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Development of a permeability test rig

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The target of this Bachelor’s thesis was to develop a permeability test rig for Kemira Espoo Research Center’s Oil & Mining laboratory. A permeability test rig is used to measure a capacity of transmitting a fluid in a porous material. In the iron process, permeability is one of the critical factors which have to be defined from iron pellets and sintered iron.

The permeability test rig was developed by using information about similar kind equipment and was designed to meet Kemira’s needs.

The development work resulted in a fully functional permeability test rig which can be used in everyday work and to support the development work in Kemira.

Keywords	Permeability, Porous media, Iron process

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Tämän insinöörityön tarkoituksena oli kehittää laite permeabiliteetin mittaukseen. Insinöörityö tehtiin Kemiran Espoon tutkimuskeskuksen Oil & Mining -osastolle. Permeabiliteetin mittausta käytetään määrittämään huokoisen materiaalin kykyä kuljettaa nestettä tai kaasua kyseisen materiaalin lävitse. Permeabiliteetti on yksi kriittisimpä ominaisuuksia mikä täytyy määrittää raudan valmistuksessa käytettävistä rautapelleteistä tai sintratusta raudasta.

Permeabiliteettimittalaitteen kehitys perustui jo olemassa olevaan tietoon vastaavan kaltaisista laitteista ja se suunniteltiin Kemiran käyttötarkoitusta ajatellen.

Insinöörityön tuloksena saatiin toimiva mittalaite permeabiliteetin mittaukseen, jota voidaan hyödyntää Kemiralla osana jokapäiväistä kehitystyötä.

Avainsanat	Permeabiliteetti, Huokoinen materiaali, Raudan valmistus

Contents

Acronyms

List of symbols

1 Introduction 1

2 Background 2

2.1 Kemira Oyj 2

2.2 Background and purpose of the thesis 2

3 Permeability in porous media 3

3.1 Flow in porous media 3

3.2 Permeability 3

3.3 Testing the permeability in a laboratory environment 5

3.3.1 Test setup for define the permeability 6

3.4 Klinkenberg effect 7

4 Permeability test rig 8

4.1 Design 9

4.2 Components 12

4.2.1 Fan 12

4.2.2 Pressure difference measurement 13

4.2.3 Flow measurement 14

4.3 Operating 15

4.3.1 Results 16

4.4 Maintenance 16

5 Testing 17

6 Conclusions and summary 19

References 21

Appendices

Appendix 1. Part list of permeability test rig.

Appendix 2. Mechanical drawings of permeability test rig

Appendix 3. Excel template for calculation of results

Acronyms

BF	Blast Furnace. One of the processes in iron making.
DR	Direct reduction. One of the processes in iron making
DRI	Direct Reduced Iron. Iron which is produced with DR process
O&M	Oil & Mining. One of Kemira’s business segments.
JPU	the Japanese Permeability Unit
IS	The International System of Units
N_2	Nitrogen (in gas phase)
He	Helium
PVC	Polyvinyl chloride, synthetic plastic polymer

List of symbols

Q	Flow rate
Q_{air}	Airflow rate
κ	Permeability
A	Area (the cross-sectional to flow)
μ	Viscosity
$\Delta\rho$	Pressure difference
L	Length (over the pressure drop)
κ_a	Absolute/ intrinsic permeability
κ_q	Gas permeability
κ_{air}	Air permeability
κ_{liq}	Liquid permeability

1 Introduction

In most production processes, the quality and the properties of the raw materials have a significant influence on the end product. One of these processes is the production of iron where the quality and especially the properties of the raw materials play a very important role from beginning to end of all process steps which are needed in the iron production. Like most other mineral and metal production processes, the iron production also starts from the mining of iron ore from the ground. The iron ore itself is not directly suitable for use as iron because iron in the ore is not in form of metallic iron and it includes a large amount of gangue. To remove the gangue from the ore and to get iron to suitable format for further processing (e.g. for steelmaking), the ore has to be processed.

After mining the iron ore, process usually consists of three main stages: concentration, agglomeration and reduction of iron. When iron ore are mined, the ore contains lumps of varying size; the biggest in diameter can be more than 1 meter and smallest ones around 1 millimeter in diameter. During concentration, the particle size is reduced to lumps (size from 7 to 25 millimeters across) and fines (less than 7 millimeters). If the quality of the ore is appropriate and reduction is done by the blast furnace (BF), the agglomeration step is not needed for the lumps. But if the quality are not appropriate, the particle size has to reduce to fines or even to powder that the gangue is possible to remove. The fines and/or powder have to be agglomerated to the required format with suitable properties for reduction process. The fines are agglomerated by sintering, and powder is agglomerated by pelletizing. [1]

In the reduction process stage, the ore is processed to metallic iron. Most of reduction processes are done by the blast furnace or direct reduction (DR). In both of these processes, gases play a very big role; in the BF process, iron is smelted by using a hot blast of air, while in the DR process, iron is reduced by reducing gas (natural gas). In both of these processes, the ore and the gas have to get into a good contact with each other so that the process is working properly. If the contact is not good enough in the DR process, the ore does not reduce to metallic iron. If the contact is not good enough in the BF process, the ore doesn’t smelt, and in the worst case, it can cool down the whole blast furnace. For that reason, permeability is one of the critical properties for the ore. Permeability is also very important other process stages like in agglomeration by sintering; the permeability of a sinter bed directly influence productivity of a sinter plant because the sintering time of the sinter bed relates very much to permeability of the sinter. [2, 3]

