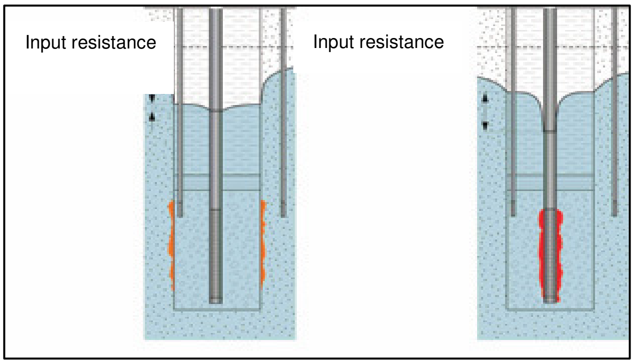
Deutsche Brunnenbauertage 2009 [*exhibition for German well builders*]

Well ageing: Are glass beads an alternative to filter gravel according to DIN 4924?

Innovation in well construction | According to DIN 4924, natural filter gravel today contains increasingly fine particles (autochthonous 'dust' and quartz shivers) and predominantly irregularly rounded, platy or lentil-shaped quartz gravel and stone shivers. In addition, the quartz grains are prone to breakage when built into the well. In practical well construction it could be confirmed that with the use of glass beads in the well ring space both mechanically caused fine grain and shivers can be avoided, and that a clearly lower incrustation tendency is to be expected. For the biochemical processes in a well in the natural underground, analogue results are to be expected due to the surface affinity of the incrustations.

Well ageing is a commonly occurring problem with the extraction of ground water and for the well operator, which is connected with an increasing loss in capacity [1–4]. Previously when it came to this topic causal research had mainly focussed on (bio) chemical and mineralogical processes in the well filter and filter gravel. The cause and consequences of reversible and irreversible chemical-biological ageing processes on the well filter and in the gravel filling are well known through numerous research papers since the sixties and currently published in [4] in summary (Ill. 1).



Ill. 1 Schematic drawing of the location of an outer (a) and inner colmation (b) on the well.
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During examinations in the Netherlands, the mechanical particle filtration was recognised as a further important control process of irreversible well ageing [5]. Research showed that approximately a third of all wells in loose stone aquifers are affected by the problems of a mechanically caused 'outer colmation'. The particles settle in particular on the bore hole material) (Ill. 1 (a)).

Well construction companies report that after well desanding often no significant improvement of the well capacity has been reached in comparison to conventional 'clear pumping'. Examinations in solid rock wells in Franconia showed that in the slots of slot and slot bridge filters, broken gravel and splits of quartz gravel grains irreversibly constrict the free flow (Ill. 2).

In a first application case, in autumn 2007, glass beads were built into a solid rock well as a mechanically stable support medium (see 'Marbles for the well – Expert idea is supposed to prevent blockage of the filter.' In: Fürther Nachrichten, dated 7 Sept. 2007).

The previous examination results provoked the authors to continue the material research with the glass beads from the company Sigmund Lindner (Warmensteinach), used in 2007.

Current problems

In practice, for some time it has been shown that on the one hand the filter gravel supplied to the construction site increasingly contains fine particles (autochthonous 'dust' and quartz shivers) but, on the other hand, predominantly irregularly rounded, platy or lentil-shaped quartz gravel and shivers can be found. Both phenomena can be connected to the well ageing process, which progresses at differing speeds and intensiveness. There are two topic complexes which are of importance for the further practical research work:

- hydraulic effects of the grain geometry on the desanding and regeneration of wells; and
- agglomeration behaviour of incrustations on more or less smooth glass beads and on the uneven surfaces of the quartz gravel filling.

According to the DVGW worksheet W 119, the desanding of wells with double packers and the 5-fold target output encounters hydraulic limitations according to the model examinations of Nillert (2008) [6], which require a re-orientation in the requirements for the desanding and the filter gravel filling. Based on the great permeability contrast between the aquifers and the filter gravel, the development and regeneration techniques common today only reach a part of the gravel packing around the well filter. The causes are the low tractive force of the water during the pumping procedure and the heterogeneous geometry of the porous pore canals in the gravel filling. Both prevent a complete washing out of fine grains (autochthonous and allochthonous) and of incrustations in the gravel filling.

