Assessing the Applicability of Quaternary Sediments as Gravel Pack Material for Dewatering Wells

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Abstract Installation of dewatering wells in the Rhenish lignite district requires huge amounts of gravel pack material, which is a limited natural resource. Even though opposing certain requirements on the quality of gravel pack material for wells in drinking water supply (no initial Fe-(hydr)oxides; minimum quartz-content), in this study, two Quaternary gravels have been considered for application in dewatering wells. Long-term hydrogeochemical exchange was estimated by column experiments, whereas Fe-clogging affinity was evaluated using the experimental model (Weidner *et al.* 2011). With this combined approach, no arguments against the application of these Quaternary materials could be found.

Keywords Quaternary gravel pack material, iron incrustation, experimental clogging model, long term metal release, elution column experiments

Introduction

The open-pit lignite mining in the Rhenish district requires a large number of wells for local dewatering of aquifers with well depths up to 750 m. This results in a high demand of easily accessible well materials, one of which is the gravel, used as filter material between screen and borehole wall. There are certain requirements on the quality of the gravel material, designed to reassure the general functions of the gravel pack: hydraulic permeability, prevention of sand erosion from the aquifer, mechanical integrity of borehole and well, and hydrochemical inertia (as little interaction with the groundwater like dissolution or precipitation of minerals or ionic exchange as possible). Regarding these criteria, quartz is one of the most suitable minerals. Thus, in Germany gravel used in drinking water supply has to contain at least 96 wt- % of quartz, as specified by DIN 4924 (German Institute of Standardization 1998). Furthermore, it is reported by several authors that high initial contents of ferric Fe minerals in the gravel might cause an acceleration or amplification of Fe(III)-(hydr)oxide precipitation and therefore well clogging (Tamura *et al.* 1976; Houben 2004; Geroni and Sapsford 2011).

The mining company RWE Power AG has been using gravel from a Tertiary deposit that fulfills the requirements of DIN 4924 and has no measurable initial content of Fe(III)-(hydr)oxides. However, as resources of this Tertiary gravel are limited, the question of applicability of cost-effective alternative materials, available in close vicinity to the location of use is of high interest. When considering wells for dewatering of open-pits, that question gains a special importance, since most available technical standards like DIN 4924 have been defined for wells in drinking water supply, for which construction and operating conditions are substantially different from those in mine dewatering (*e.g.* construction methods and dimensions, design life, drawdown depths, aeration of screen pipe and aquifers).

In this study, alternative gravel materials from two Quaternary deposits were considered for application in dewatering wells. As the two materials do not strictly fulfill the requirements given by DIN 4924, their properties and geochemical behavior in interaction with groundwater have to be evaluated before the gravel can actually be used for well assembly.

Firstly, the possible dissolution of minerals of the Quaternary gravel was investigated through column experiments by measurements of hydrochemical changes in water flowing through the gravel. Secondly, to preclude an increased clogging affinity due to the initial Fe content, experiments were conducted using a combined hydraulic/hydrochemical experimental clogging model developed at RWTH Aachen University (Weidner *et al.* 2012).

Materials

The gravel materials, considered in this study are produced in the Rhenish lignite mining district, near the three open-pits Garzweiler, Hambach and Inden (fig. 1). The production of the conventional material is situated in Weilerswist, around 25 km southeast of the open-pit Hambach, whereas the alternative materials are available in direct vicinity of either the open-pit Garzweiler (Frimmersdorf gravel pit) or Hambach (Dorsfeld gravel pit).

All three deposits consist of fluvial sediments from the river Rhine. One main difference between the conventional and alternative materials is the geologic time of their sedimentation. The conventional gravel consists of old, Tertiary sediments (Pliocene Kieseloolite Formation), which have been fluvially transported a long way from the Maas-Moselle-region and buried deep into the anoxic underground (Fliegel 1910, Kemna 2008), whereas the alternative materials are shallow Quaternary gravels, recently deposited in proximity to the source area under oxic conditions and covered by thin layers of loess (Fliegel 1910, Quaas 1908). Obviously, this results in a low level of maturity of the alternative materials including lower contents of quartz than claimed by DIN 4924 (< 96 %) and relatively high content of Fe(III)-(hydr)oxides (between 0.1 and 0.2 wt- % Fe) that can already be noticed optically.

