation length ratio. The load curve of a glass bead, however, displays the properties of an amorphous object (Fig. 4) which takes the load only up to the break threshold (here: ca. 4,800 N) and then split into minute particles that are unable to accept any further load.
- Parameter no. 7: The dynamic breaking characteristics are currently still being determined. Results will be available in late 2009.
- Parameter no. 8: Abrasion resistance was determined in a mill with accelerator. The abrasion of the glass beads and filter gravel grains < 0.2 mm was rinsed out of the mill after 9 hours. This mass was then compared to the mass of the test objects. Glass beads suffered a

loss due to abrasion (mass loss) of ca. 0.5 percent per hour of grinding, the filter gravel by up to ca. 6 percent per hour (Fig. 5). Overall, the mass loss for glass beads was lower by a factor of about 13 for the entire testing period than for filter gravel (up to 53 percent mass loss).

- Parameters no. 9 and 10: The surface relief and the surface profile of glass beads and filter gravel were determined by means of scanning electron microscopy (Fig. 4). The surface differs significantly as expected. The gravel grain surface displays a distinctly irregular structure with high points and depressions that can be found only here and there on the surface of glass beads. The surface profile of a glass bead 1.5 mm +/- 0.2 mm and of a grain from the 1-2 mm fraction is shown in Figure 6.

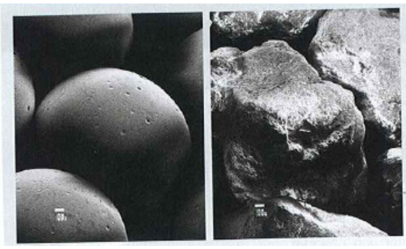
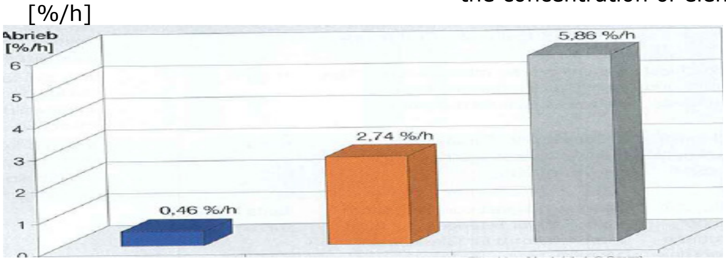


Fig. 4.1 and 4.2: REM image of a glass bead compared to a filter gravel grain of the same grain size. The "smooth" surface of the glass bead prevents the formation of tensile stress when the load is applied and reduces the agglomeration of incrustations.
Source: Authors

Abrasion [%/h]

Abrasion [%/h]



Glass bead type S (1.25-1.65 mm)	Filter gravel no. 2 (1-2 mm)	Filter type no. 1 (1.4-2.2 mm)

Testing particles

Fig. 5: Loss of mass due to mechanical abrasion of glass beads (1.25 to 1.65 mm) and of two similarly graded, commercially available types of filter gravel (1 to 2 mm and 1.4 to 2.2 mm)
Source: Authors

- Parameter no. 11: The peak-to-valley heights, determined as the height difference between the highest and the lowest point along a scanning track 0.5 mm in length, are up to 1.21 µm for quartz gravel, for the glass beads, however, up to 0.58 µm.
- Parameter no. 12: The specific surface of a glass bead 1.25 mm and 1.5 mm in size (+/- 0.2 mm) has a mass of less than 0.01 m^2/g. Compared to this, filter gravel reaches a specific surface of up to 0.95 m^2/g mass (with a granulation of 1.4 to 2.2 mm).
- Parameter no. 13: The chemical resistance of the glass beads and the filter gravel to pH-controlled regenerants was confirmed in principle by means of the testing solutions used in conventional amounts. However, material-dependent differences were found when dissolving elements out of the bulk materials at different acid concentrations. Figure 7 shows an example of the concentration of elements in a 15-hour treatment using a synthetic hydrochloric acid that is free of elements (diluted 1:5).