2 Background

2.1 Kemira Oyj

The commissioner of this thesis is Kemira Oyj, a global chemicals company. Vision of Kemira is to serve customers in water-intensive industries. Main business areas for Kemira are Pulp & Paper, Municipal & Industrial Water Treatment, and Oil, Gas & Mining. With chemicals Kemira also provides application know-how and expertise. All in all, Kemira improve its customers' water, energy and raw material efficiency. In 2014 Kemira had annual revenue of EUR 2.1 billion and around 4,250 employees. Kemira is headquartered in Helsinki (Finland) and its shares are listed on the NASDAQ OMX Helsinki Ltd. [4]

Kemira has three research centers which are located in Espoo (Finland), Atlanta (USA) and Shanghai (China). The research centers are not only functioning as research centers but they also support regional business in its own region by providing technical customer support. Each research center also has own specialization areas. [5]

This thesis was carried out for the Espoo research center’s Oil & Mining department.

2.2 Background and purpose of the thesis

One of Kemira’s Oil & Mining (O&M) research departments is located in Espoo research center. O&M research in Espoo is focusing, inter alia, to research and develop chemicals for iron processing. To research and develop chemicals for iron processing several kind of process equipment are needed to cover different process stages and conditions. With process equipment also a lot of different kind of laboratory measurement equipment and analyzers are needed. O&M departments laboratories are equipped well but however there still are lack of some measurement equipment, like a permeability test rig. Some actions for acquire the permeability test rig has done already before this thesis but these all has postponed for different reasons. Target in this thesis was to develop and build the permeability test rig.

3 Permeability in porous media

3.1 Flow in porous media

A porous medium consists of a material in a particulate phase that includes empty spaces, microscopic pores. Usually the particulate phase is solid and microscopic pores are filled of a flowing fluid. Some of these pores are connected to each other while others are unconnected. Depending of a material, connected and unconnected pores can be distributed to a regular or random manner in the medium. Porous media can be divided as fractured or granular media and furthermore by mechanical properties as consolidated or unconsolidated media. In a consolidated porous medium, the particles are connected by a binding material while in an unconsolidated porous medium the particles are without any binding material and are loose from each other. [12]

Flow in porous media is generally described by linear relation between some fluxes and the relative driving forces but because a large number of constitutive equations (in different fields of physics) can be used to describe relationships of those, describing flow in porous media can be hard. Especially the complex geometry of porous media set a lot of challenges for it. In theoretical and experimental investigations the scale of the application is normally considered to limit the things to be considered. Generally these scales are microscopic (“pore” scale), mesoscopic and macroscopic (“field” scale). [12]

At the macroscopic level permeability is one of the physical quantities which describes well behavior of flow in porous media. [12]

3.2 Permeability

Permeability is a physical quantity which defines ability of porous media to transmit fluids. It is mostly dependent on the porosity of the material and on the size and shape of the pores. In granular materials, such as rock or agglomerated iron, permeability is also dependent by the size, shape and packing arrangement of the grains (Figure 1). Fluid properties influences also to permeability. Permeability is used in applications on geology, mining and in oil and gas production; e.g. to estimate oil and gas productivity. [6, 7]