Methods

Firstly, to estimate the likelihood of the gravel minerals to dissolve or react in contact with water, columns of PMMA (acrylic glass) of 60 cm length and 10 cm diameter were filled with the disturbed, wet gravel. The gravel was evenly compacted and provided with stabilizing filter plates at top and bottom of the columns. Both Quaternary gravels were assembled in two columns each, while for comparison a fifth column was filled with the conventional Tertiary gravel. Flow and pressure head were kept constant during the experiment except for two stop-flow periods. Tap water of Ca-HCO_3-type was used as inflow.

In the beginning of the column experiments, conservative tracer experiments with LiBr were conducted, to determine the effective porosity (pore volume: pv) of each col-

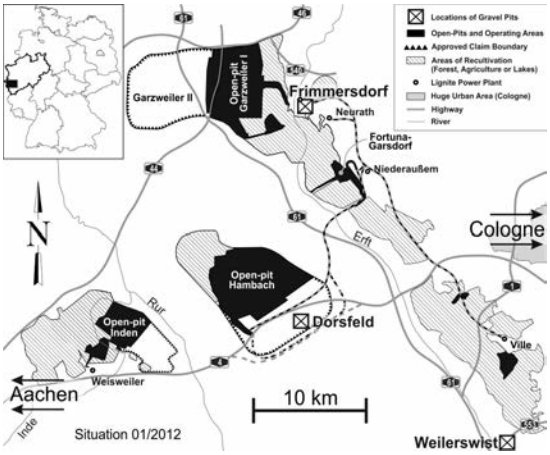

Fig. 1 The Rhenish lignite mining district in western Germany and locations of the gravel deposits of the conventional material (Weilerswist) and the alternative Quaternary materials (Frimmersdorf, Dorsfeld; modified after DEBRIV 2012).

umn. Subsequently, a continuous flow through the columns was applied over more than three months with two stop-flow periods, intended to study effects of diffusion controlled transport. The hydrochemistry of the in- and outflow water was characterized by daily measurements of pH and electrical conductivity (eC). Weekly samples were analyzed regarding their amounts of Fe, Mn, Al and Si via ICP-MS to quantify possible effects of dissolution or precipitation of minerals in the gravel. From the change of concentrations with time, the mass flow M_i per number of pore volumes exchanged (*pv*), normalized to the gravel mass in the column was calculated [mg t^{-1} pv^{-1}]:

$$M_i\,(pv) = \frac{\mu_i\,(pv)}{m_{gravel}} = \frac{\mu_i\,(\tau)\cdot V_{tot}\cdot n_e}{m_{gravel}\cdot Q(\tau)} = \frac{c_i\,(\tau)\cdot V_{tot}\cdot n_e}{m_{gravel}} \qquad (1)$$

with $\mu_\mathrm{i}(pv)$, $\mu_\mathrm{i}(\tau)$: mass flow rate [mg pv^{-1}] or [mg min^{-1}], respectively, with i = {Fe, Mn, Al or Si}, *pv*: number of pore volumes exchanged [-], τ: time [min], m_gravel: total gravel mass [t: metric ton], V_tot: total column volume [m^3], n_e: effective porosity [-], $Q(\tau)$: flow rate [m^3 min^{-1}], $c_\mathrm{i}(\tau)$: concentration [mg m^{-3}].

Secondly, to evaluate the clogging affinity of the two alternative gravel materials in comparison to the conventional gravel, the experimental model of a well section was used that was presented at the IMWA conference in 2011 (Weidner *et al.* 2011). In the model (PMMA flow channel; fig. 2), the process of Fe clogging was simulated in an accelerated way (Henkel *et al.* 2012).

Within each experiment, during the clogging step, incrustations were produced in the unsaturated zone ("clogging zone") by application of a low water level in the outflow chamber. Each experiment consisted of nine clogging steps of around 5 h net operation time (afternoon). In the evening, progression of Fe-precipitation in the gravel was successfully retained by saturating the clogging zone and stopping the flow through the channel (overnight shutdown). Each morning, flow through the clogging zone was enabled by applying a higher water level in the outflow chamber, to estimate the change in the hydraulic conductivity in the clogging zone from pressure measurements in the gravel during the evaluation step. The evaluation steps were also used to adjust the hydrochemical values that changed during the overnight shutdown periods. For the two segments of the gravel (I & II) at least 500 measurements of the hydraulic head were automatically recorded per evaluation step to calculate at least 150 single values of the hydraulic conductivity *K* per segment using Darcy equation:

$$K = \frac{Q}{A\cdot i} = \frac{Q}{b_{channel}\cdot(h_1+h_2)/2\cdot(h_1-h_2)/l} = \frac{2\cdot Q\cdot l}{b_{channel}\cdot(h_1^{\,2}-h_2^{\,2})} \qquad (2)$$

with *K*: hydraulic conductivity [m s^{-1}], *Q*: water volume flow [m^3 s^{-1}], *A*: flow cross section area in the middle between two pressure measurement points 1 and 2 [m], *i*: hydraulic gradient [-], b_channel: channel width [m], h_1, h_2: hydraulic head [m], *l*: distance between point 1 and 2 [m].