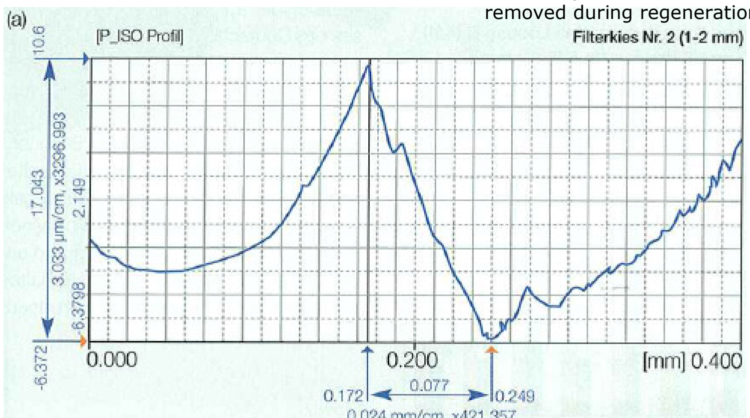
Discussion

As expected, glass beads differ from filter gravel in all parameters examined in the material tests performed thus far. These differences are controlled on the one hand by the differences in solidness of amorphous (glass) and crystalline (gravel grain) structures, and on the other hand by the presence of surface tensions and anisotropies in the structure of the material. In addition, the material properties play a role, as expected, in exposing the materials to chemicals. The following physical and chemical characteristics were determined in particular.

- Parameter no. 3 (roundness): Glass beads very nearly approach the ideal spherical shape due to the manufacturing process, while quartz filter gravel are usually oval in shape due to the manner in which they are formed.
- Parameter no. 4 (grain distribution): The nearly ideal roundness of glass beads allows the densest packing of spheres to be formed whose tetra-hedron-shaped hollows allow a defined characteristic grain out of the aquifer to pass through. This characteristic grain of the first order results from the multiplication of the reversal point in a conventional sieve analysis according to DVGW worksheet W 113, multiplied by the irregularity factor. However, it can also be determined by the grain spectrum at a greater discriminatory power by means of digital image analysis, e.g. at grain sizes of tenths of a millimetre, and the mass of the respective fraction can be quantified. The choice of the grain that is able to pass and that is to be removed can, however, also be determined by dividing a glass bead diameter, which had previously been selected according to W 113, by a factor of 6.7. When comparing this calculation

with the very finely adjustable grain spectrum of a digital image analysis of unconsolidated sediment, the proportion by weight of the removable grain at the time of desanding can be determined, thereby allowing suffusion of the soil into the well and the permanent presence of sand in the well to be prevented (Fig. 1).

- Parameter no. 5 (breaking load, static): the larger the grain size of the fill material, the larger the load bearing capacity of the two materials. However, the difference in breaking loads rises exponentially between glass beads and gravel grains of the same size. The larger the glass bead, the larger is the load bearing capacity difference compared to the same size gravel grain fraction (Fig. 2).
- Parameter no. 6 (breaking property, static): Compared to filter gravel, glass beads can accept very large static loads > 4 kN up to their breaking threshold before breaking into fine particles. Acid-polished glass beads can accept higher static loads compared to matte beads since the solidness of an amorphous solid material is controlled by the anisotropies at the surface. These usually minor anisotropies generate tension at the surface of the sphere and are largely removed on polished beads (Fig. 4.1 and 4.2) allowing tensile forces at the surface of the sphere to be avoided. This type of glass beads is useful for installation situations with particularly high loads. Filter gravel, however, forms numerous broken pieces at low strains of ca. 0.5 to 0.7 kN already; these push themselves into the pore volume of the fill material, thereby even making it possible for the grain lattice to accept more strain. In a loading case, mixtures made up of varying grain sizes develop above the grains' breaking threshold.



Filterkies Nr. 2 = filter gravel no. 2

(b) 09-14043 sample no 2: glass bead type S (1.50 mm +/- 0.2) part no. 4505-A 1820029-1
Profile = P_ISO range = [1]

Fig. 6: Surface profile of a grain from the 1-2 mm fraction (a) and a glass bead 1.5 mm +/- 0.2 mm (b)