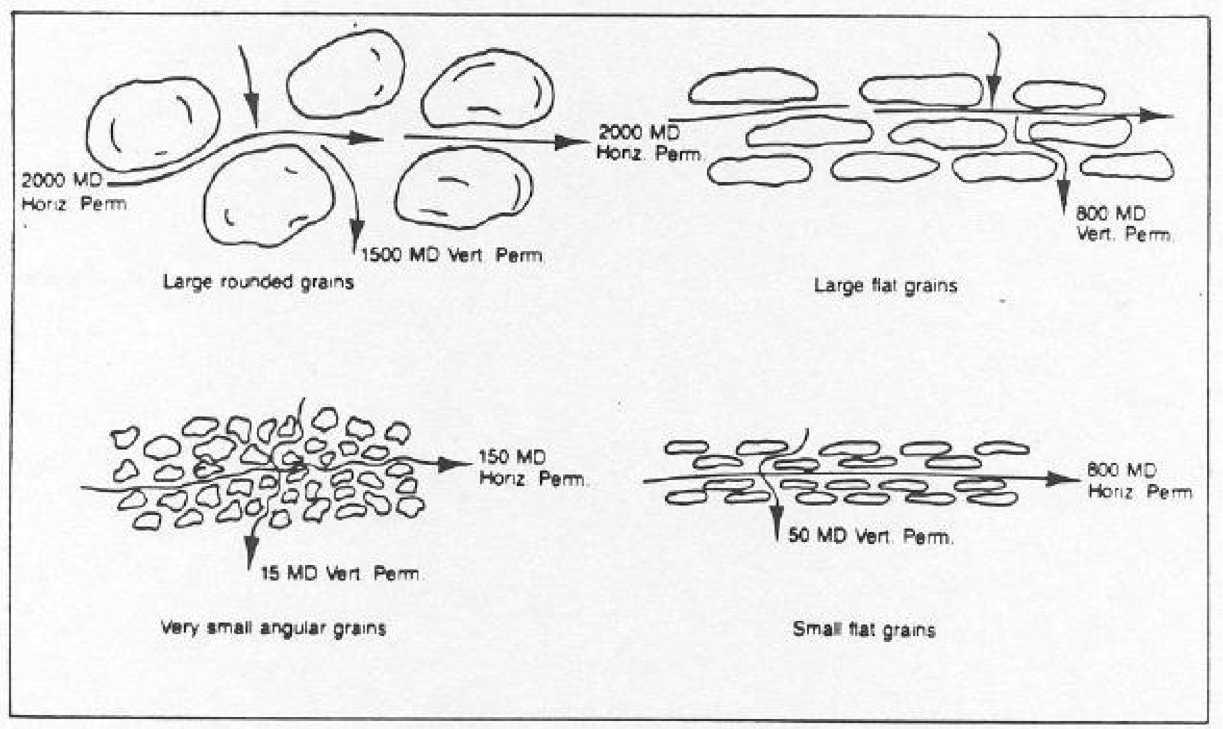

Figure 1. The effect of shape and packing on permeability.

Permeability is expressed as the velocity of a fluid, in specified viscosity and under the influence of a given pressure, passes through a sample which having a certain thickness and cross section. Permeability is possible to define with the Darcy's flow equation (Equation 1.1) with some rearrangements (Equation 1.2). [6, 7, 8, 9]

$$Q = \frac{-\kappa A}{\mu} \frac{\Delta\rho}{L} \tag{1.1}$$

$$\kappa = \frac{\mu Q L}{A \Delta\rho} \tag{1.2}$$

In Equations 1.1 & 1.2 units are: $Q = m^3/s$, $\kappa = m^2$, $A = m^2$, $\Delta\rho$ = Pa, μ = Pas and L = m.

Because Darcy law is only valid for a laminar and steady state one-phase flows through a porous medium, Brinkman law (Equation 2) is needed in cases where flow is out of these specs.

$$\Delta\rho = \frac{\mu}{\kappa}u + \mu_{eff}\Delta u^2 \qquad (2)$$

In Equation 2: u is the velocity vector of the fluid and μ_{eff} is an effective viscosity which may be different from µ. [12]

The SI unit for permeability is m2 but mostly used unit in different applications, mainly in petroleum engineering and geology, is the darcy (d) or more commonly the millidarcy (md). The darcy is equivalent to the passage of one cubic centimeter of a fluid (with viscosity 1 mPas) per second through one square centimeter of a sample in cross-sectional area under a pressure of one atmosphere per centimeter of thickness. Darcy is equivalent to 9.869233×10−13 m^2. Usually the conversion is approximated that 1 µm2 is 1 darcy. [6, 7, 8, 9]

In some applications have been developed own permeability units which fits better to these applications. One of these special permeability units is the Japanese Permeability Unit (JPU) and it is mostly used in applications of iron and steelmaking industry. JPU is defined with the Japanese permeability definition (Equation 3). [3]

$$JPU = \frac{Q_{air}}{A({}^{L}/_{\Delta\rho})^{0.6}} \qquad (3)$$

In Equation 3 units are: Q_{air} = Nm^3/min, A = m^2, L = mm and $\Delta\rho$ = mmH_2O.

3.3 Testing the permeability in a laboratory environment

In a laboratory environment the permeability is tested usually with dry gas, like air, N2 or He. Testing with liquids is usually avoided to minimize reactions between a fluid and measured material and its inconvenience and availability. When testing is carried out with a gas at low pressures it's possible to make an assumption that the gas follows the ideal gas law. To avoid some of the experimental errors during testing, the flow should be restricted to the low flow rate area to keep it as laminar as possible so that the pressure remains proportional to the flow rate. [7]

Permeability is also possible to report in way that a substance which is used to measure the permeability is informed in name of permeability. When the permeability test is carried out by using gas, the permeability can be called as gas permeability (κ_g) or air permeability (κ_{air}). Tests where is used a single fluid the permeability is called as absolute or intrinsic permeability and in the subscription of the permeability symbol is used “a” (κ_a). If water is used as the single fluid it makes an exception compared to other fluids and the permeability is called as liquid permeability (κ_{liq}). [7]

3.3.1 Test setup for define the permeability

Because any standard for permeability measurement doesn’t exist, the test setups can vary a lot. Usually test setup is based on that a fluid of known viscosity is forced through a measuring vessel. A pressure difference sensor or two pressure sensors are installed to wall of the measuring vessel so that the pressure difference is measured over the length of the measuring vessel or certain part of it. [7, 8]