From the huge number of *K*-values one mean *K*-value was calculated per evaluation step. Furthermore, after the experiment the intensity of the clogging was evaluated by analysis of total Fe contents in the gravel by a hot oxalic acid extraction of Fe (hydr)oxides (Wen-

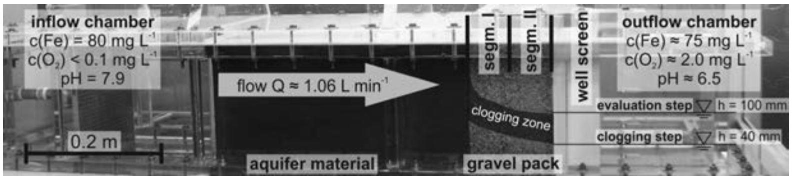

Fig. 2 *Unscaled well section model (flow channel). For a detailed description see Weidner et al. (2012).*

zel *et al.* 2001). With each of the three gravel materials, these clogging experiments were conducted at least twice, to allow for a quality control of the results.

Results

In the stationary operation phases of the column experiments, eC in the outflow remained unchanged with respect to the inflow, whereas the pH was decreased in contact with the gravel (fig. 3, left). During the stop-flow periods, higher contact times between water and gravel as well as diffusive transport were allowed in the columns, causing a decrease in pH and an increase in eC systematically in all columns. After resuming the column flow, pH and eC change back to the values recorded before the stop-flow period within at least one day.

The measurements of the (semi-)metals (fig. 3, right) in general revealed the tendency towards release of Al, Mn and Si from the gravel and capture of Fe in the gravel (negative mass flow difference ΔM_{Fe}). These effects were intensified, when higher contact times between gravel and water were admitted during the stop-flow periods, allowing for an increased hydrolysis of silica (decrease of pH). Surprisingly, in the conventional Weilerswist gravel release of Si, Al and Mn were even higher than in the alternative materials, resulting in the highest decrease of pH during stop-flow, whereas the Frimmersdorf gravel had the highest sorption of Fe and the highest increase of the electrical conductivity after the stop-flow periods. The Dorsfeld gravel only showed moderate reactions regarding pH, eC, Al, Si and Fe and no reaction at all regarding Mn. For the Frimmersdorf and Dorsfeld gravel the results of only one of the two columns were chosen for illustration, but except from the first value for (semi-)metal elution at the beginning of the experiments, the replicated experiments gave similar results.

The results of the clogging experiments (fig. 4) showed that the hydraulic conductivity of all three gravel materials decreased systematically with progression of clogging time (cumulative net operation time of the nine clogging steps). The comparison of all experiments revealed a scattering of the initial K-value, no matter if comparing different gravel materials with each other or comparing two experiments with the same gravel. These scattering effects most likely resulted from slight differ-

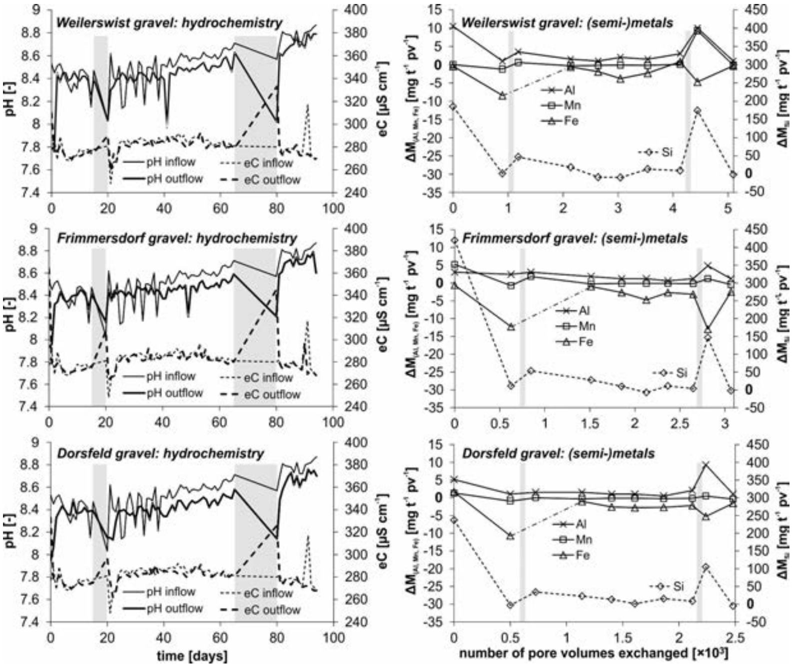

Fig. 3 *Development of pH and eC (left) and mass-flow difference* ΔM_i *(outflow minus inflow) of (semi-)metal i released from the columns (right) during the long term elution experiments. Positive and negative values of* ΔM_i *indicate release and capture of the considered element per metric ton of gravel material, respectively. Stop-flow periods are marked by grey areas.*

