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Research and Development of porous, high-density polyethylene screens for shallow geothermal well systems

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ABSTRACT

In this paper the first results of a research project, supported by the Deutsche Bundesstiftung Umwelt (DBU), are presented. The study intends to develop an ecologically profitable and low maintenance plastic screen for shallow geothermal well systems. The project consists of different tasks. On the one hand the hydraulic and geotechnical properties of the screens are analyzed. On the other hand one of the main aims of the study is it to investigate the aging of the screens induced by mechanical, chemical and microbiological processes. According to the results suggestions for well reconstruction and rehabilitation will be developed. The screen elements are going to be tested on long-run behavior in the laboratory and in the field. An additional focus is on the development and optimization of the manufacturing process of the screens.

1. INTRODUCTION

1.1 Demand on screen systems

Screens are a fundamental part of a well. The groundwater is separated from finest grain of the aquifer by the screen and enters the well through the screen. But a screen has several additional tasks (Sass 1994; Tholen 2012). Generally, profitability is the most important property of a screen. Not only the purchasing price, but also the characteristics of a screen system are weighty. On the one hand a large open screen area is essential for ideal well performance. On the other hand the grade of the stiffness has to be as high as possible to prevent damage to the screen caused by installation or performance of the well. A basic requirement for ideal well development is a defined minimal size which cannot sieve the screen. The developed screen has to ensure well development under predominant hydrogeological conditions. The screen has to have a robust design to sustain aging processes. The head loss caused by the screen should be as low as feasible. It is important for the well performance that the screen enables productivity along the complete filter section. Low installation weights facilitate the handling of well completion for the well digger.

1.2. Special features in shallow geothermal well systems

The planning of conventional and geothermal wells is entirely different. Not only a hydrological, but also a physicochemical characterization of the aquifer is required for geothermal utilization (Tholen and Walker-Hertkorn 2008). These special investigations can be neglected in the planning of a conventional well. The disparity is caused by different designs. Drinking water wells have typically large dimensions. In contrast, geothermal well systems only require small-sized diameters caused by comparably low discharge rates (Bucher and Stober 2012). A geothermal well system consists of at least two wells, an abstraction and a recharge well (Fig. 1). Typically the heat of the groundwater is delivered from the abstraction well by a heat pump to the heating system of the building. Subsequently the water returns into the aquifer by the recharge well. The aquifer is recharged with heated or cooled groundwater according to the case of heat or cooling load. The permitted temperature difference for shallow geothermal wells is 6 K in Germany (VDI 2001). Water-water heat pumps operate with a water temperature of 10°C. Therefore drinking water wells can be compared to shallow geothermal wells.

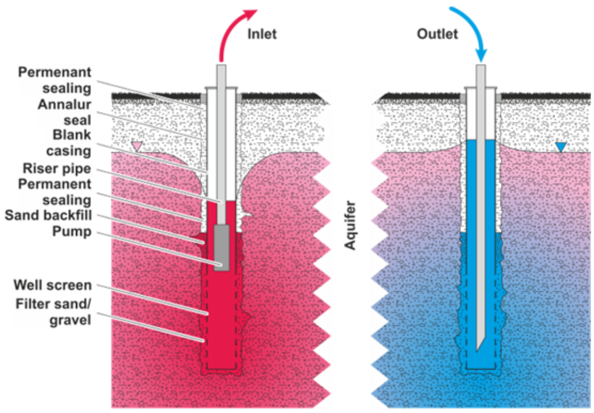

Figure 1: Scheme of a shallow geothermal well system in an unconfined aquifer (Sass and Mikisek 2012).

Recharge wells need special attention. They are subjected to extreme conditions by turbulent flow due to water recharge and optional oxygen input into the aquifer. These processes can be responsible for rapid well aging, which decreases the well capacity. Susceptible to ageing are the pump, the riser pipe the blank casing and primarily the screen and the gravel pack (Houben and Treskatis 2003).

