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# Wet Treatment of Construction Waste with Focus on Chamber Filter Press

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# Nassaufbereitung von Baurestmassen mit Fokus auf die Kammerfilterpresse

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**ABSTRACT**

The wet treatment of construction waste is often used in Austria in combination with a chamber filter press. It is examined how this process could be further developed in order to have better and more valuable output material and to decrease the amount of needed water. The economic situation is examined to see if a further investment in construction waste recycle is valuable.

The market of construction waste is growing especially in China. In this region also a lot of new patents concerning the wet treatment are issued. The evaluation of the process shows that high pressure is preferred and that also the filter cloth has an influence on the result. Concerning the needed amount of water a laboratory chamber filter press is fabricated.

For the laboratory work a limestone suspension is used and different operating modes are performed: constant pressure, constant filtration rate and constant filling rate. Then the resistance of the filter cloth and cake are calculated and compared. Furthermore, the solid content in the filtrate is analyzed.

The tests show that the mode of operation has no influence on the final result in terms of cake dryness and solid content in filtrate. But the type of filter medium is decisive it has a big influence on the filtrate quality. It is recommended to use a filter medium that is specially designed for chamber filter presses. Another crucial factor is the pressure difference. Generally speaking, the results are better (higher cake dryness and faster cycles, for instance, higher throughput) if the pressure difference is high. It is recognized that there are still solid particles in the range of up to 15 g/l in the filtrate. That is the reason why another cleaning step might be needed before reusing the water.

**ZUSAMMENFASSUNG**

Der Prozess der Nassaufbereitung von Baurestmassen wird in Österreich oft in Kombination mit einer Kammerfilterpresse betrieben. Es wurde untersucht, inwieweit es einer Verbesserung bedarf, um ein besseres und wertvolleres Endmaterial zu erhalten, sowie den Wasserbedarf zu senken. Die wirtschaftliche Situation wird ebenfalls untersucht, um zu zeigen, ob sich ein weiteres Investment in diesem Sektor lohnt.

Der Markt von Baurestmassen wächst und hier im Speziellen in China. In dieser Region werden auch viele Patente betreffend der Nassaufbereitung eingereicht. Die Untersuchung des Prozesses hat gezeigt, dass hohe Drücke bevorzugt werden und dass auch die Wahl des Filtertuches einen Einfluss auf das Ergebnis hat. Betreffend den Wasserbedarf wurde eine Laborkammerfilterpresse konstruiert.

Für die Laborarbeiten wird eine Kalkmischung verwendet und es werden verschiedene Betriebsweisen durchgeführt: konstanter Druck, konstante Filtratmenge und konstante Befüllung. Danach werden der Filtertuch-, sowie der Filterkuchenwiderstand berechnet und verglichen. Des Weiteren wird der Feststoffanteil im Filtrat analysiert.

Die Versuche ergeben, dass der Betriebsmodus keinen Einfluss auf das Endergebnis in Bezug auf den Trockengehalt des Kuchens und den Feststoffgehalt im Filtrat, hat, sehr wohl aber die Wahl des Filtertuchs. Es empfiehlt sich, ein Filtertuch zu verwenden, welches eigens für Kammerfilterpressen konstruiert wurde. Ein weiterer entscheidender Parameter ist der Differenzdruck. Hier gilt generell, dass die Kammerfilterpresse bei höheren Drücken bessere (höherer Trockengehalt des Kuchens und schnellere Zyklen, zum Beispiel, höherer Durchsatz) Ergebnisse liefert. Es zeigt sich weiter, dass im Filtrat noch Feststoff in der Größenordnung bis zu 15 g/l zu finden ist, weshalb ein weiterer Behandlungsschritt des Filtrats vor der Wiederverwendung nötig ist.

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# 1. Industry overview of filter press

The importance of the reuse of construction waste grows. The reasons therefore are that the environmental awareness gets more and more important and that the amount of construction waste is increasing as well. Another factor is that the raw products become more expensive. Therefore, it is important to develop a process that makes the reuse economical and technical meaningful. A possibility is the wet treatment with a chamber filter press. This technology is often used in Austria but as the wet treatment uses large amounts of water it is not suitable for all regions worldwide.

To gain knowledge about the choice of the filter medium laboratory tests are done with a specially designed chamber filter press. Laboratory tests are carried out at different pressure differences and with a limestone slurry mimicking construction waste to see if the pressure difference has an influence on the filtration process. The obtained results are interpreted to see if the used technology is suitable for the treatment of construction waste.

For a better understanding some theoretical basics about the filtration process and the chamber filter press are presented at first. Afterwards some facts about construction waste are discussed in general. The focus lies on the legal regulation, the treatment, the amount and the composition of construction waste. In the following chapter the market situation of building materials is examined. In the last part of the work the laboratory tests are described and the results are presented and discussed. From the discussion an outlook for further laboratory tests is derived.

## 1.1 Definition and mechanism of filtration process

The main functions of a filtration process are the removal of contaminants from a valuable or useful fluid and the recovery of one or more valuable phases from a mixture of phases. Therefore, a standard filtration process involves the following steps: Sedimentation to remove all the water from the initial mixture is followed by accelerated sedimentation. During this step the degree and the rate of separation is

increased with the help of hydrocyclones and centrifuges. Then a filtration is performed, followed by a thermal evaporation that can be done by a fluidized-bed dryer [1]. Parameter that influence the process of filtration are the pressure differential across the filtering plate and the temperature of the suspension [2].

During the filtration process some important mechanisms occur. Larger, denser particles may settle out within a filtration system and they may potentially accumulate because of sedimentation. If the particle is larger than the pore in the filter medium then it will be held back. This mechanism is called sieving. Inertial impaction occurs when the particle does not follow the streamline of the fluid, but continues on its existing path to intercept with the filter medium. Interception appears if the particle, following a streamline, comes into contact with the filter medium and is retained. Below a certain size the motion of a particle will be influenced by both the overall streamline of the fluid and also Brownian motion. If the surface charge of the particle is opposite to that of a fibre or pore in the filter medium the particle's path is diverted onto the medium where it remains. Generally it can be said that the pore size of the medium does not necessarily correlate directly with the minimum size of the particles that will be captured. But it may indicate the likelihood of a particle for being captured. Of course, the largest pore size of the medium is a distinctive measure of the maximum size of particle that can pass [1].

### *1.1.1 Filtration parameters*

Flow through the filter will depend upon the nature of the suspended solids and their concentration, the liquid viscosity, the pressure difference available and a number of other variables [3]. The actual flow rate through the filter medium will normally be measured in a test rig. Then the filter can be sized from the calculation of required area:

$$A = \frac{\dot{V}}{\bar{F}} \tag{1.1}$$

An acceptable cake thickness must be determined by test. Acceptable means in that case that the filter cake is thick enough that it can be scrubbed from the filter cloth but

it should not be thicker than the chamber depth. The required filtration area is found from:

$$A = \frac{V_c}{d_{max}} \tag{1.2}$$

The larger of these two measures of filtration area is then the one to be used [3]. An important parameter of every filtration process is the cycle time. The cycle time includes the filling, the filtration and the cleaning of the filter cloth. Factors effecting the cycle time of a typical filtration process are the type of sludge and sludge feed concentration. Generally it can be said that the higher the sludge feed concentration, the shorter the cycle time. An average cycle time for a typical metal hydroxide sludge would be in the range of one to three hours [4].

### *1.1.2 Filter medium*

There exist different filter medium designs. These are either a series of pores in a film, membrane or plate, or pores between yarns in a woven fabric. Other possibilities are a network of pores in a mass of fibres in a non-woven or spun mat or felt or a network of pores through a layer of loose material, like sand or gravel. There is also the possibility of a network of pores in a layer of sintered particles [1]. An important parameter for the classification of the filter medium is its flow resistance. This resistance should be as low as possible. If it is higher than the resistance of the filter cake another filter cloth ought to be used.

## 1.2 Classification of filter press

The filter press is a general-purpose technology that can be used in a huge number of applications. This wide variation in applications is reflected in the variety of designs, options and sizes available [1]. The targeted application decides upon the size and shape of the press, the applied pressure, the resistance of the membrane and the material characteristics of the feed slurry [5].

There are two different types of filter presses, which are mainly used in industrial processes: the frame and plate filter press and the chamber filter press. In this thesis, the chamber filter press is referred to only. The chamber filter press consists of a robust frame in which the filter plates are gathered. These plates are mostly quadratic and are held by a side bar or an overhead bar. The filter cloth, which should confine the solid in the chamber, is fixed on the filter plate. Between the two plates, there is space where the filter cake is formed. The whole assembly is confined by an end and a head plate, respectively. Perpendicular to the end plate a hydraulic cylinder is located, which is responsible for the pressing and thus tightening the plates against themselves. Through the head plate suspension inflow pipes are attached. During the filtration process all the filter elements are pressed together by hydraulic pressure. The suspension reaches the head plate either in the middle or on one of the edges. The formed filtrate is then derived through one of the many collecting channels. In order to remove the filter cake the plates have to be separated. This can be done automatically or manually [6]. There are two variations of the chamber filter press on the markets: the side bar and the overhead beam chamber filter press. The advantage of the latter is that access to the plates for cake discharge and cloth changing is easier [1].