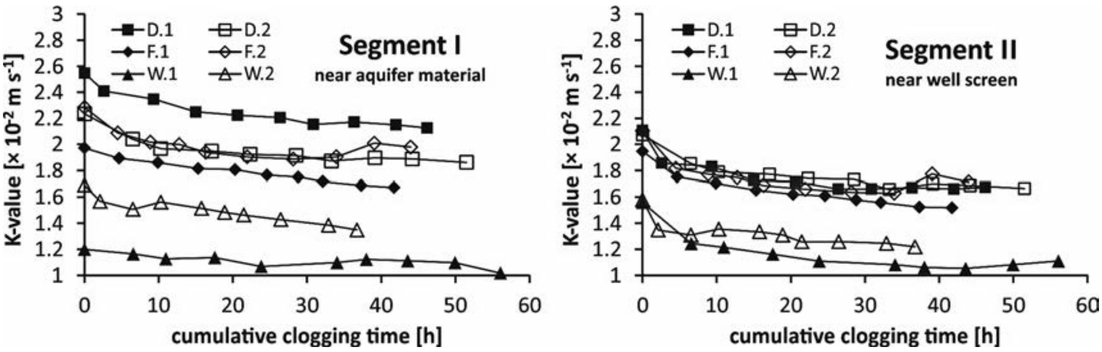

Fig. 4 *Change in hydraulic conductivity K during the clogging experiments with the three considered gravel materials (D: Dorsfeld gravel, F: Frimmersdorf gravel, W: Weilerswist gravel). Repetitions of experiments with the same gravel are indicated by open symbols (D.2, F.2 and W.2).*

ences in the assembly of the gravel pack in the model and were more prominent in segment I of the gravel (near the aquifer material). This could be due to vertical flow components of the near boundary flow field, varying between the assemblies of several experiments. In both segments the general level of hydraulic conductivity was somewhat lower in the conventional Weilerswist gravel in comparison to the Quaternary materials, which might be caused by a shift in the granulometry of the Weilerswist gravel towards smaller grains.

Set aside the variations in the initial situation, the hydraulic conductivity decreased more or less in the same manner and dimension in all six experiments. As the experimental duration was not exactly the same in all experiments, the initial hydraulic conductivity $K_{initial}$ is compared to the K-value after 35 h cumulative clogging time K_{35h} (Table 1). Obviously the mean relative loss in hydraulic conductivity ΔK_{mean} is highest in the conventional Weilerswist gravel.

However, the increase of Fe in the gravel pack in relation to the cumulative clogging time $\Delta c(Fe)/\Delta t$ was very similar for all five considered experiments, with slightly less Fe attaching to the Frimmersdorf gravel. In experiment W.1, no samples for analysis of the Fe content could be taken, but the same calculation of a third experiment with the Weilerswist gravel not further described, led to an increase of iron concentration with time of 0.19 g kg^{-1} h^{-1}.

Conclusions

In comparison to the Tertiary Weilerswist gravel, the Quaternary Frimmersdorf and Dorsfeld gravels seem to possess very similar properties with respect to long term elution as well as clogging affinity. In some respects, the alternative materials seem to perform even better than the conventional DIN-conform Weilerswist gravel. The Weilerswist gravel showed the highest hydrochemical interaction with tap water within the column experi-