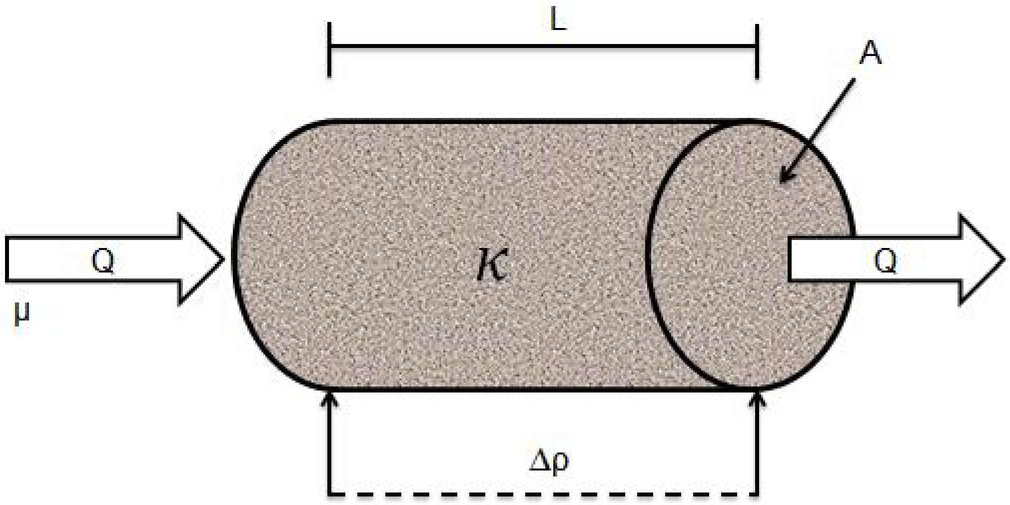

Figure 2. Definitions used in the equations of permeability.

In some applications permeability is also possible to calculate with computer modeling of flow in porous media. However, in many cases computer models may include assumptions of porous media. Especially in cases where the porous media structure is not uniform, modelling of it takes a lot of resources and modelling algorithms come very complicated.

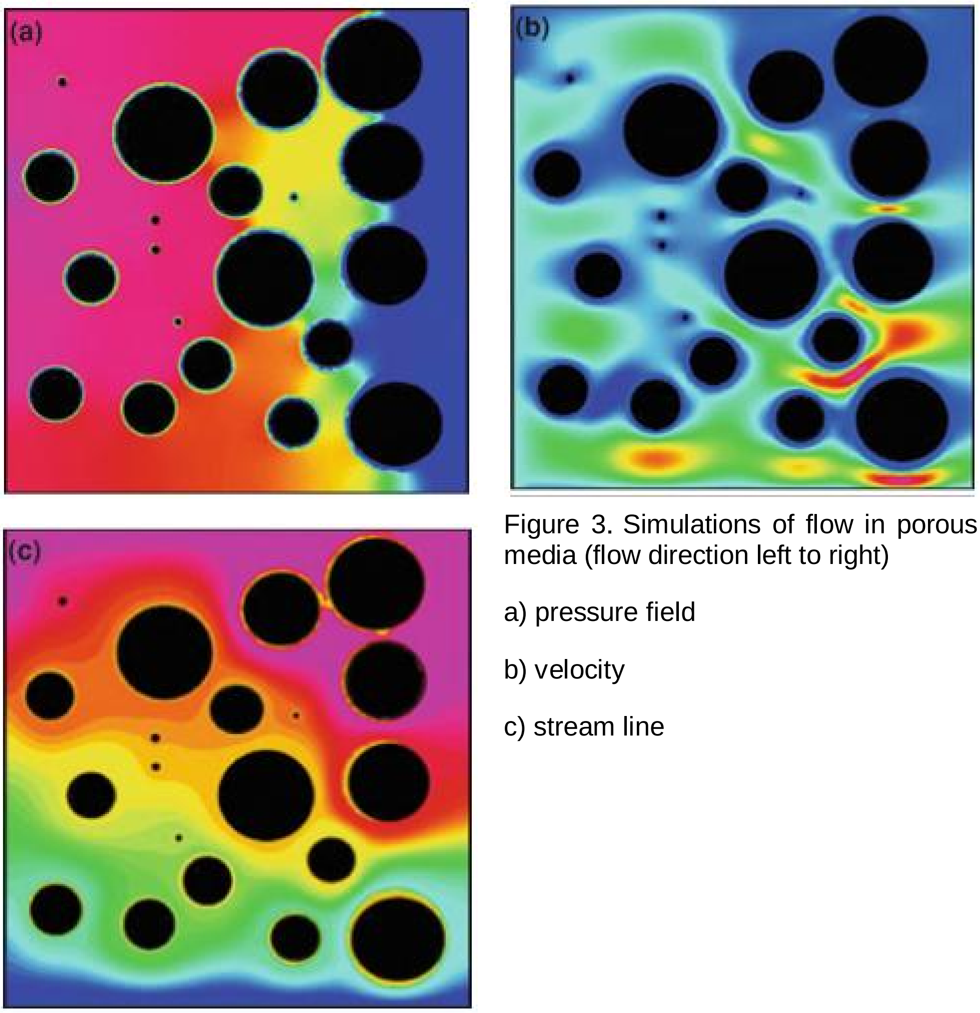

Figure 3. Simulations of flow in porous media (flow direction left to right)

a) pressure field

b) velocity

c) stream line

3.4 Klinkenberg effect

Permeability is a constant value for minerals and rocks which stay unchanged by different liquids which have different physical properties (if the liquids are not reactive and flow rates are laminar). But with gases, the permeability can be and most of cases is higher than absolute permeability of medium even at low pressures. This is called as Klinkenberg effect (named after L.J. Klinkenberg who discovered it) and reason for this is different kind properties and behaviors between the gases and the liquids. [7, 10]

A typical behavior for laminar flow of the liquids is that velocity profile of a liquid is zero at the walls and maximum at the center of the passageway but at the gases the velocity profile is a finite in the direction of flow which is reason of gas molecules that are in constant motion. This behavior of the gases is also called as “slippage”. Because of this slippage the gases have a higher flow rate than the liquids at a given pressure differential. As the slippage is quite finite it is more important to get notice it with low permeability mediums than high permeability mediums. [7, 10, 11]

Klinkenberg discovered the effect of the gas slippage for permeability during his experiments and developed an equation to calculate (Equation 4.) equivalent liquid permeability from gas permeability which is measured under low mean flowing pressure of fluid.

$$\kappa_{liq} = \frac{\kappa_g}{(1+{}^{b}/_{\rho})} \tag{4}$$

In Equation 4: b is a constant for a particular gas in a measured medium and ρ is the mean flowing pressure.