### *1.2.1 Cake filtration*

To enable efficient dry cake removal of the solids and to ensure high recovery of water, pressure filtration may be the preferred technique over vacuum filtration or thickening [7]. During cake filtration the solid is held back by the filter medium and the continuous phase flows through the medium as filtrate. Thus a filter cake is formed. As the filter cake is growing gradually the filter cake depth increases and thus the flow resistance increases as well. That is why the liquid rate is reduced and the flow resistance and the pressure loss rise [6]. Because pores of the formed filter cake are smaller than the pore size of the filter media, very small particles can be separated. That is the reason why the purity of the filtrate rises when the cake is thicker. The relationship between filtrate volume rate, pressure difference and filtration area is shown in the formula of D'Arcy:

$$\dot{V} = \frac{\Delta p * A}{\eta * (R_K + R_T)} \tag{1.3}$$

The resistance of the filter medium is generally regarded to be constant and independent of all the other parameters. The resistance of the cake, however, has some dependency. It depends on the height of the cake which in turn relates to the porosity and the solid particle diameter. If this simple relationship holds, the resistance of the cake can be defined by a factor $\alpha_{H,}$ which is called resistance coefficient of the cake:

$$R_K = \alpha_H * H \tag{1.4}$$

With the help of the height of the cake the concentration ratio $\bar{c}$ from the cake volume to the filtrate volume can be calculated [6]:

$$\bar{c} = \frac{H * A}{V} \tag{1.5}$$

There are two different filtration operation modes: discontinuous and continuous. An example for the discontinuous filtration is a pressure filter where the suspension is conveyed by a pump against a fluid permeable filter media. While the fluid passes through the solid particles of the suspension a filter cake is formed. If the allocated space for the filter cake is full or the maximum pressure difference is reached, the filtration process is terminated. The cake is washed and dried. Then the pressure filter is cleaned and closed again in order to perform a new filtration cycle. An example for a continuous filtration is the vacuum drum filter, where the suspension is introduced constantly and also the filtrate and filter cake are removed at a constant rate. Generally it can be said, that the continuous filtration is perfectly suitable for the production of bulk goods with constant requirements. The discontinuous filtration is more flexible and can therefore be used if the single steps should be adapted to the production process [6].

### *1.2.2 Cyclones and hydrocyclones*

Cyclones work on the principle of inertial forces generated by the velocity of the incoming fluid stream as it enters tangentially and passes through a conical geometry

of the device. The rotational action of the fluid creates a centrifugal force, so that a multiple g-force is acting on the particles instead of the gravity settling rate given by Stokes' law [1]. Particles are separated from the fluid in the so-called centrifugal field. As the solid material is heavier than the fluid, it is enriched in the underflow. The fine material is running off at the overflow [6]. This function principle is shown in Figure 1.

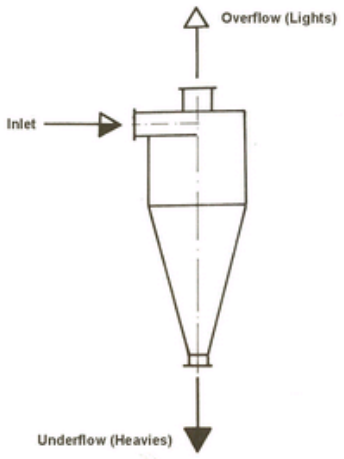


**Figure 1: Function principle of a hydrocyclone [8]**

The cyclone contains no moving parts and may be dry or wet in operation [1]. The rotational flow is just caused by the diversion of the liquid flow [6]. The feed suspension is introduced tangentially with a high velocity at the top of the unit of the hydrocyclone from where it descends in a helical path on the inside wall of the conical section. This generates a large centrifugal acceleration, causing particles to be thrown out of the suspension towards the wall, ultimately to be discharged from the bottom of the conical base of the unit. A hydrocyclone should be fabricated from materials that resist both abrasion and corrosion. For the operation a modest inlet pressure between 1 and 2 bar is needed to cope with the flow resistance [1].

## 1.3 Applications of filter presses

The market is very broad for filter presses. They were first used in the wine industry to press the grapes. Nowadays they are often used in the wastewater treatment to drain the sludge before it can be deposited [9]. Another common application field is the treatment of construction waste. Thereby stationary plants with the following

preparation steps are used: crushing, sieving, magnetic separator, wet treatment, eddy current separator and sensory assorting [10].

The wet treatment technology is often used in combination with a composter to treat construction waste. In Austria and Switzerland, this technology has been used for many years on an industrial scale [11], [12]. As contamination could be removed more effectively with this technology the recycled material has a higher density and also a better quality, which means that it can be sold more easily and to a higher price [13]. Another advantage is that the grain size is homogeneous as the material is sieved before and therefore further treatment is easier [14]. Some products can be treated with only a wet process as the dust formation would be too high to use a dry treatment technology. Another advantage of the wet process is that the quality of the end product does not really depend on the input material as it is always wet, no matter which moisture content the input material has. So it can be said that there is a higher equability [15]. But often the end product should be completely dry, and then this quality criterion cannot be used, as an additional drying step has to be applied. If the wet treatment technology is used, heighted sulphates and chlorides can be reduced, so that the remaining product can be used in a broader application field [16], [17]. Generally a wet beneficiation process allows a reduction of all soluble salts. Even more so if a specific washing stage is included. The main advantage, however, is that washable contaminants can be removed at the same time. The dust formation is low, as this technology uses water [13]. Nevertheless often dry technologies are preferred as the water management is too complex and also expensive [18], [19]. In some regions it is even forbidden to use water for this application, as water has to be saved [15].

In the field of landfill remediation, the so-called jig bed technology is used mainly. This technology has its origin in the ore, sand and gravel mining. It is also used in the floor washing to reduce contaminants and more and more in the recycling industry [20]. The wet processing produces satisfying assorting and preparation results; it is easily maintained and has low energy consumption in comparison to other treatment technologies [21].

In the iron ore beneficiation wet processing is found as well. There the following process is performed: First, a dry pre-crushing is done, followed by a wet assorting, which combines magnetic separation and sensor technology for bigger grain sizes. Such plants can be found in the USA, in India, in Finland and in Belgium. This method can be used for all kinds of suspensions and valuable split grain can be produced [22].

### *1.3.1 Some problems with filter presses in industrial use*

Although the filter press has been used for a long time in a lot of different fields of application there are still some problems. Some of these problems and their solutions are presented below.

- Filter cake that adhere strongly to the filter cloth may not be removed automatically through their own weight as the filter chambers are opened. So the cake has to be scraped off manually from the filter cloth. If the cake sticks to the cloth, there is no discharge and the next cycle may result in leaks and the plates may be distorted when closing the plate pack. This problem has been solved with the use of better filter clothes that are produced nowadays. There are also cake scrapers and cloth-washing systems available to remove the cake.
- Some slurries have very poor filtering properties and flow is drastically reduced already after formation of a rather thin filter cake. Therefore the chamber depth ought to be very narrow. This could be a limit for filter press applicability.
- To cope with high throughputs economically the size of filter plates, number of filter plates per machine and number of machines are increased.
- If the filter cycle is a bit too short, sloppy cakes with wet centres may result. Advanced electronics allow for a fairly accurate interplay between time, pressure, backpressure and filtrate clarity. So the risk of sloppy cakes is reduced.
- Opening and closing the filter press is time consuming. Nowadays most of the filter presses have automatic plate moving systems to save time and labour [23].

### *1.3.2 Advantages of filter presses*

According to other equipments the filter press offers several operating and maintenance advantages. The most important ones are listed below.

- They are simple to operate and maintain as they have very few moving parts and the filter elements and media are easily accessible.
- Thorough cake washing or extraction can be accomplished very simply. There is no danger of cake sloughing during emptying the process fluid and refilling it with wash liquor.
- The filter cake can be discharged wet or dry, as desired.
- Cake may be either blown dry with air or a cake consolidation cycle can be run for maximum cake dryness.
- There are no exotic materials of construction. In most standard filter presses the plates are made out of polypropylene and most of the other parts are made out of steel.
- The entire operation can be fully automated.
- Filter presses are very cost competitive compared to tank type pressure leafs, pressure tubes and vacuum filters [4].

## 1.4 Industry flow sheet of a wet treatment including a filter press

The most common wet treatment process is based on an attrition, which is supplemented by a separation step often based on gravity. Mostly this separation is done with a so-called sorting hose, but can be extended by other separation techniques that separate solids [24]. In the sorting hose the fine material is gathered in the upper part of the hose whereas the coarse material is settling on the bottom. The pulping and density sorting is done with a vibrating hose and a grinding medium. The separation happens in the hose as layers are formed. The less dense material is filled into a funnel, from where it can be washed out. In order to have a good uplift force also coarse material as for example sand is used. The less dense material can be washed out more easily. During this process wastewater is produced that shall be subject of treatment with the aim to reuse it in the process. With this wet treatment

process up to 100 t/h can be treated. As input material bulk material with a grain size up to 32 mm can be used [24].