According to the results of examinations [3] in numerous loose stone wells on the Lower Rhine, the 'inner surface' of natural gravel grains is partly responsible for the iron deposits and the catalytically controlled redeposition of previously cleaned grain surfaces as well as the accompanying irreversible reduction in capacity,. The larger the inner surface of the gravel grains, that is, the unevenness and coarseness of the gravel grains, the greater the 'resedimentation of iron ochre potential' and the lower the sustainability of well regeneration, that is, through the regeneration the catalyser is activated again.

Ill 2 Parts of a slot bridge filter with trapped pieces of gravel and splintered quartz grains in the openings.

A simple calculation example should make clear the influence of the surface on this process (see [3]). The filter gravel is simplified as a collection of beads with a uniform grain size of 2 mm. Due to the expected loose bedding, the beads should be cubical, that is, arranged in the loosest bedding. Initially they are surrounded by a mono-molecular layer of iron oxide with an insignificant thickness. A pore canal with a length of 1 mm then corresponds with a surface of $[4 \cdot 0.25 \cdot 2\text{mm} \cdot \pi] = 6.28\ \text{mm}^2$. The sedimentation of iron ochre grows at first into the bottlenecks of the pores. The resulting tube-shaped pore canal, with a diameter of 0.83 mm and a length of 1 mm, has a surface of 2.6 mm², a reduction by the factor ≈ 2.4. If you remove the incrustation from the bottlenecks of the pores, the catalytic effect of the iron oxide surface is again increased by this factor. The settlement surface for iron bacteria is also increased by the same amount.

Research approach

At the trade fair 'geofora 2007' in Hof a. d. Saale, a preliminary report was published on the use of glass beads as an alternative for filter gravel in wells in northern Bavaria, which were in particular danger of incrustation. Essential basic principles of this application, the measurement of the bead sizes and the characteristics of glass beads in comparison to filter gravel during the filling and the well development were published in [7].

Long-term and scientifically founded practical experience with this medium is not yet available; however, this is being collected with diverse applications of well operators and well constructors during various projects across Germany. The connection between the 'coarseness' of gravel grains and the often quick 're-sedimentation of iron ochre' of wells is the starting point for the question of whether wells with smooth, almost equally-sized glass beads in the ring area have a lower or comparable agglomeration potential of iron oxides than wells with conventional gravel fillings, according to DIN 4924.

In the following, we report about the results of basic research at the University of Bayreuth, which is concerned with the agglomeration behaviour of iron hydroxides on smooth glass beads and conventional filter gravel on a laboratory scale.

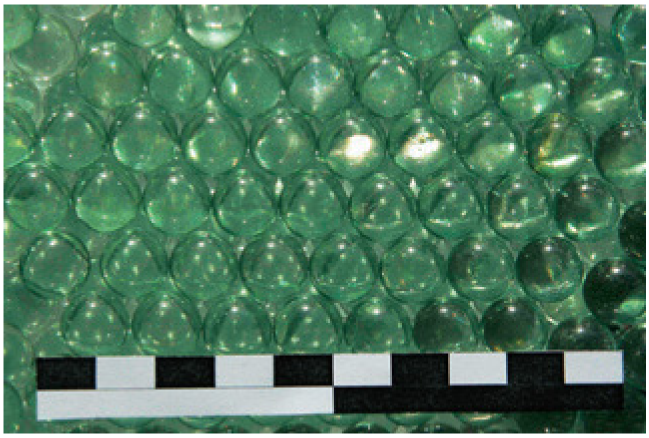
Standards and demands for filter gravel packing in the well

The filter gravel packing is the most important interface between the aquifer and the well filter. It is already the case that, when constructing a well, the sanding and the colmation must be prevented and a regeneration or sanitation of the construction must be taken into consideration in the measurement of the filter gravel grain size. This basic principle is anchored in the professional world as 'state-of-the-art' following basic research projects (e.g. [8]) and practical tests, and was included in the working sheets of the DVGW specifications, which refer to well construction.