The constant b depends both, the measured medium and the gas which is used to measuring. Usually it has to be determined individually for each combination of measured medium and the gas by doing several tests at different flowing pressures and extrapolating these to infinite pressure. There is also some generalized iterative equations which can be used to solve the constant b but usually those are not used. [7, 10]

4 Permeability test rig

Permeability test rig is equipment which is used to define a permeability of a material. Most of permeability test rigs are based on same arrangement of test setup (see chapter 3.3.1 – Test setup for define the permeability). Materials and parts of permeability test rigs are varying a lot depending on measured material. Biggest affects to structure of permeability test rig comes from a fluid which is used to measure the permeability and also from pressure of the fluid.

4.1 Design

Before this thesis, Kemira has made some inquiries about acquisition of a permeability test rig. These inquiries worked as basis for this thesis and the permeability test rig also was sized by using this information. Technical information for suitable type parts was found from these inquiries as well as air is the fluid that the permeability test rig uses to define the permeability.

First step in design was to plan a flow sheet and find suitable components to the test rig. Main components in permeability test rig are a fan (or a pump/compressor) to move the fluid which is used to measure the permeability, a flow meter for the fluid and pressure difference measurement. Pressure difference measurement can be a single pressure difference transmitter or done from two pressure transmitters. More about these parts in chapter “4.2 – Components”. Flow sheet (Figure 4) was designed to basis of inquiries and information which addressed in chapter “3.3 - Testing the permeability in a laboratory environment”. As a suction of the fan may be quite high the fan is supplied with a under pressure relief valve for safety reasons.

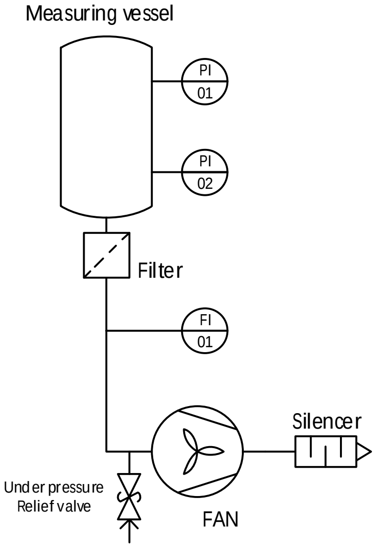

Figure 4. Flow sheet of permeability test rig

After the selection of main components of permeability test rig the next step was to design the measuring vessel. Measuring vessel is a part of permeability test rig where a sample of measured material is during test. Basis to design the measuring vessel was the information which got from the inquiries. Based to that information the measuring vessel was designed so that its diameter is around 80 mm, length is around 200-300 mm and pressure sensors are 150 mm from each other. Then the volume of the measuring vessel is enough that it is possible to measure representative amount of the sample.

Measuring vessel was decided to make from a clear PVC pipe as it allows following of behavior of measured sample during tests. Inner diameter of pipe which used to the measuring vessel is 81.4 mm and length is 260 mm. Volume of the measuring vessel of this permeability test rig is 1.353 dm3 which means approximately 3 kg of iron granulates. This is also most usual sample batch size which is made with granulator of Kemira's laboratory. As the 3 kg is quite big amount of sample to handle in laboratory environment, wish from Kemira's laboratory personnel was that the measuring vessel should be easy to remove from the test rig. For this reason PVC pipe connector was included to bottom of the measuring vessel. Between this connector and the pipe a net was also assembled (Figure 5 and 6) which keeps the sample in the measuring vessel and doesn't allow it go into the fan. To counter piece of this connector was included place for a filter that also the smallest particles of sample is possible to keep away from the fan.

Figure 5. Measuring vessel

Figure 6. Filter and bottom of the measuring vessel

The permeability test rig was designed to build so that working with the measuring vessel is allowed different directions and values of measurements and controls of fan are easily visible and used. Wheels also were included to the test rig to make the equipment easy to move.

Figure 7. Permeability test rig

4.2 Components

4.2.1 Fan

Movement of air was decided to handle with a lateral channel blower-exhauster. Reasons for choosing that type of fan were its smooth air flow (no pulsation) and low maintenance need. This type of fan also is silent and no lubrication is required so there is not risk for that the air would be messed with lubricant.

Working principle in a lateral channel blower-exhauster (Figure 8) is based to an impeller with radial blades which draw air from inlet port and force it forward into outlet port. Pressure and flow yield is based on both the impeller/blades design and housing configuration and relationship to the impeller. Lateral channel blower-exhauster is possible to use pressure as well to vacuum yield. [14]

To control the fan, the fan was chosen with motor that is suitable for use with frequency converter. With frequency converter the speed of fan is easy to control.