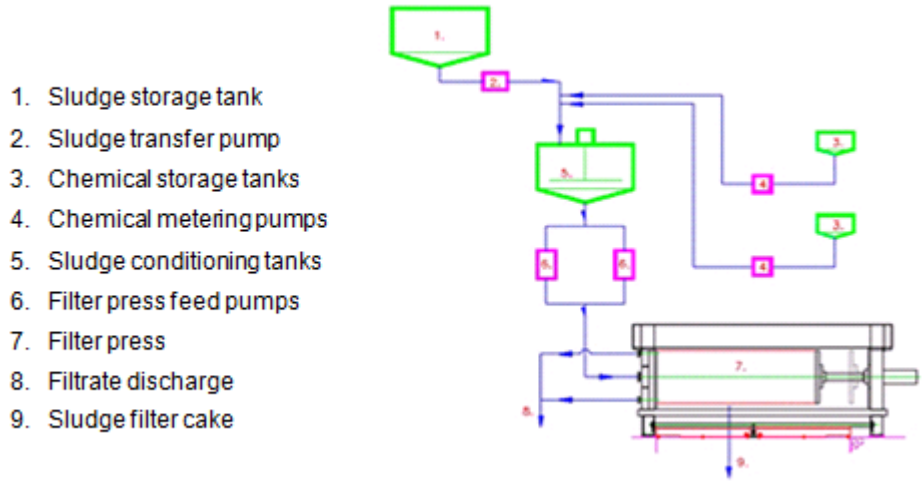


**Figure 2: Basic sludge flow line diagram [4]**

Figure 2 shows a typical line flow diagram. The typical filter press dewatering system includes the filter press, sludge feed pumps as well as sludge storage and sludge conditioning tanks with slow speed mixers, sludge transfer pumps, chemical feed, storage equipment, necessary piping, valves, and controls. There are two types of filter press systems available. One works with high pressure, 16 bar, and the other with low pressure of 8 bar. Mostly the low pressure filter press is used. But for more difficult applications like biological water activated sludge, aluminium sludge or where maximum cake dryness is required, high-pressure filter presses are generally utilized [4]. In the shown process the sludge is gathered in a sludge storage tank (1). Then the suspension is pumped with a sludge transfer pump (2) into the sludge conditioning tanks (5). Some chemicals are added from the chemical storage tanks (3) with the help of chemical metering pumps (4). From the sludge conditioning tank the suspension is pumped into the filter press (7) with filter press feed pumps (6). In the filter press the sludge is discharged (8) and the filter cake is formed (9).

At the beginning of the filter press dewatering cycle, the filtrate flow can be as much as 40,000 to 80,000 litres per hour. This part of the cycle is often referred to as “fast fill”. During this period the cake chambers of the filter press collect the major amount of sludge solids. As the chambers become progressively more filled with sludge solids, the pressure inside the filter press plate pack rises and the filtrate flow

decreases rapidly. Towards the end of the cycle, the filtrate flow gradually drops to virtually zero. This portion of the cycle is referred to as the cake consolidation step. During the cake consolidation step, more sludge solids are being forced under pressure into the cake chambers, which in turn displaces more water from the loosely formed sludge cake. This enables the filter press to produce more compact and drier sludge cakes than other methods of dewatering [4].

### *1.4.1 Sludge conditioning*

Effective sludge conditioning or pre-treatment relates to the raw sludge. The aim is to effectively reduce viscosity, reduce flow resistance during subsequently formed filter cake, increase filtration rates or foster solid particle aggregates in the sludge feed. These changes can be made chemically or physically. Chemically conditioning involves coagulation and flocculation of the sludge fine particles to produce a filterable structure. The physical means of conditioning sludge include processes such as heat treating and freezing [4].

### *1.4.2 Feed pumps for filter presses*

A proper pumping system which does not impart excess shear or deteriorate the sludge particles or the chemically formed floc is very important in the design of a filter press dewatering system. The four most common types of pumps are ram or piston pumps, double diaphragm pumps, piston membrane pumps and progressive cavity pumps [4].

### *1.4.3 Handling dewatered filter cakes*

Normally the filter press allows the cake to fall out freely. Then the cake can be handled in different ways for disposal to landfill, incineration drying or used as a final product. It can either be discharged into trucks or into dumper boxes or into conveyors. The last one is mostly used in bigger plants where a large quantity of filter cake occurs [4].

## 1.5 Industry news analysis of filter press

### *1.5.1 Global news*

Most of the news is about market reports which are done by different companies about the perspectives of the filter press market. Yahoo Finance says that the global dewatering equipment market is valued at USD 3,99 billion and that it will grow further. They also say that the belt filter press is the fastest-growing technology type and the second-largest segment in the global sludge dewatering equipment market. In this perspective the Austrian company Andritz AG is mentioned as one of the major players. Other important players are Alfa Laval from Sweden and Veolia Water Technologies from France [25]. WhaTEch Agency also provides a report about the global filter press market and gives company profiles about many firms, amongst others Andritz AG [26]. Global Market Insights sees a significant growth in the European sludge dewatering equipment market. France, UK and Germany are market leads. For North America, a modest growth is predicted [27]. The Diesel Magazine talks about the usage of filter presses in the US biodiesel market [28].

### *1.5.2 Patent analysis*

The patent analysis was done with the tool “Techmeter” [29]. Techmeter develops and uses data mining and scouting-algorithms to recognize future technologies from dynamic patent networks early. The specialities of Techmeter are data mining algorithms that recognize changes in the network topology from technology networks very early. The most promising future trends can so be identified. During the searching process the links are captured to selective, individual key technology fields. The patent analysis was carried out for the following keywords:

1) demolition waste processing (with 16 patents as outcome with most of them from the US and South Korea),
2) wet processing sand (117 patents as outcome with most from the area China and United Arab Emirates) and
3) wet processing filter press (24 patents as outcome with most of them from China and the United Arab Emirates).

The found patents are listed in appendix 1. The patents that are relevant for the wet treatment of construction waste are described in detail. Most patents come from Asia and here especially from China. The reasons, therefore, can either be the growing economy or that inventions are faster and easier patented in China than in Europe. Nevertheless the interest in recycling is growing also in China and so more and more new technologies and processes are invented. In 2012 a mobile combination treatment station for repeated use of demolition waste was, for example, patented in China. In 2014 a dry and wet processing combined device for recycling of construction waste was patented in China. A closer description of these patents can be found in appendix 1.

# 2. Construction waste

## 2.1 Definition and origin

Construction wastes are materials, which accumulate during construction, conversion and demolition works. The main part comes from the demolition, conversion and renovation sector. Only about 10% accumulate during new construction works. Construction wastes come from building engineering, civil engineering as well as from road and bridge constructions. In the building engineering sector mainly concrete, brick and other masonry waste accumulates. In the civil engineering sector, the main parts are excavation materials, but also wood, iron and concrete. Recycled building materials are mineral aggregates, which are suitable for further treatment and are handled in a recycling plant [30]. Excavated soil means all unbound material, which accumulates during excavation works. This material mainly originates from the civil engineering sector and adds the largest mass to the scales. The composition of excavated soil varies strongly as it is depending on the local geology and the building project. Both natural material and building material are seen as excavated material. Road construction waste accumulates during construction activities on traffic areas. The main producers are road construction and logistic construction. This material consist of mainly hydraulic bound matter, such as concrete, bituminous bound matter, such as asphalt and unbound matter such as bulk material. Building rubble is all mineral matter, which accumulates during demolition works. This material has a very heterogeneous composition. Construction site waste means all residues that accumulate during building, renovation and expansion works [31]. Bound matter is a mixture of aggregates, which is bound by a binding agent that can be either bitumen or a hydraulic binding with water which are termed either bituminous or hydraulic bound matter. Unbound matter is a mixture of aggregates without any binding agent [32].

## 2.2 Composition

Construction wastes accumulation mainly from the following material flows [30].

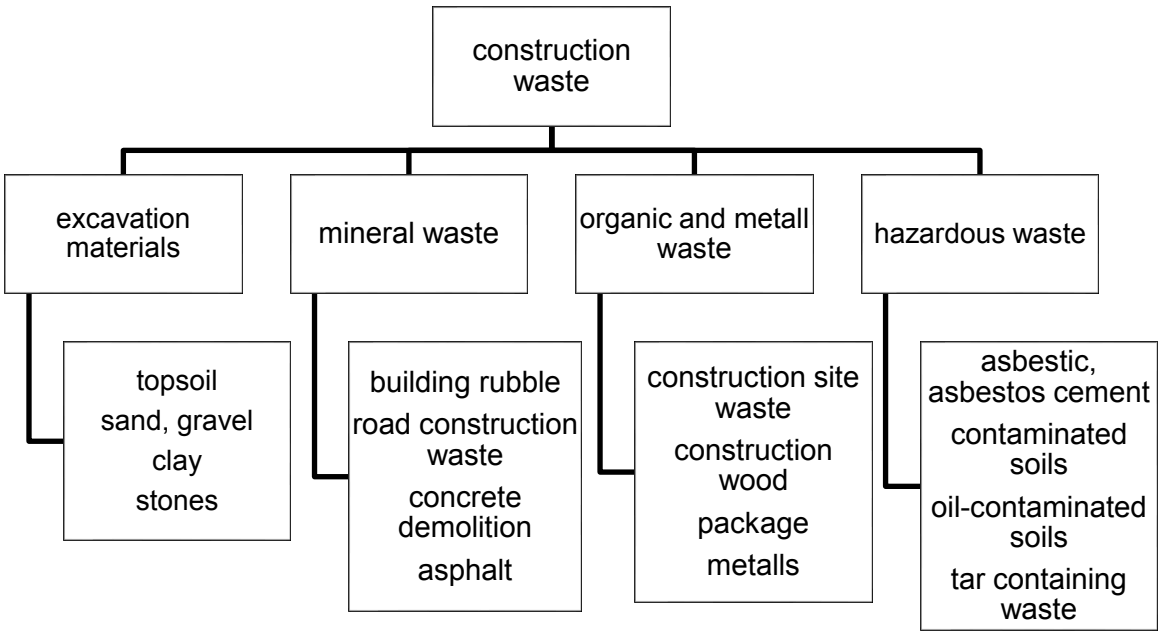


**Figure 3: Construction waste - material flows**

**Table 1: Construction waste – composition [30], [31]**

| Characterization according to OENORM S2100 (2005) | Composition |
|---|---|
| Building rubble | bricks, concrete, ceramic, stones, tile work, mortar, plaster |
| Road construction waste | asphalt concrete, base course materials |
| Concrete demolition | construction components or finished-parts made from concrete, concrete carriageway, screed |
| Asphalt | asphalt concrete |
| Construction site waste | insulating material, plasterboard, stones, plastic tubes, clippings from different building materials, composite material |

## 2.3 Amount

In Austria the amount of construction waste added up to 6.9 million tons for the year 2009 [30]. In 2015 the amount of construction waste grew by about 46% in comparison to 2009.[1] So it added up to 10 million tons. This high growing rate is due to a higher building activity and a better statistical recording [33]. As the amount depends on the extent of activities in the building industry, the numbers vary over the years and are difficult to predict. Table 2 shows the numbers from the years 2009, 2001 and 1995 [30].