Since the sixties, numerous authors have been repeatedly concerned with the topic of 'sanding and desanding' as well as the topics of 'regeneration' and 'sanitation' of wells. Thus, the
'basic demands' and the 'guide parameters' can be derived from the measurement of well filter gravel as follows:

- Adjustment of the supply rate to the capacity of the developed aquifer, avoidance of a too 'deep lowering' and thus triggered turbulences and entrance losses (guide parameter: specific yield).
- Filtering of only one hydraulic and hydro-chemical homogenous aquifer in a hole to avoid vertical short-circuiting and an accelerated well ageing (guide parameter: Redox relationships and hydraulic permeability of the layer sequence).
- Large, permeable pore volumes in the filter gravel packing suitable for the nominal grain of the aquifer; adjustment of the filter slot to the filling grain (guide parameter, nominal grain, filter factor, slot widths, according to DVGW worksheets W 113 and W 118).

Ill 3a Filter gravel with irregularly formed grains and with Iron and layer silicate deposits in the cavities of the grain surfaces.



Ill 3b Silicate glass beads with smooth surface in the densest filling.

Characteristic of the material	Quality goals
Washed and free from ‘undersized particles’	Low material losses free from ‘undersized particles’ and compaction when developing the well; reduction of the development time
Well-rounded gravel grains	Increasing the porosity and hydraulic permeability compared with the aquifer; reduction of the lowering and pressure losses; improvement of the development ability and yield
High quartz share	Avoidance of volume changes through swellable or broken minerals
Smooth surface	Minimising deposits
Low irregular form	Low demixing when filling; avoidance of pressure losses through colmation

Table 1 Material characteristics which are generally advantageous for well construction and quality goals for gravel (outside of the currently valid DIN 4924)

The general demands for the filter gravel in well construction, which today are defined as ‘quality goals’, irrespective of DIN 4924, are summarised in Table 1.

The above-named material characteristics were itemised and demanded in the old DIN 4924 for filter sands and filter gravel for well filters, in issue 1972/02 under the point ‘Delivery conditions’. Among other things, the ‘old’ DIN 4924 determined the following material characteristics under ‘Delivery conditions’:

- no crushed or broken stone debris may be delivered;
- the form of the individual grains should be close to the bead form;
- the surfaces of the grains should be smooth;
- filter sand and gravel should consist of pure quartz (96% SiO_2); and
- under- and oversized grain mass share may be a maximum of 10%.

The adherence to these demands on the material characteristics of sands and gravel, which is indispensible for well construction, would have led to a serious shortage of material. Therefore, the currently valid DIN 4924, issue 1998-08, was revised as the generally accepted rules of technology for sands and gravel for well construction and the demands for the well construction material reduced:

- the admissible mass share of under- and oversized grain have been significantly increased for the grain group of over 2.0 mm diameter;
- the smooth surface of the grains were no longer demanded; and
- in the grain group of up to 5.6 mm, the form of the individual grains no longer needed to be round, but only rounded on the edges.

Filter gravel characteristics as an ageing factor

As a porous medium from a natural mixture of grains, the poured filter gravel package, with its interface to the well filter and to the aquifer, is the decisive reaction space for the well ageing processes and the hydraulic performance of a well. The following characteristics of the filter gravel and its adjacent media also influences the well ageing:

- grain shape (deviation from the ideal bead form);
- inner surface of the grains (coarseness);

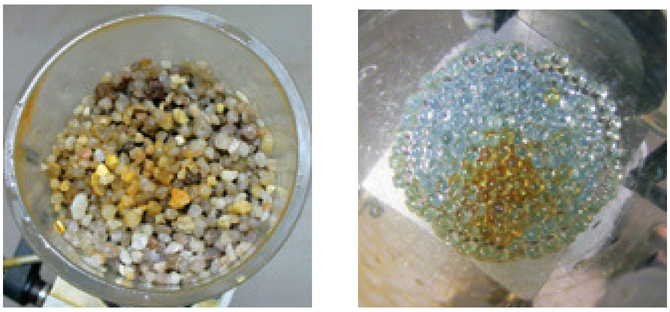
- measurement of the passable gap volume and the geometry of the pore canals resulting from the grain form and bedding density; and
- suspended fine grain share in the water from the aquifer, and subordinate from the filling, which can accumulate in the pore canals either outside of the range of the desanding and regeneration techniques, or based on the aligned well inflow.