2. PLASTIC WELL SCREENS

Conventional plastic screens are nowadays produced by Polyvinyl chloride (PVC), Polyethylene (PE), Polyamide (PA), Acrylonitrile butadiene styrene (ABS) und polypropylene (PP). They are fabricated as blank casing and subsequently processed to screens by punching (Fig. 2a) or slotting (Fig. 2b). Continuous-slot or disc screens consist of single PVC, PE, PA, ABS and PP elements. Fine-meshed wire screens are made of High-Density Polyethylene (HD-PE) blank pipes (Fig. 2c).

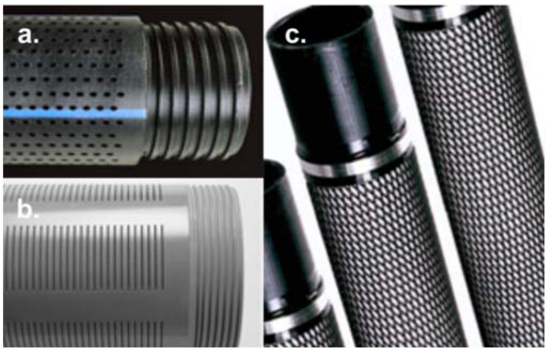

Figure 2: Conventional plastic screens of a. Punched filter. c. Slotted filter. c. Fine-meshed wire screens.

Porous HD-PE screens are fabricated differentially. Granulated material is cross linked by sintering. Hence a sphere packing structure is generated (Fig. 3a, b). The sintering process is regulated by the parameters temperature and time (Fig. 3c). By operating at temperature ranges from 140 to 240°C it is possible to produce screens with a relative density of 70 %, thus a porosity of 30 %.

The pore size of the screens can be adjusted by variation of granulate grain size from 0.02 mm to 1 mm (Heidenreich and Walch 2012). These screens do not have any micro-porosity. They consist of a hydrophobic and nonpolar material. Therefore initial growth of microorganisms and deposition of colloids in and at the screen is prevented (Okumbo and Matsumoto 1982).

3. RESULTS

3.1 Analysis of interior structure and porosity

The interior structure and porosity of the screens is qualitatively and quantitatively visualized by X-ray computed tomography (XCT). Three profiles have been done parallel to the screen wall (Profile A, B and C) and one profile has been done perpendicular to the screen wall (Profile D) in a segment (Fig. 4a).

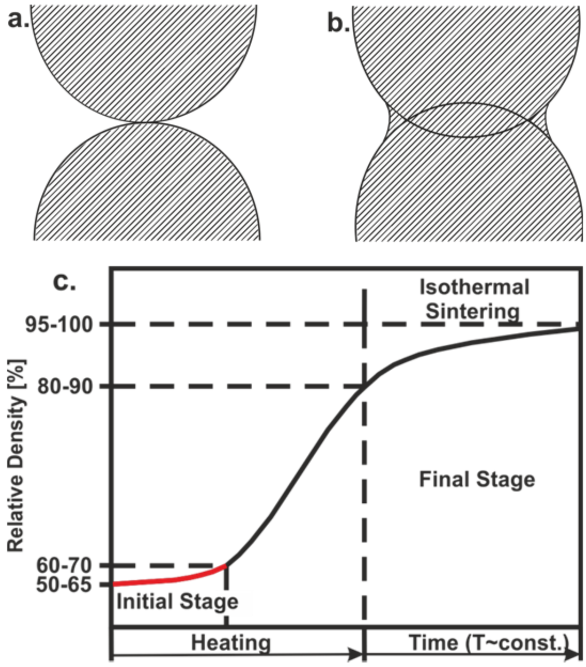

Figure 3: a. Initial sphere packing structure of granulated material. b. Cross linking of particles in the initial stage of sintering (according to Hornbogen and Warlimont 2006). c. Schematic process of sintering (according to Salmang and Scholze 2007).

The segment of a screen with pore size $500 \cdot 10^{-6}$ m shows a homogenous structure and a porosity of 35 % (Fig. 4b). This is a typical porosity of a sphere packed structure. The results of $200 \cdot 10^{-6}$ m screens differ (Fig. 4c). The XCT visualizes a decreased porosity at the interior (Profile C) and outer (Profile A) wall of the screen. As a start an optimization of the sintering process improved the porosity of the interior wall up to 28.8 % (Fig: 4d).