**Table 2: Construction waste - amount**

| Characterization according to OENORM S2100 (2005) | Amount in tons (2009) | Amount in tons (2001) | Amount in tons (1995) |
|---|---|---|---|
| Building rubble | 3,200,000 | 3,300,000 | 2,650,000 |
| Road construction waste, asphalt | 1,300,000 | 1,500,000 | 1,830,000 |
| Concrete demolition | 1,700,000 | 200,000 | - |
| Construction site waste | 300,000 | 1,100,000 | 2,000,000 |
| Others | 370,000 | 1,400,000 | 1,000 |
| Total amount | 6,870,000 | 7,500,000 | 6,600,000 |

There is a constructional classification to see which material can be used for which construction project. Grad S material is frost-proof and frost-resistant and can be used as upper and lower unbound base courses in the field of road construction and where high resistance against attrition is needed. Grad I material is also frost- proof and frost-resistant and can also be used for upper and lower unbound base courses. Grade II material is frost-proof and frost-resistant and can be used as lower unbound base courses as well as for hydraulic bound base courses. These three grades have nearly the same properties but their application fields are different. Grad S material has the broadest application field whereas grad II material can just be used for lower base courses. Grad III and grad IV material can be used as hydraulic unbound base courses and as bulk material [32].

[1] 2009 was the first year after the global financial crisis triggered by the collapsing housing sector.

## 2.4 Treatment

The main part of the construction waste is treated. In 2009 about 5.5 million tons were treated. So only about 1.4 million tons were allocated to landfills [30]. In 2015 about 8.2 million tons were treated [33]. To guarantee an appropriate treatment, the separation of waste into the different waste fractions has to be done well. Impurities should also be removed. In Austria, there are enough treatment plants to treat 70% of the occurring construction waste though not all of the plants are in full operation, yet. This number of 70% is written down in the “Abfallrahmenrichtlinie (2008/98/EG)”, and it has to be fulfilled until 2020. As the trend in Figure 4 shows the amount of treated construction waste is growing continuously over the last years.

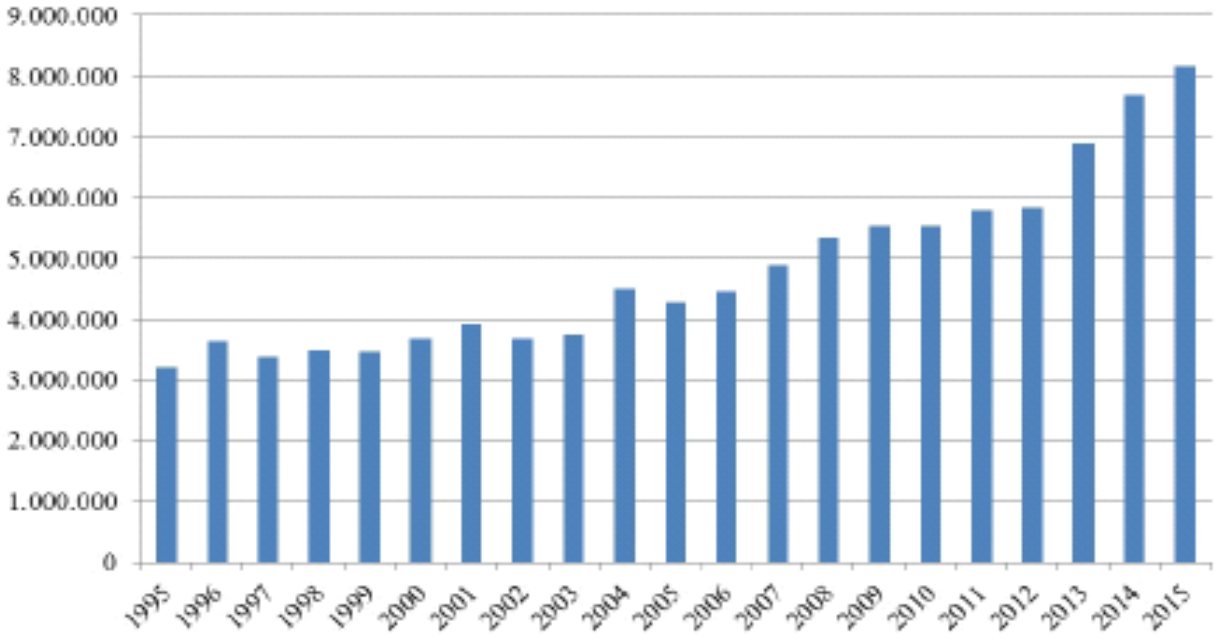


**Figure 4: Construction waste in treatment plants in tons [33]**

To get an output material, which can be used in an appropriate way, the input material has to have high quality. In order to reach this high quality a pollution sensing on the construction site is done, as well as a recovery - orientated removal. Then the construction waste has to be declared when arriving at the treatment plant. There a visual testing is performed in order to see if the material is contaminated or not. If any contamination, which cannot be eliminated, is found the whole material has to be rejected. Otherwise, the material can be recycled. The different fields of application depend on the recycling material’s quality class [30].

There are four different quality classes: A+, A, B and C. The licit parameters for the different quality classes are shown in Table 3. Matter from quality class A+ is recycled building material, which can be used in hydro-geological sensible or less sensible areas. They can be used bound or unbound without any cover material. Matter from quality class A is recycled building material, which can be used in bound form or in unbound form with cover material in hydro-geological sensible regions. In hydro-geological less sensible regions it can be used either bound or unbound without any cover material. Matter from quality class B is recycled building material, which can be used in hydro-geological less sensible areas either in bound or unbound form as well as in unbound form with a cover material. This material can also be used as aggregate in hydro-geological sensible areas. Matter from quality class C is recycled building material, which can be used for building purposes but some restrictions apply [32].

**Table 3: Quality classes**

TS..... dry substance

| | Unit | Quality class A+ | Quality class A | Quality class B | Quality class C |
|---|---|---|---|---|---|
| **pH-value** | - | 7.5 – 12.5 | 7.5 – 12.5 | 7.5 – 12.5 | 7.5 – 12.5 |
| **Electric conductivity** | mS/m | 150 | 150 | 150 | 250 |
| **Chromium** | mg/kg TS | 0.3 | 0.5 | 1 | 1.5 |
| **Copper** | mg/kg TS | 0.5 | 1 | 2 | 5 |
| **Ammonium** | mg/kg TS | 1 | 4 | 8 | 30 |
| **Nitrite** | mg/kg TS | 0.5 | 1 | 2 | 8 |
| **Sulphate** | mg/kg TS | 1500 | 2500 | 6000 | 6000 |
| **Hydrocarbon index** | mg/kg TS | 1 | 3 | 5 | 40 |
| **PAH** | mg/kg TS | 4 | 12 | 20 | 25 |

In order to safeguard a constant quality of the recycled material a quality assurance system is required. Such a system needs to cover the following tasks: company structure, management responsibilities, procedures, treatments and devices to

realise the quality objective, as well as guidelines for the input control, for the self- and external monitoring and for the mandatory recording.

## 2.5 Legal regulations

There are different legal regulations concerning construction waste in the USA and the EU, respectively. In the following part, the main regulations are discussed.

In the USA there are different regulations in each state, but in general it can be said that the most construction and demolition (C&D) wastes end up in either a municipal solid waste landfill or a landfill devoted exclusively to C&D wastes. Municipal solid waste landfills are subject to the Environmental Protection Agency's (EPA) landfill criteria, while state and local governments regulate most of the C&D landfills. EPA regulations do prohibit, however, hazardous wastes from being placed in a C&D landfill. EPA also regulates building materials that contain lead and asbestos [34]. C&D debris is not federally regulated, except to the extent that solid waste landfill must follow a few basic standards. States, therefore, have the primary role in defining and regulating the management of C&D debris. Many states exclude certain materials from the legal definition of C&D debris, using terms such as hazardous, unacceptable, potentially toxic or illegal. The generation, transport, treatment, storage and deposition of hazardous waste is regulated by the Resource Conservation and Recovery Act (RCRA). This act is a federal law that encourages environmentally sound methods from managing commercial and industrial waste as well as household and municipal waste [35]. The solid waste management has undergone a dramatic change throughout the US. It has become one of the largest budget factors for local governments. Landfills are reaching their capacity limits. The construction of new facilities for either recycling or disposal is enormously contentious [36].