The presence of particles and colloids in the ground water has been known for a long time. These are suspended solids which can usually pass the porous media used in well construction due to their small size. An accumulation of the fine particles in the porous space can strongly reduce the permeability there so that the well capacity is reduced. This phenomenon is known, for example, in infiltration wells where an increased concentration of solid material leads very quickly to obstruction of the porous space near the well. The accumulation of the particles is the result of different physical and physicochemical processes. Recently, such filtration processes were also identified to be the cause for the decline in production of supply wells [9, 10].

According to DIN 4924, filter gravel is supplied in defined grain fractions and with a quartz content of usually > 96%. Upon closer observation; however, it consists of round-edged quartz gravel, stone shivers, like greywacke or quartzite, as well as the splitters from broken vein quartz or quartzes of metamorphous or magmatic stones, depending on the storage location. Some examinations from the author prove that the fine grain share of < 5µm in the big bags delivered to the construction sites can be 10% of the overall weight.

In the visual examination of various material samples from common market filter gravels, an intensive yellow-brownish colouration could sometimes be found that was quite conspicuous. It comes from a fine surface coating of the individual grains with iron oxides and FeOOH. This can be observed on grains that consist of weathered magmatic or metamorphous quartzes. A coating of the grain surfaces with clay minerals was observed with quartz gravel from storage locations near kaoline-rich stones. A reason for the increase in the named fine grain share in the examined filter gravel samples can be explained with the mechanical strain and the resulting debonding of the ‘FeO/FeOOH’ or ‘clay mineral dust’ from the individual grains. A mechanical change of the individual grains could be recognised in many samples and was manifested in the grain analysis without a significant increase in the small grain share or a decrease in the large grain share. In a visual examination, quartz splitters were recognised in the fine grain shares, which could come from the weather-caused breakdown of quartzes in the accumulation and the shifting process in the storage locations, and were not completely removed in the sieving and washing process. Along these structures, the quartz grains can break upon being filled into the well (Ill. 3a + 3b).

Ill. 4a+b Experimental pillars with filter gravel and glass beads before the start of the experiment



Ill. 5a+b Open experimental pillars with filter gravel (left) and glass beads (right) after the end of the experiment

Diameter of the beads	Volume of the bead [mm³]	Number of beads for [-] 10^5	Solid material volume	Pore volume [%]
2	4.189	125	52.4	47.6
5	65.45	8	52.4	47.6
10	523.6	1	52.4	47.6

Table 2 Number of beads and pore volumes with a mixture of ideally round, equally sized beads in the loosest filling

In the samples of various beds, the grain form extensively deviated from the bead form. Predominantly rhomboidal and lenticular grains were observed. The share of feldspars (e.g. breccia stone fragments consisting of feldspar and mica as well as quartz and feldspar) and layer silicate (iron mica) is small in most of the examined samples, but cannot be clearly determined due to their especially fine grains as well as the strong coating of the grain surfaces with iron oxides and iron hydroxides.