3.2 Definition of cut-off grain size

Colmation experiments have been used to quantify the cut-off grain size of the particular screens. Suspensions have been artificially produced to simulate different soil types. These suspensions pass from outside of the screen through it. The grain size distribution has been analyzed to notice differences between the non-filtrated and the filtrated suspension. The difference between the two distributions correlates to the cut-off grain size, thus the minimum grain size which does not pass the screen. This property makes it possible to match a proper screen to the respective aquifer.

3.3 Analysis of hydraulic properties

An experimental rig has been developed to characterize hydraulic properties of screens. The measurement principle is based on the Darcy test according to DIN 18130-1 (1998). The hydraulic conductivity K was determined by flow from inside of the screen to outside. The time *t* and the streamed volume *V* has been quantified. A standpipe with a lateral outlet has been installed to warrant continuous pressure conditions. Furthermore the gauge level *H* in

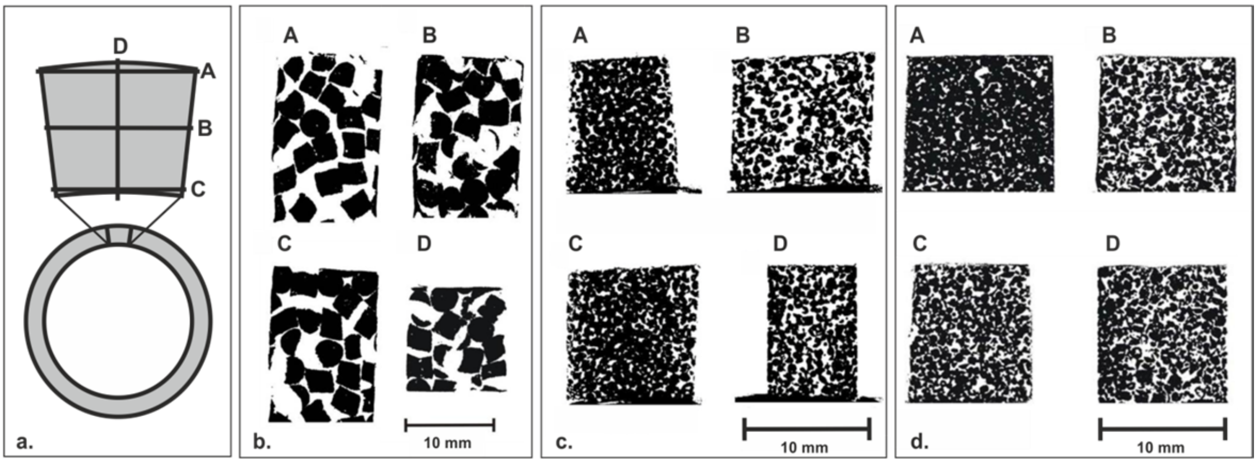

Figure 4: Image of the HD-PE porous screens´ interior structure and porosity by X-ray computed tomography. a. Profile A, B, C and D in the screen segment. b. Image of a HD-PE screen with pore size 500·10^{-6} m. c. Image of a HD-PE screen with pore size 200·10^{-6} m. d. Image of an optimized HD-PE screen with pore size 200·10^{-6} m.

the standpipe can be determined. The screen wall thickness h and the streamed skin surface A have to been known to characterize the hydraulic conductivity of the screen as well [1].

$$K = \frac{V \cdot h}{A \cdot H \cdot t} \qquad [1]$$

Screens of varying slot size and geometry can be analyzed in this experiment. In addition geothermal conditions can be simulated by tempering the streaming water. On the one hand this matters because hydraulic conductivity is a temperature dependent parameter. On the other hand it is important to research the impact of heated water to plastic screens. Plastic material is usually thermoplastic which implements changes of property as a function of temperature. Hence the limits of usability for geothermal applications can be determined. The experiments show an increase of hydraulic conductivity dependent on pore size for the HD-PE screens (Table 1). These porous screens are charac- terized by a hydraulic conductivity of $K = 10^{-4}$ m·s^{-1}. The tested slotted screens (PVC) show a similar hydraulic property, but it does not increase with rising slot size. A comparison of open screen areas illustrate that the porosity of the porous screens is up to 10 times larger than of the slotted screens. These results are reflected in the screen capacities of the different screen types. The capacity of fine pored HD-PE screens equals the capacity of slotted screens with slot sizes from 300 to 750·10^{-6} m. However, the coarsely pored HD-PE screens´ transmitting capacity of 10 m^3/h·m is outstanding. An additional comparison with multi-layered meshed screens (according to manufacturers´ data) shows that the open screen area is lower, but the screen capacity is similar.