The European Union has adopted the 7$^{th}$ Environmental Action Programme in 2013. In this programme, the strategic framework is written down for the EU's environmental policy until 2020. The programme consists mainly of already existing documents. There are three key objectives, which should be reached: The first objective is to protect, conserve and enhance the Union's natural capital. The second

one is to turn the Union into a resource-efficient, green, and competitive low-carbon economy. Moreover, the third one is to safeguard the Union's citizens from environment-related pressures and risks to health and well being [37]. In the second objective recycling of waste is an important part. It says that as much waste as possible should be recycled. This is also true for the construction waste.

However, concerning construction waste the main legislations are written down in the national law. In Austria these are OENORMs and RVS-legislations. In order to reach a consistent labelling and classification of recycled construction waste the Austrian "Baustoff-Recyling Verband" has gathered some policies, which have to be followed to be awarded by the "quality seal for recycled construction waste". Since January 1st 2016 the new "Recycling-Baustoffverordung" has come into effect. The main source is the OENORM B 3132, which regulates aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction. The act is legally binding for all construction and demolition works, for the production and usage of recycled construction waste and for the storage of waste. This act also says that a contaminant and impurity research has to be done before demolition works start and that found contaminants and impurities have to be removed [38].

Another source is the act of waste management 2002 that regulates all concerns about waste. There the definition of construction waste is found and which materials are legally accepted for recycling and which have to go to landfill. The "Verordnung über die Trennung von bei Bautätigkeiten anfallenden Materialien" says which materials have to be separated in order to allow recycling. As not all materials that occur during building activities can be recycled the „Verordnung über die Ablagerung von Abfällen" is an important legislation, too. There it is written which materials can go directly to landfill and which ones have to be treated before. It also tells which materials can go to a landfill that is located in a hydro-geological sensitive region [39].

## 2.6 Recycling

Some guidelines should be followed to guarantee a successful recycling process. Mainly materials made from low-emission raw materials and recycling materials

should be used. Furthermore, no additives containing hazardous substances should be added. In order to make the separation process less complex only similar materials should be used and ideally these materials are easily to be separated [31]. Nevertheless, a strict controlling, analysis and, treatment system is important to guarantee a high quality product [40]. The best materials that can be used are concrete, concrete stone, lime stone and sandstone. These materials are easy to recycle and available in large amounts, which makes the process less expensive. In general, polystyrene and mineral rock wool should be avoided as these materials have a negative influence on the building material's homogeneity [39].

# 3. European market size and growth rate of building materials 2010-2014

The European market is seen as the European Union with its current 28 member states plus Albania, Iceland, Macedonia, Montenegro, Norway, Serbia, Switzerland and Turkey, which are denoted as *"EU36".* As representative primary aggregates, sand and gravel as well as crushed rock are chosen.

As shown in Figure 5 the production of primary aggregates has grown from 2,500 billion tons in 2010 to a maximum value of 2,573 billion tons in 2011. The production minimum was reached in 2013 when 2,194 billion tons of primary aggregates were produced. Since then the production has slightly increased again to 2,216 billion tons in the year 2014. From 2010 until 2014 the production of primary aggregates has fallen by 11.50% [41].

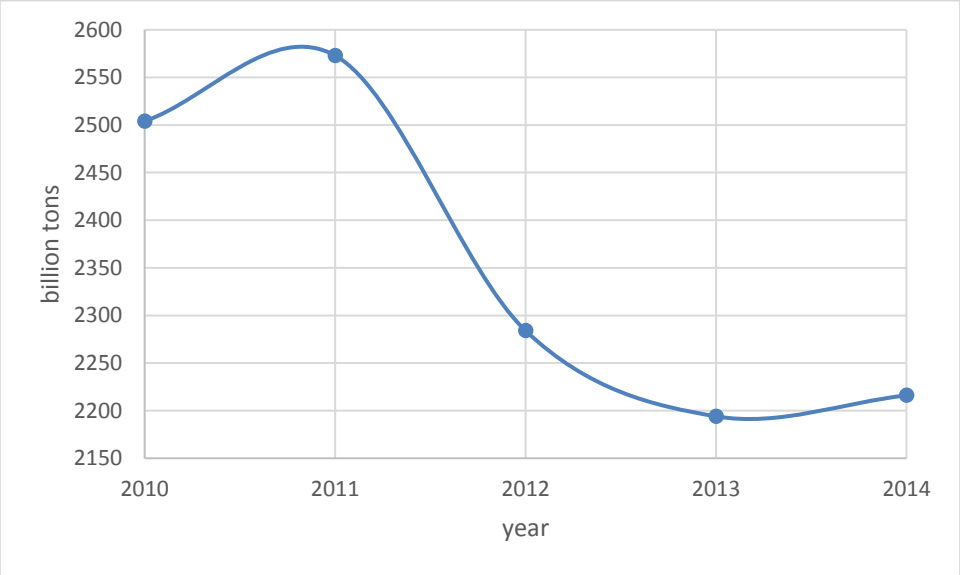


**Figure 5: EU36 production of aggregates 2010-2014**

Figure 6 shows a comparison of the exports and imports of primary aggregates from 2010 to 2014. It can be seen that in the years 2010 and 2011 the imports were higher than the exports. Afterwards the exports exceeded the imports but the whole sector lost on importance as the production declined, which is also shown in Figure 5. The exports and imports correlate very well with the production curve as the maximum lies in the year 2011 and the minimum value was reached in 2013. In this year

around 102 billion tons were exported and around 97 billion tons were imported. This numbers can be compared with the maximum values of 2011. Here 115 billion tons were exported and 116 billion tons were imported. From 2010 until 2014 the exports grew by 3.03% while the imports fell by 3.89% [41].

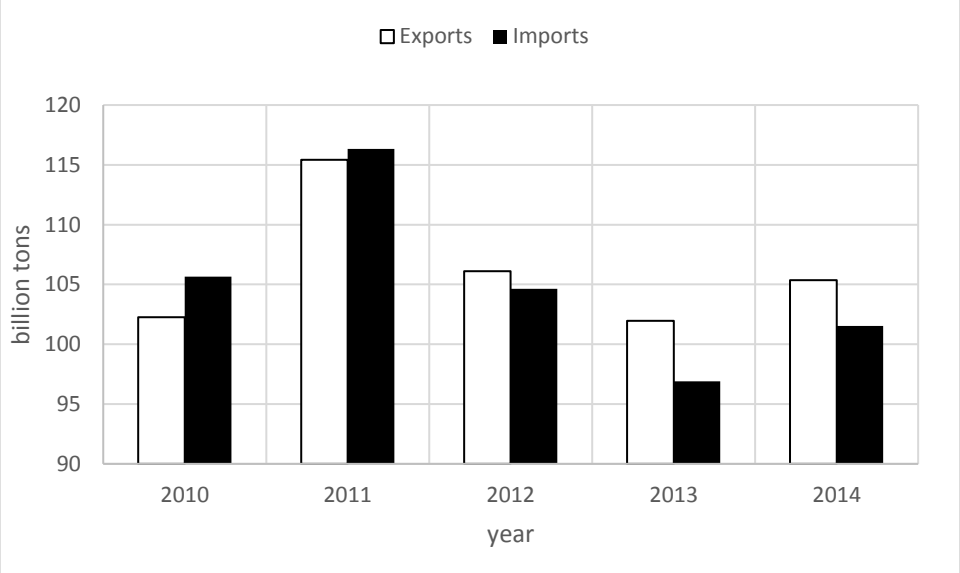


**Figure 6: EU36 exports & imports of aggregates 2010-2014**

Generally, it can be said that the primary aggregates market has already hit its lowest point and is growing again, especially the exports. In the year 2014 the difference between exports and imports was about 3.82 billion tons. It is predicted that this gap will stay constant in the near future. So it might be useful to invest into new technologies for this sector as especially the market for treatment technologies in Asia will grow a lot. In Europe the market will stay relatively stable.

# 4. Laboratory tests

Laboratory tests should show if construction waste can be treated with a chamber filter press. Therefore, tests are carried out at different pressure levels to see which pressure difference gives the best results. The type of filter medium is varied as well. It should be shown whether the specially designed filter cloth for chamber filter presses has a better performance than a filter cloth used for standard drum or disk filters. The filter cloth for chamber filter presses is referred to as *"special filter cloth"* and the one for the drum or disk filters as *"normal filter cloth"*. The mode of operation is differed to give pieces of advice how the filter press should be operated in an optimal way. From the results it should be derived whether further research in this field is needed. Moreover it should be checked whether another technology should be chosen for the treatment of construction waste.

## 4.1 Material

As no sample from a construction site is provided a limestone suspension is used to mimic construction waste. The limestone mix has a particle size of $x_{90}$ = 193.32 µm. That means that 90% of the sample has a particle size that is equal or smaller than 193.32 µm. The particle size analysis is carried out with the "HELOS (H2395) & RODOS R2+R5®". The measurement was carried out twice: once with a depression pressure of 1 bar and once with a depression pressure of 1.5 bar, with however little difference. Two or more analysis were combined to one curve, for example, with two different measurement ranges: coarse and fine, respectively. The data sheet of the analyses can be found in appendix 4.

## 4.2 Introduction to tests

In the following chapters the laboratory work is described and explained. First the experimental plan is shown to see which and how many measurements are planned. There is a distinction between pretests and main tests. In chapter 4.3 the used methods are described. There is also an explanation of the different operating modes that are applied. Afterwards the experimental setup is shown. In the subchapters

4.3.3 and 4.3.4 the experimental procedure is described to see how the tests are carried out. Again there is a distinction between the different operating modes.