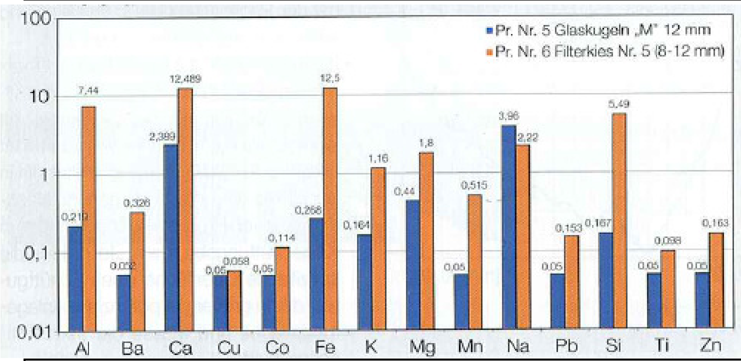
- Parameter no. 8 (abrasion): The loss of mass in grinding filter gravel simulates the process of pouring into a well by means of pipes. In this process, the individual filter gravel grain can lose up to half of its mass, thereby forming additional autochthonous subsize grain particles in the fill.
- Parameters no. 9 to 11 (surface relief, surface profile, peak-to-valley heights): Glass beads have a surface that is only very slightly profiled, a fact that is confirmed by the results on agglomeration properties raised by Treskatis et al. (2009). In contrast, agglomerations located in the depressions located in the surface of quartz grains, which are in part several micrometers in size, can adhere permanently an increase in layer thickness (Fig. 6.1 and 6.2: up to 17.04 µm of total height difference in the surface profile of the gravel grain measured, compared to 3.03 µm for the glass bead; profile length measured: 0.4 mm). As a result, these agglomerations can only be insufficiently removed during regeneration and mineralize in the course of time.
- Parameter no. 12 (specific surface): The difference in the specific surface of a glass bead of less than 0.01 m^2/g compared to filter gravel (up to 0.95 m^2/g) explains the reduced sustainability of well regenerations for gravel fill wells which are frequently encountered in the field. The larger the specific surface of a bulk material, the larger the potential agglomeration surface and mass of the incrustation products.
- Parameter no. 13 (resistance to pH-controlled regenerants): The dissolved amount and the type of elements depends primarily on the primary mineral content of the bulk material. For glass beads made of soda-lime glass, the elements of Ca, Na and Si are dissolved (e.g. up to 12 mg/kg Na, see Fig. 7), while Al, Ca and Si dominate for gravel. Add to this heavy metal impurities in gravel, such as e.g. Ba, Cu and Pb, which result from the

additional impurities of the filter gravel and the iron sulphide sediments, such as e.g. pyrite. All in all, the concentration of elements in the test solutions generated by means of pH-controlled regenerants is greater and more varied for filter gravel than it is for glass beads.

filter gravels from a variety of deposits were compared. Significant differences were found in mechanical strength, morphology of the grain/sphere surface and roundness that are responsible for the agglomeration properties of incrustations. For glass beads, with their almost ideal roundness, a very minor specific, internal surface was

Overview of resistance to regenerants: Solution B (4/4) (glass beads type M 12 mm/filter gravel no. 5 (8-12 mm))

Elements dissolved out [mg/kg] [blue] Pr. no. 5 glass beads "M" 12 mm
[orange] Pr. no. 6 filter gravel no. 5 (8-12 mm)



Elements dissolved out

Fig. 7: Distribution of the elements dissolved out of glass beads and gravel grains after 15 h of treatment with a solution of synthetic hydrochloric acid 1:5

The preliminary material tests show that the minerally amorphous glass beads have hydraulic advantages and favour a reduction of agglomeration of incrustations, which are limited for genetic reasons in the DIN filter gravels examined. This indicates that the discriminatory power of the DIN sieve analysis, which is relatively imprecise in determining the characteristic grain, due to an inaccurate determination of fill bead size, can quickly lead to the wrong well dimensions for fine-grained sediments consisting of similar grains. Further tests are currently being performed in this regard in bench-scale tests within the framework of the R&D project.

Summary

The physical properties of glass beads and filter gravel of a variety of grain spectra and provenance were systematically examined in laboratory tests using technical aspects of application used in well construction. Glass beads and commercially available

found, with minor roughness and peak-to-valley heights. Filter gravels, however, have genetically determined distinctly structured rough surfaces that provide great potential for agglomerations. We deduce from this that regeneration frequency and sustainability of regeneration are affected by this.

Of particular importance for the productiveness and the clogging properties are the breaking loads and breaking characteristics. For filter gravel, a low breaking load of less than 0.7 N compared to more than 4 N for glass beads can be expected. Under the installation conditions used in well construction, glass bead breaks and splinter formations are not expected. The abrasion of a glass bead is lower by a factor of 13 than for the same size filter gravel. Thus, glass beads do not contribute to the formation of subsize particles or clogging particles.

With the aid of digital image analysis, we were able to determine the grain distribution of natural sediments as a model with high resolution of grain grades. This will allow us to adjust the size of the sphere more accurately to the mobilisable (sub-size) grain from the aquifer in the course of further testing. The objective is to achieve an improvement in the desanding and regeneration capability of the well.

Due to their genetic history, filter sands and filter gravels are contaminated with a variety of primary minerals and do not consist of pure SiO_2 alone. Therefore, when these fill materials are exposed to acids, Al, Ba, Cu, Fe, Mn and Pb are dissolved out in particular, in addition to the quartz indicator Si as a main element. No element concentrations that are alarming from a toxicological point of view can be found for glass beads since it is primarily Ca, Na and minor amounts of Si, Mg and K that are dissolved out.