3.4 Well performance tests

The characterization of the specific yield and hydraulic performance was analyzed initially on a

Table 1: Hydraulic properties of different screen types.

Screen type	Pore and slot size [10^{-6} m]	Hydraulic conduc-tivity [m·s^{-1}]	Open screen area [%]	Screen capacity [m^2·h^{-1}]
HD-PE (pored)	20	5·10^{-5}	40	2.4
	40	1·10^{-4}	45	5.9
	80	1·10^{-4}	42	6.4
	200	2·10^{-4}	37	11.1
	500	6·10^{-4}	40	33.1
PVC (slotted)	300	2·10^{-4}	4	2.1
	500	2·10^{-4}	5	3.1
	750	2·10^{-4}	7	4.2
HD-PE (meshed)	100	-	8	3.0
	200	-	20	8.0
	250	-	23	3.9

test field in Aschaffenburg, Germany (Fig. 5). Five wells have been installed, which are 4 m long with a filter section of 2 m. Two of the wells are used as monitoring wells characterized by an interior diameter of 80 mm. The three other wells ($Ø_{interior}$ = 100 mm) are equipped with a slotted PVC screen (slot size = 500·10^{-6} m) and two porous HD-PE screens (slot size = 200, 500·10^{-6} m). The wells are drilled with a lateral distance of 1.9 m to each other. The bedrock is characterized by a semi-confined pore aquifer with 1.0 m depth to the water table. The aquifer consists of a well-sorted medium sand of a hydraulic conductivity of 3.2·10^{-4} m/s. The top layer is an anthropogenic filling which is 1.2 m thick. Its grain distribution is similar to poorly sorted sand. The filling is characterized by an average hydraulic conductivity of 6.5·10^{-4} m/s.