In Table 4 the used test parameters are summarized. Filter area $A_{vacuum}$ means the size of the filter for the vacuum tests and filter area $A_{pressure}$ means the size of the filter used for the tests with overpressure.

**Table 4: Test parameters**

| | |
|---|---|
| **Filter area $A_{vacuum}$ [m²]** | $1.96*10^{-3}$ |
| **Filter area $A_{pressure}$ [m²]** | $6.36*10^{-3}$ |
| **Dynamic viscosity η [Pa*s]** | $1.00*10^{-2}$ |
| **Density ϱ [g/m³]** | $9.98*10^{2}$ |

### *4.2.1 Experimental plan*

The experimental plan consists of pretests and main tests. The pretests are carried out to test the equipment and analysis methods. The main tests are separated into different test series with different "*operating modes"*. In the first series the *constant pressure* is applied. The second test series uses a *constant filling rate* and in the third test series a *constant filtration rate* is set. In Table 5 the experimental plan is summarized to see which test condition belongs to the pretests and which to the main tests. This distinction between pretests and main tests is always the same throughout the whole work.

**Table 5: Experimental plan**

| | **Pretests** | **Main tests** |
|---|---|---|
| **Vacuum** | X | |
| **Overpressure without chamber filter press** | X | |
| **Overpressure with chamber filter press** | X | X |
| **Water only** | X | X |
| **Suspension** | X | X |

| | | |
|---|---|---|
| **Constant pressure** | X | X |
| **Constant filtrate rate** | | X |
| **constant filling rate** | | X |
| **With stirrer on** | X | X |
| **With stirrer off** | X | |

Pretests

For the first test series tab water and a filter cloth of the type 3B27-0150-229-V0-SEFAR TETEX DLW V-27-8001-SK045 are used. First the test is performed by -0.3 bar. This is referred to as *"vacuum".* Then the test is carried out at +0.3 bar. The tests with overpressure are performed with and without a stirrer. Since only pure water is used, it is believed that the stirrer has no influence on the result. Furthermore, the tests under vacuum and overpressure should provide the same outcome since the absolute pressure difference is the same. The set pressure stays constant during the whole experiment.

Each operating mode (vacuum, overpressure with and without stirrer) is tested several times to check the reproducibility of the results. Afterwards the experimental results are graphically presented and analyzed which involves the calculation of the filter cloth resistance.

In the next step a limestone suspension is used. For these tests the concentration is always kept at 50 g/l and 0.5 l suspension are used. Such a concentration results in a height of the filter cake as envisioned. These tests are carried out in the same way as the tests with tab water and overpressure. The stirrer is used with two different speed rates set at 600 and 300 rpm, respectively. The same analysis as before is performed.

A more detailed description of these pretests and the obtained results are included in [42].

Main tests

Based on the results from the pretests the number of test runs is determined. In general, the tests are repeated three times, only if there are very similar results to the

pretests there is just one test run, because than the uncertainty is already known. The suspension's concentration is set at 50 g/l.

## 4.3 Methods

### *4.3.1 Experimental setup – Pretests*

There are two different setups for the pretests: One for the pretests with vacuum and one for the pretests with overpressure. The setup for the pretests with vacuum is described in [43].

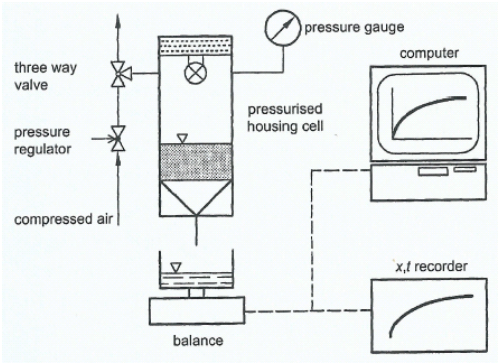


**Figure 7: Schematic experimental setup pretests for overpressure [44]**

The setup for the pretests with overpressure differs a little bit from that for the main tests. Figure 7 shows the schematic set-up for the pretests with overpressure. The main parts of the setup are the pressurized housing cell, the balance, the computer and the recorder. The housing cell is connected to a pressure gauge, where the pressure can be regulated. The suspension is filled into the housing cell via the three way valve. If the test is started the suspension passes the filter cloth, which is located in the lower part of the housing cell and drops into a vessel that stands on a scale. The scale is connected with the computer and the recorder to have a continuous measurement of the weight of the filtrate. A more detailed description of the used setup can be found in [42].

### *4.3.2 Experimental setup - Main tests*

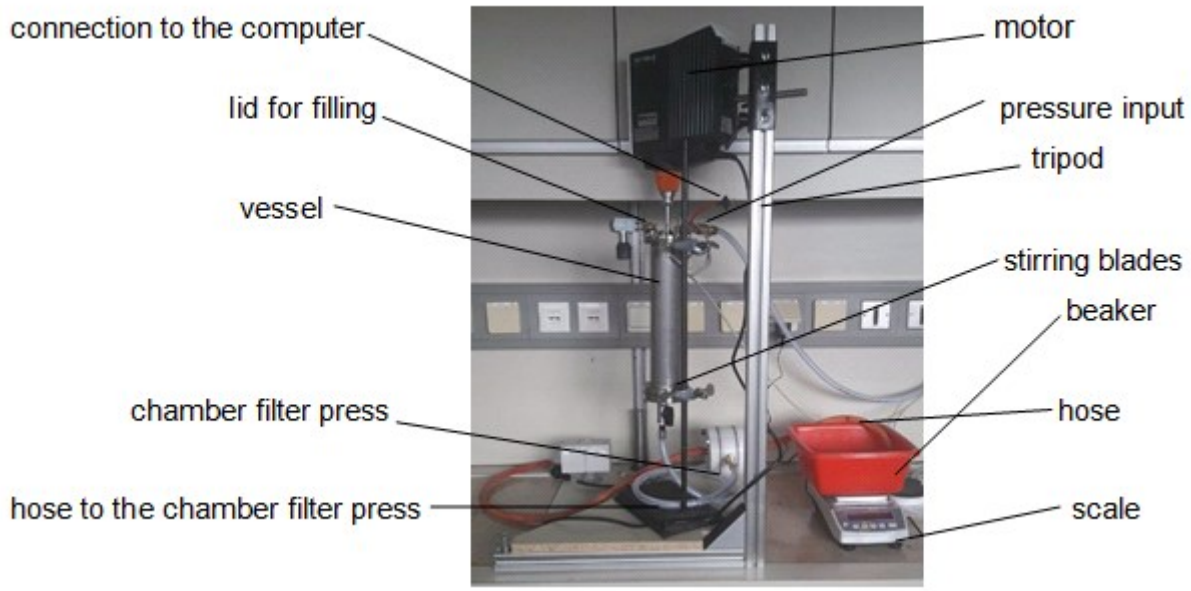


**Figure 8: Experimental setup main tests**

Figure 8 shows the experimental setup for the main tests. The experimental device is designed with the purpose to have similar conditions as in an industrial-scale chamber filter press. In order to have a well-mixed suspension two stirring blades are used. A beaker is placed on a scale at the end of the hose to gather the filtrate. The scale is connected with the computer to have documentation over time. These values are presented graphically in a diagram. The pressure difference is measured as well and saved in an EXCEL®-file. These measurements are performed with the program SignalExpress® and the acquired data can be converted into EXCEL®-files. There is a connection to a computer, where relevant measured values are documented during the experiment. There is the possibility to use the chamber with an exit just on one side or with an exit on every side. With one exit the height of the cake is twice as high as if there are two exits. In further tests the chamber filter press with one exit is used only. The setup is slightly different for the three various operating modes. These two different setups are shown schematically in Figure 9 and Figure 10.

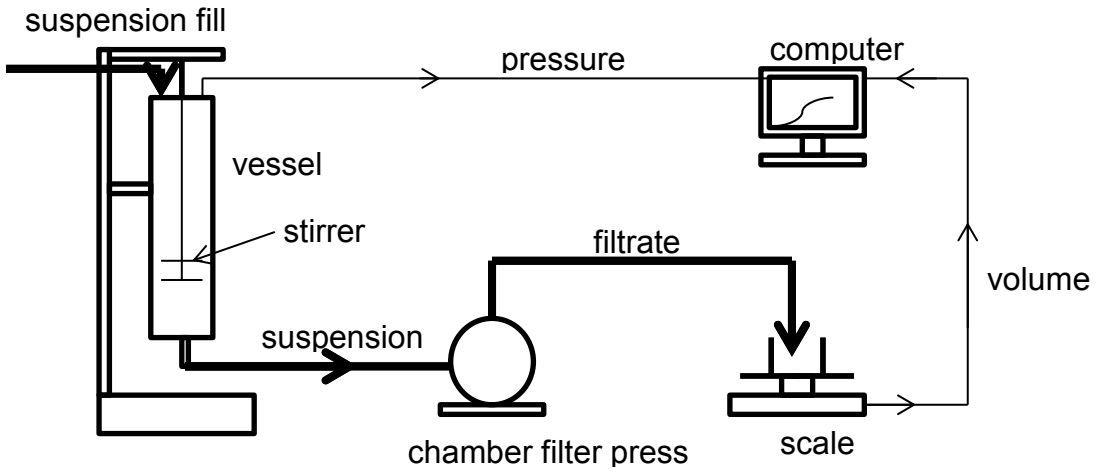


**Figure 9: Schematic experimental setup 1 – main tests**

The setup that is shown in Figure 9 is used for the experiments with *constant pressure* and *constant filtration rate*. The suspension is filled into the vessel with a funnel. From the vessel the suspension runs via a hose to the chamber filter press. Most of the solid particles form a filter cake while part of the liquid exits as filtrate and it runs off into a beaker that is placed on a scale. This scale is connected to a computer. The vessel is also connected to the computer via a cable to measure the pressure in the vessel.