Glass beads have mechanical and physical advantages compared to natural filter gravels and can make an important contribution to avoid clogging and to reduce incrustations when used in suitable unconsolidated sediments and bedrock, and thereby to an overall reduction in desanding and regeneration expenses.

Acknowledgements

This R&D project is funded by the Federal Ministry of Economics and Technology based on a resolution by the German Bundestag (sponsorship ID no.: KU2027701BN8: "Shoring of drill holes for water production - glass beads as a filling, supporting and filter material for modern well construction; examination of the sand retention properties (filter effect) of glass beads compared to gravel, tendency towards iron clogging of glass beads in wells and under laboratory conditions, installation properties of glass beads in drilled wells" dated 12/03/2009).

Table 1: Methods and boundary conditions of material tests on glass beads and filter gravel of various grain sizes					
No.	**Parameter**	**Measuring method**	**Boundary condition**	**Number of tests per granulation/material**	**Equipment used**
1	Specific weight	Displacement method		n = 20	Pycnometer
2	Fill weight	Volume-related weight determination of fill	A 1-dm^3 measuring beaker is filled with the fill material and the increase in weight is determined.	n = 20	1-dm^3 measuring beaker
3	Roundness	Comparing width b to length l	Roundness quotient = b/(l x 3): a quotient of 1 indicates an ideal sphere		digital image analysis by means of Camsizer®
4	Grain distribution	digital image analyses and sieve analyses of real inliner drill probes from glaciofluviatile sediments in South Germany	Unconsolidated rocks selected up to 10 mm grain size; glass beads up to 12 mm bead size; test quantity: 100 g	n = 1	digital image analysis by means of Camsizer®
5	Breaking load with static stress	Determining the average breaking load depending on the material and the granulation/grain diameter	Determining the average breaking load at 90 % drop in force; testing velocity 50 mm/min	n = 20	Inspect table 20 kN according to Hegewald & Heschke
6	Breaking property with static stress	Comparing the breaking properties of filter gravel and glass beads of various diameters	Determining the breaking load as a function of path length and deformation	n = 1	Inspect table 20 kN according to Hegewald & Heschke
7	Breaking properties with dynamic stress	Bombarding a steel plate to simulate the impact of the grains/spheres on the well installation piping and on glass beads as well as on filter gravel (under conditions found at the edge of drill holes)	Velocities of 66.2 km/h (free fall) for filter gravel (12 mm) and 64.3 km/h for glass beads (12 mm)	Tests currently underway	
8	Abrasion resistance	Simulation of the loss of mass by abrasion during mechanical regeneration, e.g. in the impulse method according to DVGW W 130	Determination of the loss of mass by abrasion of grains/spheres; testing quantity 330 ml	n = 1	Willy A. Bachofen "WAB Multilab"
9	Surface texture	digital surface images with SEM		n = 1	Scanning electron microscopy (SEM)
10	Surface profile	Determination of the surface profile across a defined scanning distance; scanning the surface of gravel grains and glass beads to determine the external relief		n = 1	Surface profiler
11	Roughness	Determining the peak-to-valley height as the height difference on a scanning distance of 0.5 mm		n = 1	Pertometer
12	specific surface	Determining the overall surface (outer surface + surface of the pores opened to the outside) of the spheres and gravel grains by means of gas adsorption		n = 1	BET
13	chemical resistance	Analysis of elements dissolved from the glass beads and gravel grains after inserting them in a variety of pH-controlled regenerant test solutions	Synthetic test solutions were prepared from commercially available products (acids) since these contained trace element impurities. All in all, 15 h of treatment time; spheres and grains were completely submerged at T = 20°C	n = 1	ICP

Source: Authors

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Authors:

Prof. Dr. habil. Christoph Treskatis
Bieske und Partner
Beratende Ingenieure GmbH
Im Pesch 79
53797 Lohmar
Tel.: 02246 9212-22
Fax: 02246 9212-99
E-Mail: c.treskatis@bup-gup.de
Internet: www.bieske.de

Dipl.-Ing. Michael Danhof
Dipl.-Ing. Michael Dressler
Sigmund Lindner GmbH
Oberwarmensteinacher Str. 38
95485 Warmensteinach
Tel.: 09277 994-0
Fax: 09277 994-99
E-Mail: danhof@sigmund-lindner.com
dressler@sigmund-lindner.com
Internet: www.sigmund-lindner.de

Dipl.-Ing. Frank Herrmann
Ochs Brunnenbau
Schieräckerstr. 32
90431 Nürnberg
Tel.: 0911 32430-30
Fax: 0911 3143-52
E-Mail: herrmann@ochs-bau.de
Internet: www.ochs-bau.de