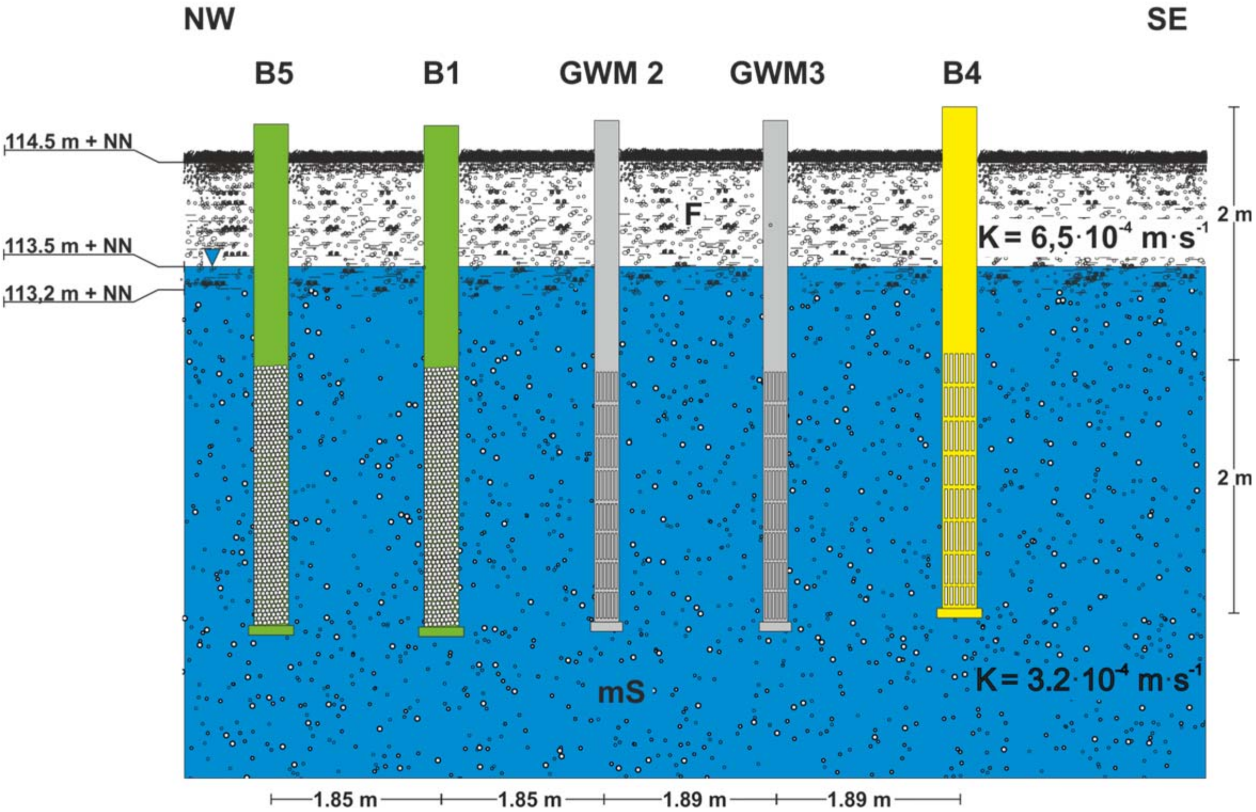

Figure 5: Scheme of the well performance test field in Aschaffenburg, Germany.

Hydraulic and physic chemical analyses took place in the test field in 2012 and 2013. Step-discharge tests have been performed to determine and compare the specific yield of the different wells. The results are illustrated in figure 5. The analyses of the data according to Bierschenk (1964) indicate laminar and turbulent drawdown. Turbulent drawdown occurs well-specifically, whereas the laminar behavior is driven by the aquifer (Treskatis et al. 1998).

The 200 and $500 \cdot 10^{-6}$ m porous HD-PE screen feature a similar specific yield of the 0.0028 $m^2 \cdot s^{-1}$ (Fig. 6a, b). The difference between the two screens is that the coarsely pored screen is characterized by an increased turbulent drawdown. The slotted PVC screen shows an insignificant turbulent drawdown and the largest specific yield of 0.0035 $m^2 \cdot s^{-1}$ (Fig. 6c). According to these results the slotted screen is best qualified for an application in this bedrock.

3.5 Characterization of geotechnical behavior

Analyses of geotechnical properties have been realized by five different measuring principles. The screen elements have been subjected to uniaxial compression and tensile tests. Additional test were collapse and bursting tests by compressed air application.

The three-point bending test completed the analysis program. The results of all tests show no correlation to the pore size of the screens (Table 2). But it can be noticed that the screens of pore size $200 \cdot 10^{-6}$ m are characterized by the largest strength for all kinds of stress loads. The elongation without necking due to the tensile test is similarly low for all porous screens (1 %). A comparison with slotted normally walled screens clarifies the equality in properties (Tholen 2012).

Table 2: Geotechnical properties of different screen types.

Screen type	Pore and slot size [10^{-6} m]	Collapse pressure [10^5 $kg \cdot m^{-1} \cdot s^{-2}$]	Tensile strength [10^5 $kg \cdot m^{-1} \cdot s^{-2}$]	Elon-gation without necking [%]
HD-PE (porous)	20	3.7	29.2	1.2
	40	2.7	30.1	1.3
	80	2.9	27.4	1.5
	200	8.1	54.5	1.5
	500	2.4	28.2	1.4
$PVC_{normally\ walled}$ (slotted)	-	~5.0	44.0	-
$PVC_{thick\ walled}$ (slotted)	-	~11.6	64.1	-