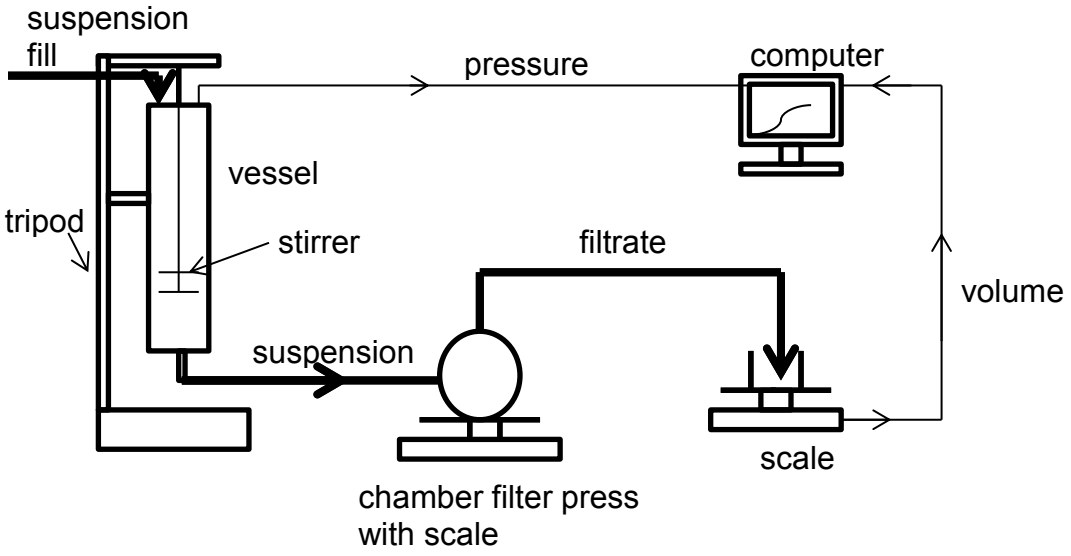


**Figure 10: Schematic experimental setup 2 – main tests**

The other setup, which is shown in Figure 10 is used for the tests with *constant filling rate.* This setup contains the same elements as the first experimental setup. However, the two setups differ in one detail. In the second setup a second scale is

used to determine the weight of the chamber filter press over time. This scale is connected to the computer. In this setup the readings of the scale under the beaker have to be noted manually.

The main element of these experimental setups is the chamber filter press test cell. Figure 11 and Figure 12 show this element more detailed. In the middle there is a perforated plate that has a diameter of 8.7cm. Between this plate and the o-ring the filter cloth is placed. The filter cloth has to be a little bit larger than the perforated plate. In this case the filter cloth has a diameter of 9 cm. The chamber is closed with an o-ring and a sealing ring. The chamber wall is fixed with four bolts and nuts. The chamber filter press can have one or two exits. These exits are placed opposite to each other in a 90 degree angle to the inlet. The chamber is connected with the stirring vessel with a 109 cm long flexible hose and with an inner diameter of 1.1 cm. The hose for the outlet has a length of 68 cm.

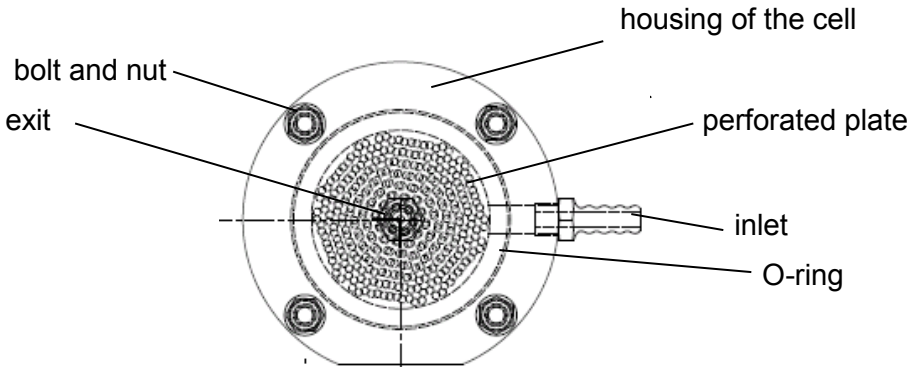


**Figure 11: Chamber filter press - side view**

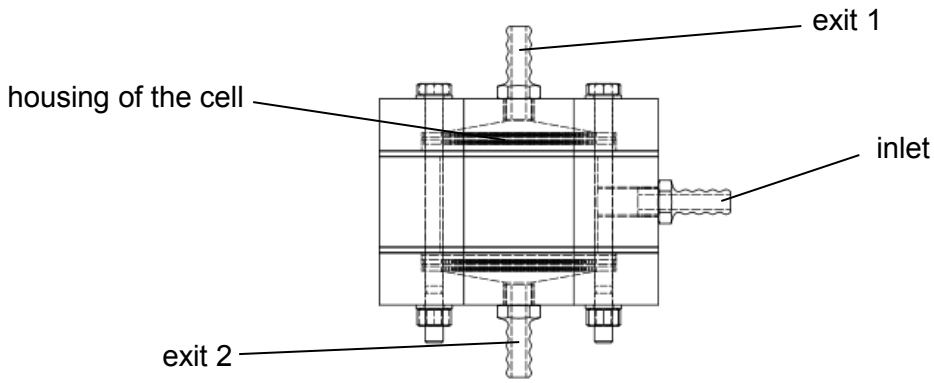


**Figure 12: Chamber filter press – top view**

### *4.3.3 Experimental procedure – Pretests*

The lid for filling is removed and the desired quantity of suspension is filled in, using a funnel. Sedimentation can occur between the filling up and the beginning of the filtration, it is therefore important to work as fast as possible. The valve of the compressed gas is opened and the measuring is started when the first filtrate enters the receiver. The quantities of filtrate versus time are recorded by using an electronic weighting scale that is connected to a computer. The end of the filtration is recorded and so the duration of the filtration process can be calculated. The pressure difference is maintained for a further minute to see that the filtration process has really ended. Then the compressed gas valve is closed, the filter housing is vented and the lid is opened. The thickness of the cake is measured with a tape measure after the cake has been withdrawn from the filter cloth. The thickness is measured at two locations to get a measure about the variability of the filter cake height. The housing of the cell is removed and the cake is withdrawn. The humid cake is weighted. Afterwards the cake is dried in a drying oven until it reaches a constant weight. The drying conditions are reported. The temperature is set at 105°C. The dry mass of the cake is measured. From this data the solid fraction in the filter cake can be calculated using the following formula [44].

$$TS = \frac{M_{s,tr}}{M_{s,f}} * 100 \quad (4.1)$$

### *4.3.4 Experimental procedure - Main tests*

Before the filling starts the pressure valve and the valve on the vessel are closed, the stirrer is switched off and suspension is prepared. The tests with water are executed as follows:

1) The water is weighted and filled into the vessel with a funnel.
2) The lid for the filling is closed.
3) The pressure is switched on.
4) The programs for the measuring are started.
5) The valve is opened and the filtration process begins.
6) The valve is closed again when no more water reaches the beaker.

7) The pressure is switched off.
8) The measurement is stopped.

The tests with constant end pressure and with the limestone suspension are carried out according to the following steps:

1) The solid is weighted and filled up with water to get a target concentration of about 30 g/l. The water is also weighted. Here the concentration is 30 g/l as a volume of 1l is needed to fill the vessel and if more solid would be used the suspension would be too viscous.
2) The suspension is stirred in a beaker glass by hand.
3) The program for the scale is started and in the meanwhile the suspension is filled into the vessel with a funnel. The automatic stirrer is switched on.
4) The opening for the filling is closed.
5) The program for the pressure measurement is started.
6) The valve in the pressure line is opened.
7) The filtration is carried out until no suspension reaches the chamber press any more.
8) The measurement programs are stopped.
9) The pressure is turned off.
10) The empty tray for the filter cake is weighted.
11) The chamber press is opened and the filter cake is discharged.
12) The wet filter cake is weighted together with the tray and put into the heater for about 24 hours to ensure complete filter cake dryness.
13) The tray for the filtrate is weighted and some filtrate is put into it. The solid content of the filtrate is also dried in the heater for about 24 hours.

# 5. Data evaluation

## 5.1 Filter equation

The relationship between filtrate volume stream, thickness of the cake, filtration area, pressure difference and other specific stream properties is written down in the so-called *"filter equation".* The filter equation can be obtained by inserting equation (1.4) and equation (1.5) into equation (1.3).

$$\frac{dV}{dt} = \frac{\Delta p * A}{\eta * (\alpha_H * \frac{\bar{c} * V}{A} + R_T)} \tag{5.1}$$

After rearranging equation (5.1) the following equation is derived.

$$\Delta p = \frac{\eta}{A} * \left\{ \frac{\alpha_H * \bar{c}}{A} * V + R_T \right\} * \frac{dV}{dt} \tag{5.2}$$

The integration of equation (5.2) after time gives the following equation.

$$t = \frac{\eta * \alpha_H * \bar{c}}{2 * A^2 * \Delta p} * V^2 + \frac{R_T * \eta}{A * \Delta p} * V \tag{5.3}$$

The integration of equation (5.2) after volume gives the following equation.

$$V = \frac{R_T * A}{\alpha_H * \bar{c}} * \left( -1 + \sqrt{1 + \frac{2 * t * \Delta p * \alpha_H * \bar{c}}{\eta * R_T^2}} \right) \tag{5.4}$$

In order to use equations (5.3) and (5.4) the following conditions have to be fulfilled.