Parameter	Unit	D.1		D.2		F.1		F.2		W.1		W.2	
Segment		I	II	I	II	I	II	I	II	I	II	I	II
$K_{initial}$	×10^{-2} m s^{-1}	2.55	2.11	2.23	2.07	1.97	1.94	2.28	2.10	1.20	1.56	1.69	1.57
K_{35h}	×10^{-2} m s^{-1}	2.17	1.67	1.88	1.67	1.70	1.54	1.93	1.66	1.10	1.08	1.35	1.22
Δ K	%	14.9	20.9	15.7	19.3	13.7	20.6	15.4	21.0	8.3	30.8	20.1	22.3
ΔK_{mean}	**%**	**17.7**				**17.7**				**20.4**			
$c(Fe)_{initial}$	g kg^{-1}	1.10		1.10		2.03		2.03		< 0.01		< 0.01	
$c(Fe)_{max\ final}$	g kg^{-1}	10.65		11.22		9.63		10.47		n.a.		7.93	
Δ c(Fe)	g kg^{-1}	9.55		10.12		7.60		8.44		n.a.		7.93	
Clogging time	h	46.2		51.5		41.7		44.0		56.1		36.7	
Δ c(Fe)/Δ t	**g kg^{-1} h^{-1}**	**0.21**		**0.20**		**0.18**		**0.19**		**n.a.**		**0.21**	

Table 1 *Results of the clogging experiments. D: Dorsfeld gravel, F: Frimmersdorf gravel, W: Weilerswist gravel, 1: experiment 1, 2: experiment 2, n.a.: not analyzed.*

ments, the lowest initial hydraulic conductivity and a somewhat higher loss in the K-value after 35 h (average of 20.4 %) in the clogging experiments.

The Frimmersdorf gravel had the second highest interaction with the tap water, especially concerning electrical conductivity and Fe sorption, while the Dorsfeld gravel showed the lowest interaction with tap water. The clogging experiments with the Quaternary materials showed no recognizably higher clogging affinity (both 17.7 % average loss in the *K*-value after 35 h) or measurable autocatalytic effect of the clogging reaction, even though high initial Fe-contents in the alternative materials were found.

Altogether, with this combined approach no substantial drawbacks for the application of the alternative gravel materials could be found. In most respects, an even better performance can be expected of the two alternative gravels. Thus, regarding mineral dissolution and clogging affinity, both of the considered Quaternary gravels can without reservations be used as gravel pack material in dewatering wells.

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References

DEBRIV (2012) Rheinisches Braunkohlenrevier. Website of the DEBRIV – Deutscher Braunkohlen-Industrieverein – Bundesverband Braunkohle. www.braunkohle.de/pages/grafiken.php?page=255, visited March, 9th 2013

Fliegel G (1910) Erläuterungen zur Geologischen Karte von Preußen und benachbarten Bundesstaaten, Blatt Sechtem, Gradabteilung 66(16). Königlich Preußische Geologische Landesanstalt, Berlin, 73 pp

German Institute of Standardization (1998) DIN 4924: Sande und Kiese für den Brunnenbau – Anforderungen und Prüfungen. Beuth, Berlin, 8 pp

Geroni JN, Sapsford DJ (2011) Kinetics of iron (II) oxidation determined in the field. Appl Geochem 26:1452—1457.

Henkel S, Weidner C, Roger S, Schüttrumpf H, Rüde TR, Klauder W, Vinzelberg G (2012) Untersuchung der Verockerungsneigung von Vertikalfilterbrunnen im Modellversuch – Ein Beitrag zum Prozessverständnis der chemischen Verockerung in der Tagebauentwässerung. Grundwasser 17(3):157—169

Houben GJ (2004) Modeling the buildup of Iron Oxide Encrustations in Wells. Groundwater 42(1):78—82

Kemna HA (2008) A Revised Stratigraphy for the Pliocene and Lower Pleistocene Deposits of the Lower Rhine Embayment. Neth J Geosci 87(1):91—105

Quaas A (1908) Erläuterungen zur Geologischen Karte von Preußen und benachbarten Bundesstaaten, Blatt Buir, Gradabteilung 66(8). Königlich Preußische Geologische Landesanstalt, Berlin, 49 pp

Tamura H, Goto K, Nagayama M (1976) The effect of ferric hydroxide on the oxygenation of ferrous ions in neutral solutions. Corros Sci 16:197—207

Weidner C, Henkel S, Lorke S, Rüde TR, Schüttrumpf H, Klauder W (2011) Investigation of clogging processes on vertical filter wells using an experimental model. In: Rüde TR, Freund A, Wolkersdorfer C (Eds) (2011) Mine Water – Managing the Challenges. 11th Congress of the International Mine Water Association, RWTH Aachen, Germany, p 79—83

Weidner C, Henkel S, Lorke S, Rüde TR, Schüttrumpf H, Klauder W (2012) Experimental modeling of chemical clogging processes on dewatering wells in lignite mining. Mine Water Environ 31:242—251

Wenzel WW, Kirchbaumer N, Prohaska T, Stingeder G, Lombi E, Adriano, DC (2001) Arsenic fractionation in soils using an improved sequential extraction procedure. Anal Chim Acta 436(2):309—323