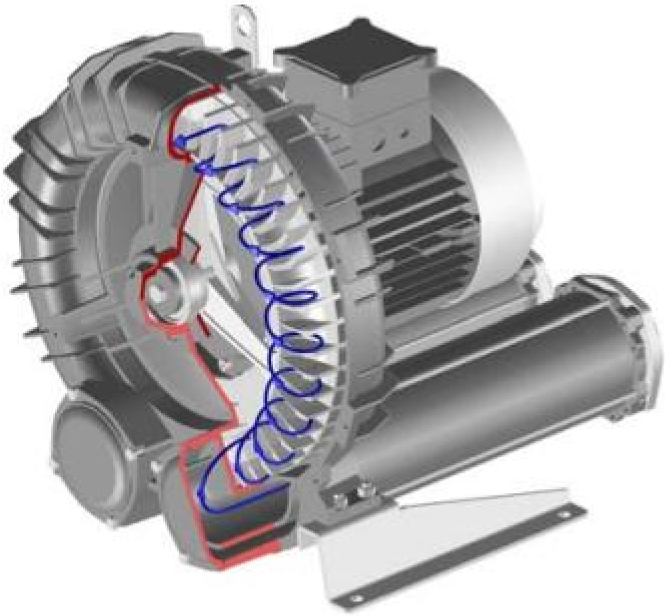

Figure 8. Lateral channel blower-exhauster. Fan of the permeability test rig.

4.2.2 Pressure difference measurement

Pressure difference measurement was decided to carry out with two pressure sensors. Working principle of selected sensors is based to piezo resistive measurement. In piezo resistive measurement, the resistance of piezo resistive component changes as function of mechanical stress which influences to it. Pressure sensors are built so that the measured pressure causes the mechanical stress to piezo resistive component and the sensors calculate the pressure from resistance of piezo resistive component.

Pressure information from the sensors is provided as a current signal. Permeability test rig have displays for both sensors which represent the current signal as the real value of pressure.

Figure 9. Pressure sensors.

4.2.3 Flow measurement

Measurement of air flow in the permeability test rig was decided to handle with calorimetric air flow sensor. Reasons for that were its reliability and low maintenance need with reasonable price and easy to set up. A downside of this sensor type is speed of response to flow changes which was noticed during tests of the permeability test rig.

Principle of calorimetric flow measurement is based to ability to measure velocity of flow as function of heat energy dispersion. Typical set up includes two thermistor placed in the tip of probe or wall of the sensor. One of the thermistors is used as reference thermistor which measures the temperature of flowing medium. The other thermistor is heated with a specific power and a differential resistance (temperature) of these two thermistors is measured. Flow influences to the differential resistance by cooling down the heated thermistor. The velocity of flow is calculated from the degree of change. [13]

Air flow information from the sensor is provided as a current signal. Permeability test rig have display for the sensor which represent the current signal as the real value of air flow.

Figure 10. Air flow sensor from inside and outside.

4.3 Operating

Operating of the permeability test rig is very easy and it includes only two controllable parameters; start/stop for fan and speed of it. Measuring vessel inner diameter is big enough that filling it with a sample is possible easily. Also removing of sample is made as easy as possible. The measuring vessel can be removed totally from the test rig with sample which allows that sample can be moved to next equipment in the measuring vessel. Basic operating includes next steps:

1. Adjusting the speed of fan. Adjusting the speed is made without sample. The fan is switched on and the speed of the fan is modified to wanted value. Value of speed is possible to see accurately as rotation frequency from the frequency converter which controls the fan. After the speed has modified to right level the fan is switched off.
2. Measuring. Sample is loaded to the measuring vessel so that the measuring vessel is full of sample. Then the fan is switched on and measuring is started. Measurements are recorded as wanted (e.g. after 1 and 2 minutes of measuring). After measuring is done the fan is switched off.
3. Removing of the sample. To remove the sample from the measuring vessel the pipe connector is loosened and pressure sensors are unplugged from the cable connector. Then the measuring vessel is uninstalled from the measuring vessel and it is easy to empty to wanted place. After the measuring vessel is emptied it can be cleaned if needed and installed back to the permeability test rig for new measurement.

Figure 11. Controls & measurement values

Figure 12. Connectors of the measurement vessel and pressure sensors

4.3.1 Results

Because the permeability test rig presents only flow and pressure values during the measurement, the value of permeability has to calculate afterwards. In this application permeability is wanted as JPU (Equation 3) and to calculate it easily, the values are fed excel –template (Appendix 3) which has made for this purpose. Value of flow is fed as m/s and pressure values as mbar. The template converts flow to m/min and pressures to mmH_2O. The template also calculates the pressure difference from pressure values.

In the template the equation is made simpler by reducing area of pipe from the equation (Equation 5).

$$JPU = v_{air} * (\frac{L}{\Delta\rho})^{0.6} \tag{5}$$

In Equation 5 units are: v_{air} = m/min, L = mm and $\Delta\rho = mmH_2O$.

4.4 Maintenance

Permeability test rig is designed so that need of maintenance is as low as possible. Maintenance for the test rig is basically only cleaning. Cleanable parts in permeability test rig are the measuring vessel, filter and silencer. The measuring vessel and filter is inspected after every measurement and cleaned if needed. The silencer doesn't need cleaning normally but if the samples include a lot of fine particles it is good to check at time to time. If the silencer appears to be contaminated, it can be removed with a tool and purged with pressurized air.