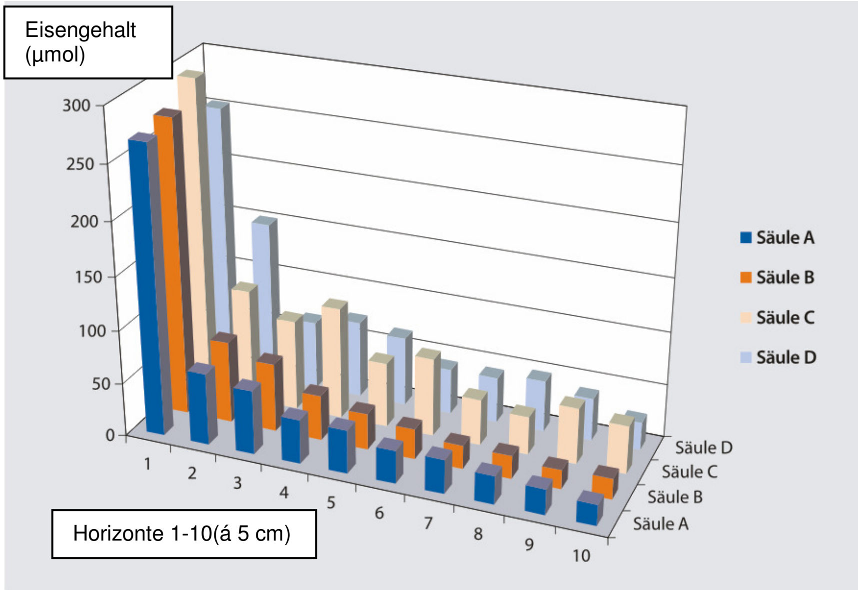
Mechanical well ageing through accumulation of particles in the porous spaces of the filter gravel packing is closely connected to the processes of their mobilisation and filtration. During well development, mostly only the fine grain shares are removed, which were added with the gravel or which resulted from the breakage of the quartz grains during filling. Since the hydraulic range of the desanding methods common today is physically limited, this cleansing process in most wells is imperfect and an essential trigger of mechanical well ageing. The most apparent blockage layer is the former borehole wall, especially if a filter cake, made of fine-grained material, remains after the borehole rinsing. Behind this, further particles can accumulate in the course of the operation of the well from the particles eroded from the aquifer (Ill. 1(a)). In well-developed wells, a mechanical filtration can also occur, which increases in the course of time. Here, the geological conditions of the aquifer are of decisive importance. Poorly sorted aquifers with a high fine grain share deliver especially high levels of particles; low permeable lines with small pore opening widths (porosities) are especially good filters, but also hydraulically less permeable than roughly sorted sediments [9].

The porosity of a sediment is thus dependent on its irregularity so that the ‘outer colmation’ is encountered in wells with filters in irregularly sorted, fluviatile sediments [2]. The greater the porosity and the more uniform the gap volume is distributed, the lower the danger of colmation caused by the deep bed filtration of the fine particles introduced from outside. In addition, the desanding effect is improved by the easier discharge of the undersized particles from the gravel packing. The largest porosity is reached in a porous medium with beads of the same size in loose filling [8]. The bead form thus influences the porosity; in contrast, the grain size doesn’t play a role as the examples in Table 2 show.

Eisengehalt = Iron contents

Säule = Pillar

Horizonte = Horizons



Ill. 6 Distribution of the iron masses in the 10 sampling horizons of the experimental pillars (Horizon 1 is on the inlet, horizon 10 on the outlet of the iron percolation solution)

Pillar description	Pillar A	Pillar B	Pillar C	Pillar D
Filter material	Glass beads (GB)		Filter gravel (FG)	
Grain size [mm]	3.8–4.4	6	3–5.6	5.6–8
Pore volume [ml]	928.9	998.9	1006.1	1006.1
Average flow rate [ml* min^{-1}]	0.6	0.61	0.65	0.59

* estimated

Table 3 Filter material, grain size, pore volumes and flow rates in the four experimental pillars (Hein 2008)

Nominal size	Pillar A	Pillar B	Pillar C	Pillar D
Dispersion length D_L [cm^2 * sec^{-1}]	7.44E-05	8.67E-05	1.10E-04	8.98E-05
Distance speed v_a [m * h^{-1}]	0.02	0.02	0.018	0.018
Dispersivity α [m]	3.0013	0.0015	0.0021	0.0018
Porous space n [%]	38.5	41.4	41.7	41.7

Table 4 Hydraulic parameters of the four experimental pillars (Hein, 2008)

With round grains of the same size, the bedding density has a decisive influence on the pore volumes of the porous medium. In the loosest bedding of beads of the same size (cube allocation) a unified cube of 1 m³ has the largest possible porosity of 47.6%. In the densest tetraeder bedding, the porosity reduces to 25.9% (Ill. 3b). In natural filling media, these two extremes do not occur since, in the well ring space, only the transition between the densest and loosest bedding can be realised due to the lacking roundness and the inner friction of the filled material. The porosity is thus a function of the allocation of the grains in the space and thus dependent on the grain form.