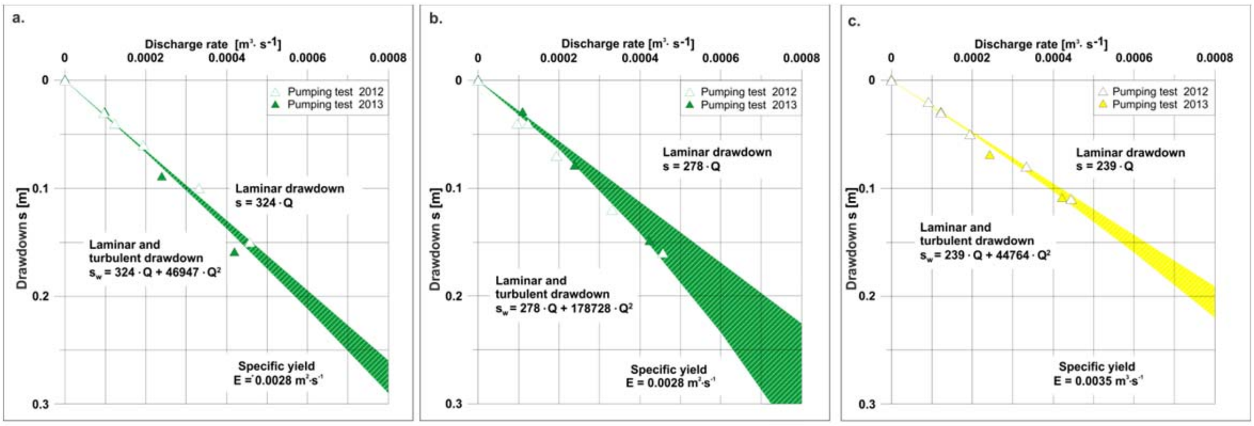

Figure 6: Results of the well performance tests from 2012 and 2013 in the test field Aschaffenburg, Germany for a. The porous HD-PE screen with a pore size of $200\cdot10^{-6}$ m. b. The porous HD-PE screen with a pore size of $500\cdot10^{-6}$ m. c The slotted PVC screen with a pore size of $500\cdot10^{-6}$ m.

4. CONCLUSIONS

The different analysis enabled a classification of the HD-PE porous screens (Table 3). Therefore a general graduation to fine, medium and coarsely pored screens is allowed. These three classes can be related to different applications and conditions. The fine-pored screens are characterised by low hydraulic conductivity and suited for fine grained aquifers. They are qualified for monitoring and soil gas remediation in unsaturated bedrock. The operation in geothermal well systems makes sense only in exceptional cases. The medium-pored screen can be well operated in sand aquifers for geothermal well systems as well as monitoring, hillside drainage and infiltration applications. The coarsely-screened elements can be installed in addition to geothermal tasks for drinking water supply and groundwater remediation in sand and gravel aquifers.

The analysed properties show that the HD-PE screens are characterized by

- a sphere packing structure,
- large open screen areas and hence large screen transmitting capacities,
- defined cut-off grain sizes for particular pore sizes,
- mechanical properties which are similar to normally walled slotted PVC screens and
- medium specific yields which vary dependent on predominant hydrogeological conditions.

Further application-oriented research is planned to simulate chemical and microbiological failure scenarios, and investigate different maintenance methods. In addition, hydraulic and geotechnical experiments will be performed to simulate geothermal load cases. Finally, a further test field will be put into operation to analyse the long-run behavior of the screens.

Table 3: Classification of porous HD-PE screens.

Pore size	Fine-pored	Medium-pored	Coarsely-pored
	20, 40 and $80\cdot10^{-6}$ m	$200\cdot10^{-6}$ m	500 and $1000\cdot10^{-6}$ m
K_{screen}	$4\cdot10^{-5}$ to $1\cdot10^{-4}$ $m\cdot s^{-1}$	$2\cdot10^{-4}$ $m\cdot s^{-1}$	> $7\cdot10^{-4}$ $m\cdot s^{-1}$
K_{Soil}	10^{-7} to 10^{-5} $m\cdot s^{-1}$	10^{-5} to 10^{-4} $m\cdot s^{-1}$	10^{-4} to 10^{-2} $m\cdot s^{-1}$
Cut-off grain size	Silt	Fine sand	Medium to coarse sand
Application	(Geotherm. well system)	Geothermal well system	Geothermal well system
	Soil gas reme-diation	Hillside drainage	Drinking water supply
	Monitoring	Monitoring	Groundwater remediation
		Infiltration	Hillside drainage

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