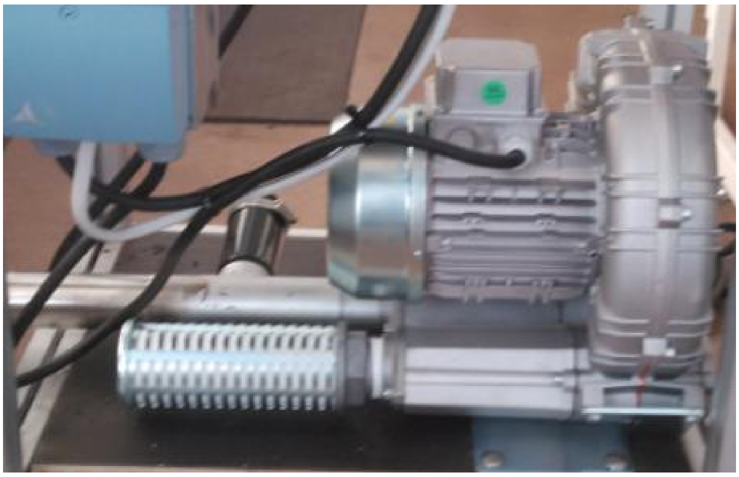

Figure 13. Silencer and fan.

5 Testing

Testing of the permeability test rig was carried out in Kemira's O&M laboratory with granulated iron (Figure 14). Tests were done so that a sample loaded to the measuring vessel and measurement was started by switching the fan on. At the same time a timer was started and values of measurements were recorded after 1 and 2 minute from begin of test. The results were calculated so that permeability was calculated for both times and the final result calculated as average of these.

Reason for recording the values of measurement at two different times, was that the flow measurement doesn't react fast at flow changes. After granulating the granulated iron includes moisture which is keeping part of granulates as one piece. During the measurement granulates are drying which may cause that some of granulates breaks down during the measurement. This causes that the permeability of sample is changing a bit during the measurement. Slow react of flow measurement together with the nature of sample are causing a problem that it may be difficult say which is exactly right time to take the measurements and calculate permeability value.

Figure 14. Granulated iron in the measuring vessel of the permeability test rig

In the first test series (results in Table 1 and Figure 15), iron was granulated in different batches and every batch, excluding the reference batches, was treated with different binders. Measurements were done immediately after each batch was granulated that granulated iron didn't have time to dry and that each batch was handled as similar as possible.

Test binder	Speed (Hz)	Permeability (JPU)	End moisture	Particle size distribution					
				d50	d10	d90	>10mm (%)	2-8mm (%)	<2mm (%)
Ref	14,98	117,13	9,64	7,02	1,05	11,84	24,00	46,60	11,90
Binder A	14,98	127,36	9,54	6,48	0,79	11,65	22,70	47,90	13,80
Ref	22,37	115,87	9,41	5,99	0,45	10,95	17,80	51,00	16,40
Binder A	22,37	128,37	9,45	6,10	0,42	11,01	18,20	48,50	17,40
Binder B	22,37	142,96	9,39	6,50	0,45	11,82	23,80	46,50	15,70
Binder C	22,37	96,40	9,54	5,15	0,34	10,84	17,00	46,90	23,40
Binder D	22,37	135,70	9,50	5,62	0,24	10,81	16,80	40,30	27,80
Ref	23,01	141,33	9,10	5,35	0,36	10,25	12,70	56,70	16,50
Binder A	23,01	132,19	9,13	5,41	0,39	10,02	10,20	58,40	18,50
Binder B	23,01	141,51	9,10	5,58	0,96	10,53	14,50	58,60	13,90
Binder C	23,01	108,96	9,06	4,59	0,36	100,91	17,50	47,60	25,80
Binder D	23,01	125,93	9,10	5,63	0,59	10,68	15,80	56,10	14,30

Table 1. Test results of the first test series.