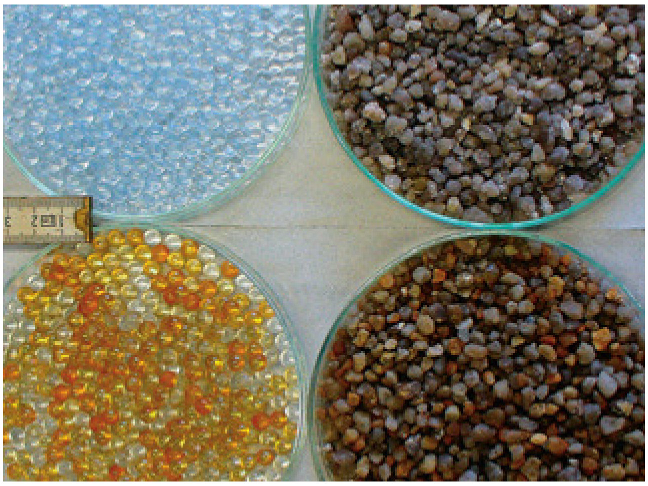
Thesis:
“The filter gravel promotes well ageing due to its heterogeneous porosity distribution in the well ring space as a consequence of the deviation of the gravel grains from the ideal bead form."

Sedimentation experiments in the laboratory

Under determined framework conditions, a simplified comparison of the chemical sedimentation of iron ochre tendency of filter materials was carried out at the Institute for Hydrology, at the University of Bayreuth, to prove the thesis quoted above. For the simulation of diverse filter material fillings in the laboratory, four pillars (each with a length of 50 cm and a diameter of 8 cm) were filled with two material types and two grain sizes. In Table 3, the filling material of the four pillars is characterised. The illustrations 4a + 4b show the course of the experiment with the two filter materials.

When filling the natural filter gravel material into the pillars C and D it was determined that the filter gravel grains broke along, presumably, tectonic breakage surfaces and, thus, strongly clouded the water in the pillars. The pillars were therefore rinsed clear several times with outgassed water before the start of the experiment. This process is equal to the desanding process in the well in view of the autochthon material removal. When filling the glass beads into pillars A and B, this process of breakage was not observed as expected.

In order to be able to compare the four pillars hydraulically, the hydraulic parameters listed in Table 4 were determined using a tracer experiment.



Ill. 7 Optical comparison of the initial material and the partially incrusted material at the end of the experiment after samples were taken

Pillar horizons (Ø 5cm	Pillar A	Pillar B	Pillar C	Pillar D
10	19.7	19.5	45.3	26.1
9	23.9	17.8	52.8	40.1
8	26.3	21.7	35.8	48.2
7	31.9	22.0	43.0	42.8
6	31.0	28.4	73.3	42.4
5	40.7	33.9	60.7	64.7
4	41.4	42.3	104.8	71.8
3	59.9	64.0	84.6	63.7
2	67.3	76.4	105.8	151.6
1	268.8	275.1	294.9	253.6
Ø Blind value	3.7	3.7	14.4	14.7
Sum	**610.9**	**601.2**	**901.1**	**805.0**
% deviation from B (1	1.6	100	49.9	33.9
Ø contents per pillar (µmol)	Ø Glass beads: 606.1		Ø Filter gravel: 853.0	

Table 5 Iron mass balance for the retrieval horizons of the four experimental pillars, values in [µmol], (Hein, 2008).

For the sedimentation experiments and the simulation of a ground water containing iron, the 1.5 fold pore volume of an outgassed percolation solution with pH = 7 and an iron content of 1 mmol/l was led through the pillars from below. For the initiation of the 'sedimentation of iron ochre', the pillars were flowed through with 1.5 fold pore volume distilled water, which was saturated with air oxygen. The flow rate was 0.6 to 0.65 ml/min (approx. 2.3 l/h), which corresponded with a distance speed of 0.5 m/d (0.0000057 m/s) in the selected experiment geometry. The flow speed is thus approximately ten to the power of three under the maximum filter tube input speed according to DVGW worksheet W 118 (V_{krit} = 0.002 to 0.003 m/s).

After the end of the experiment, the pillar material was removed in 5 cm sections and reduced with dithionite for the photometric determination of the iron contents. Illustration 5 shows the open pillars with filter gravel (left) and glass beads (right) after the end of the experiment.