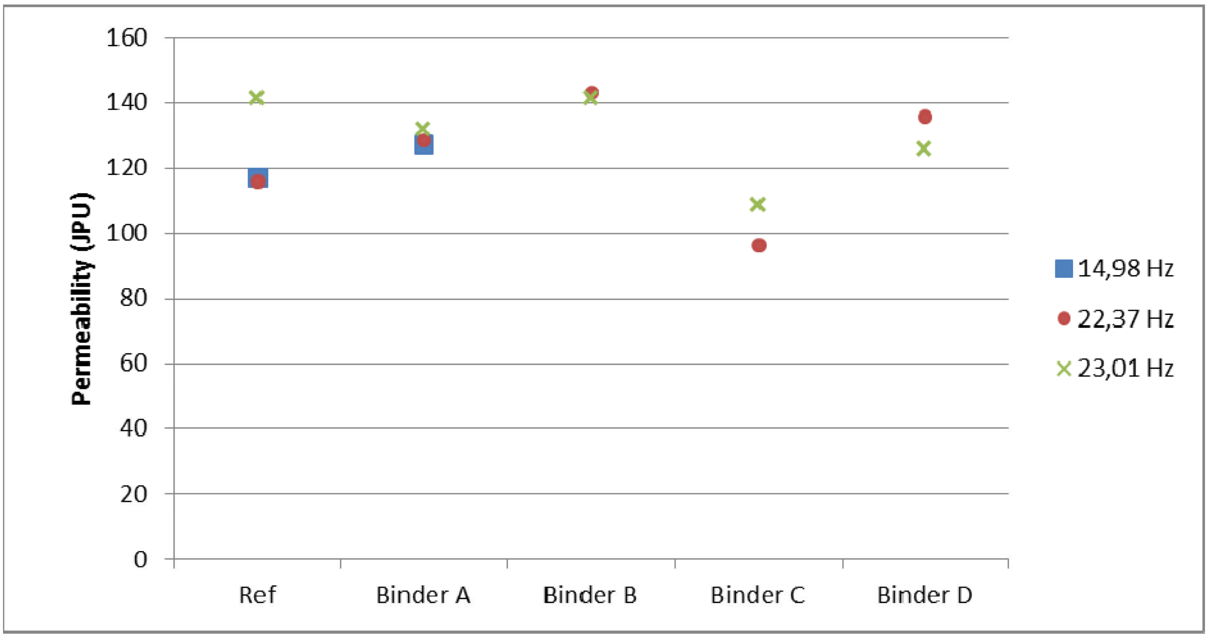

Figure 15. Test results of the first test series. Permeabilities as function of binders.

Second test series was a reiteration test (results in Figure 16). In the reiteration test the same sample was measured 6 times consecutively. The test was carried out at two times with a bit different fan speed. The sample was similar kind reference sample than in the first test series. The test with one speed was carried out consecutive so that the sample was taken away and was put immediately back to the measuring cylinder between measurements. Both measurement series were carried out with same reference batch of granulated iron but so that there was time between the series. Time between series caused that the series are not comparable with each other because the moisture of the sample was different.

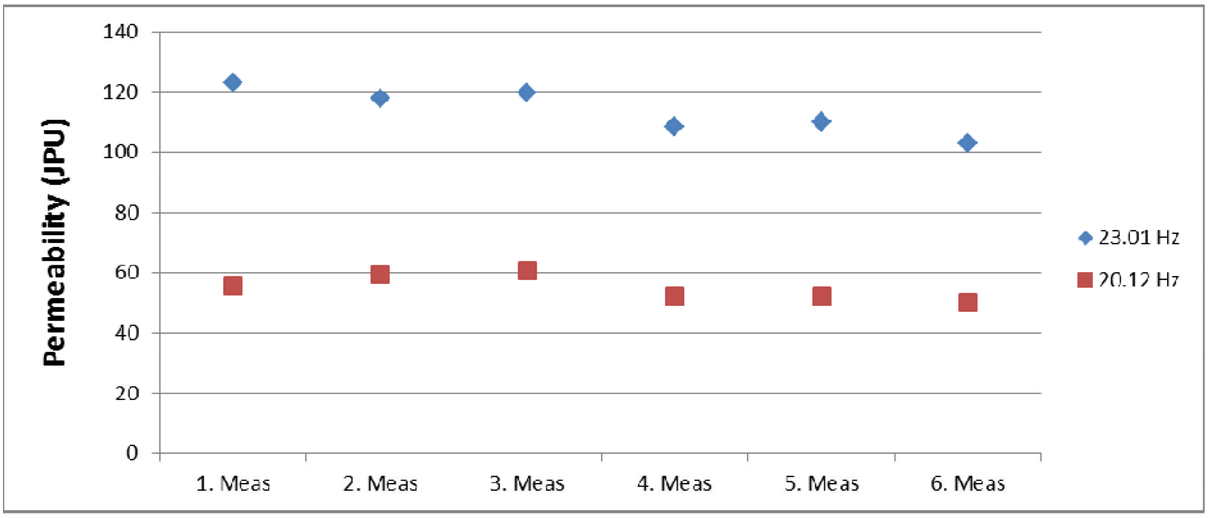

Figure 16. Reiteration test results.

6 Conclusions and summary

The results of the tests were promising. The results of the first test series were quite much as expected. Permeability in the samples which were treated with binder was higher excluding the samples which were treated with Binder C. The worse results with Binder C are still explainable with properties of Binder C. Dispersion between the samples measured with different speeds were relatively small. Remarkable was a small dispersion in the samples that was treated with Binder A and the reference samples even these were also measured with speed 14.98 Hz.

In the reiteration test, repeatability was relatively good even though the used sample was the same in every test and was allowed to dry. Results slightly reduced during measurements at the speed of 23.01 Hz, which is consistent with the nature of the sample. When measurements were made at the speed of 20.12 Hz, the sample was dried so much already that the moisture of the sample stayed more constant than in measurements at the speed of 23.01 Hz. In this test, the nature of sample manifested itself quite well as the base level of permeability dropped quite much between the measurements at different speeds because the sample had time to dry.

Overall, the permeability test rig worked as designed excluding some subjects which might need improvement. The most improved subject would be the air flow meter because the current flow meter reacts slowly to changes in the flow velocity. Flow meter that would react faster would give more information about the behavior of the sample during measurements. Exact permeability value would be also easier to define if the behavior of sample varies a lot between different samples.

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APPENDIX REMOVED DUE TO COMPANY REQUEST

Appendix 2

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