Results and interpretation of the laboratory experiments

The search for tracers in the four experimental pillars showed a similar hydraulic behaviour after the filter gravel pillars were freed from primary and secondary ‘undersized grain’ (Table 3). The very small dispersion coefficient D_L indicates an advective transport of the water through the experimental pillars. During the determination of iron content of the sampling horizons it was noticed that just behind the inlet, where glass frits supported the regular distribution of the percolation solution, clearly visible incrustations formed along the ‘preferred flow path’ in the form of a ‘central’ flue (see Ill. 5). This effect is known from preparation filters during de-ironing in the water plant.

The iron agglomeration on the filter material greatly decreased in all four pillars with the removal of the inlet so that, at the end of the experiment, the pillars were free from visually recognisable incrustations on their respective outlet. Only the glass frits on the outlets showed iron accumulation again. The larger surface and the loss of pressure with higher specific speeds at the outlets is presumably a reason for this. It can thus be concluded that the iron masses listed in Table 5 on the filter gravel grains and on the glass beads were primarily influenced by the respective surface geometry of the grains.

In the overall mass balance, approx. 600 µmol Fe/pillar in the case of the glass beads and approx. 850 µmol Fe/pillar in the case of the filter gravel was determined in the course of the experiment. Illustration 6 shows the distribution of the iron masses in the four pillars in the total of 10 sampling horizons. In the filter gravel, approx. 40% more iron mass was retarded as in the glass beads.

In general, the simplified test arrangement allows for the conclusion expected in practice that the smooth glass beads, with their comparatively small surface area, absorbed clearly less iron than the coarse and irregularly formed filter gravel (Ill. 7). This determination is true for the purely chemically-caused incrustation through the oxidation of a ground water loaded with reduced iron. With an additional microbiologically induced incrustation, differences in the agglomeration behaviour are to be expected according to these experiment results.

Table 6 shows the results of a horizon-related statistical comparison of the measured values with SPSS 16 (Tucey HSD PostHoc test, significance level 5%). If only the normally distributed horizon results are considered, the iron contents and/or their average values of all glass bead horizons are homogenous among each other and, in four of seven horizons, they are even considerably lower than the average values of the filter gravel horizons. This confirms the absolutely mass-related findings on the agglomeration behaviour of both material types.

Summary and outlook

According to DIN 4924, natural filter gravel contains increasingly more fine particles (autochthonous ‘dust’ and quartz grain fragments) today as well as mainly irregularly rounded, plain or lentil-shaped quartz gravel and stone fragments. In addition, the quartz grains tend to burst when built into the well. Both phenomena can have a negative influence on the development, capacity and ageing of the well. This results in two groups of themes for the practice of well construction, which have already been treated in the eighties within the scope of research work. On the one hand, the grain geometry affects the efficient desanding and regeneration of wells. On the other hand, differing agglomeration behaviour is expected with regard to iron incrustations on plain beads and on the uneven surfaces of quartz gravel bulk materials.

In principle, the results of simplified agglomeration tests for glass beads could confirm the lower agglomeration tendency of chemically segregated trivalent iron coming from a reduced ground water. In addition, the filling process of natural filter gravels showed that the gravel products used had a low mechanical stability. Consequently, additional fine particles and fragments will be ‘produced’ in the building process of the well. This means the desanding and regeneration efficiency will be reduced considerably, since the fragments can cause irreversible ‘colmations’ in the slits of filter pipes. This colmation type can be prevented with the higher mechanical stability of glass beads, so that the time-consuming removal of autochthonous fine fractions and fragments can be avoided with the construction of the well.

Thus, it could be confirmed for the practice of well construction that mechanically caused fine fractions and fragments can be avoided and that a clearly lower incrustation tendency is to be expected when using glass beads in the well ring space. With regard to the biochemical processes within a well in a natural underground, analogous results are to be expected due to the surface affinity of incrustations.

Acknowledgement

The authors want to thank the Sigmund Lindner company in Warmensteinach for their support of the D&R project and the provision of material samples and own research results on the mechanical behaviour of glass beads.

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