- The composition of the suspension is time invariant and independent from domain.
- Only few solid reaches the filtrate.
- The filter cake has a homogeneous and isotropic structure and it is incompressible.
- Flow through the filter medium and the filter cake are by viscous flow only [6].

There are two distinctively different *modes of operation*, for example, filtration with *constant pressure difference* or filtration with *constant filtrate flow*. Dependent upon the kind of operation mode, different special solutions of the filtration equation are obtained.

If the test is performed with *constant pressure*, the following steps are performed to get the solution of the filter equation: First the variables are separated [6].

$$dt = \frac{1}{\Delta p} * \left[\frac{\eta * \alpha_H * \bar{c}}{A^2} * V(t) + \frac{\eta * R_T}{A}\right] * dV \tag{5.5}$$

Then equation (5.5) is integrated from t = 0 until a desired time and from V = 0 until V(t). Equation (5.3) shows this step [6].

At the beginning of the filtration the filtration stream is only determined by the resistance of the filter medium, as there is no cake formed yet. With continuity of the filtration the resistance of the filter cake dominates. In most cases the resistance of the filter medium can be neglected. The filtration velocity can also be calculated with the filter equation. Equation (5.6) shows this formula [6].

$$v_F(t) = \frac{\dot{V}}{A} = \frac{\Delta p}{\sqrt{(\eta * R_T)^2 + (2 * \Delta p * \eta * \alpha_H * \bar{c}) * t}} \tag{5.6}$$

The velocity of the cake formation can be calculated with equation (5.7).

$$v_k(t) = \frac{\bar{c} * \Delta p}{\sqrt{(\eta * R_T)^2 + (2 * \Delta p * \eta * \alpha_H * \bar{c}) * t}} \tag{5.7}$$

Inserting equation (5.4) into equation (1.5) gives the relation between thickness of the cake and filtration time [6].

$$H = \sqrt{\left(\frac{R_T}{\alpha_H}\right)^2 + \frac{2 * \bar{c} * \Delta p}{\eta * \alpha_H} * t} - \frac{R_T}{\alpha_H} \tag{5.8}$$

## 5.2 Curves of quantities of filtrate and calculation of the filtration resistance

Formula 5.3 can be rearranged to get a straight line. In order to do this the equation has to be divided by the filtrate.

$$\frac{t}{V} = \frac{\eta * \alpha_H * \bar{c}}{2 * A^2 * \Delta p} * V + \frac{\eta * R_T}{A * \Delta p} \tag{5.9}$$

$$\frac{t}{V} = \frac{b}{2} * V + a \tag{5.10}$$

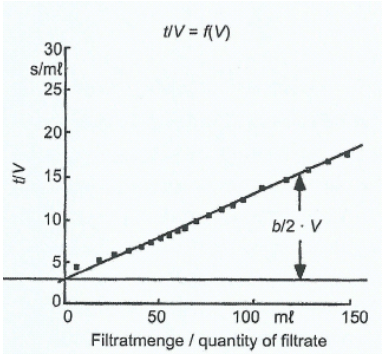


**Figure 13: Exemplary plot of equation 5.10 [42]**

In Figure 13 a plot of exemplary values of equation 5.10 is shown. The value of the intercept of the interpolation straight-line with the y-axis corresponds to the effective resistance of the filter medium, which can be calculated with formula 5.11.

$$R_T = a * \frac{A * \Delta p}{\eta} \tag{5.11}$$

The slope of the interpolating straight line gives the filter cake resistance relative to its thickness, according to the following equation [44].

$$\alpha_H(\Delta p) = b * \frac{A^2 * \Delta p}{\bar{c} * \eta} \tag{5.12}$$

$$with\ \bar{c} = A * \frac{H_e}{V_e} \tag{5.13}$$

## 5.3 Filter curve

The filter curve is an easy way to plot the filtrate volume against the filtration time. This plot is done quickly as both needed values are measured continuously. From such a graph the filtration behavior can be seen. A steep slope means that a lot of filtrate reaches the container. That means that the filtration is going fast. If there is a horizontal line that means that either the filtration has not started or that it is finished. A characteristic curve starts with a horizontal line, has than a steep slope and at the end there is also a horizontal line. For further calculations the filtration time span between onset of filtrate rise till it is finished is chosen. That is that area where the slope is steepest. This time period is called filtration period and can be seen in Figure 14.

## *5.4* Pretests

In Table 6 the test conditions for the pretests with water only are summarized. The pressure difference means always the reached end pressure. The minus sign indicates that the test is carried out under *vacuum*, plus sign denotes overpressure. The first set of tests was carried out without the stirrer rotating, whereas the second set was with the stirrer rotating.

**Table 6: Test conditions – pretests with water only**

| Test number | Δp [bar] | Stirrer | Rotations [rpm] |
|---|---|---|---|
| **PT1** | -0.3 | no | - |
| **PT2** | -0.3 | no | - |
| **PT3** | -0.3 | no | - |
| **PT4** | -0.3 | no | - |
| **PT5** | -0.3 | no | - |
| **PT6** | -0.3 | no | - |
| **PT7** | -0.3 | no | - |
| **PT8** | +0.3 | no | - |
| **PT9** | +0.3 | no | - |

| | | | |
|---|---|---|---|
| **PT10** | +0.3 | no | - |
| **PT11** | +0.3 | no | - |
| **PT12** | +0.3 | no | - |
| **PT13** | +0.3 | yes | 600 |
| **PT14** | +0.3 | yes | 600 |
| **PT15** | +0.3 | yes | 300 |
| **PT16** | +0.3 | yes | 300 |

In Table 7 the test conditions for the pretests with the limestone suspension are summarized. The first set was carried out under *vacuum* than followed one test without the stirrer rotating. The third set was with the stirrer rotating at 300 rpm.

**Table 7: Test conditions - pretests with suspension**

| Test number | Δp [bar] | Stirrer | Rotations [rpm] |
|---|---|---|---|
| **PT17** | -0.5 | no | - |
| **PT18** | -0.5 | no | - |
| **PT19** | -0.5 | no | - |
| **PT20** | +0.3 | no | - |
| **PT21** | +0.3 | yes | 300 |
| **PT22** | +0.3 | yes | 300 |
| **PT23** | +0.3 | yes | 300 |

For analyzing the pretests with overpressure (PT20 – PT23) two different *"methods"* are chosen. "*Method 1"* just takes the slope from the t/V versus volume diagram (Figure 20) to calculate the filter cloth resistance. The slope of the calibration gives the value for *b*. With equation (5.12) the resistance of the filter cake can then be calculated. *"Method 2"* is chosen if the filtration time span is short and the tests have low volume values at the beginning which gives unrealistically high V/t-values (Figure 21). If the filtration time span is short these values cannot be neglected. The end values of the filtration volume and filtration time are used for the calculation as it is believed that at this point the time corresponds best with the volume. The starting point is set to zero.

Figure 14 shows three filtration curves representative for the different operating modes. Every test mode is carried out at least three times to check upon reproducibility. In this chapter one example for each test mode is shown and evaluated exemplarily. The results and diagrams from all measurements can be found in the appendix 2.

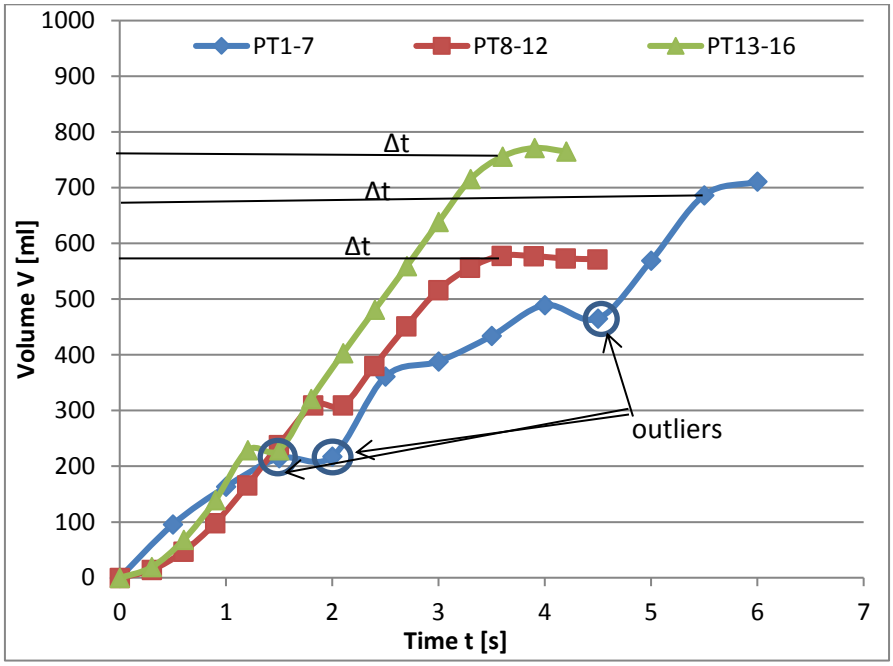


**Figure 14: Filtration curve**

In Figure 14 the origin is set when the valve is turned and filtrate started to be accumulated. In these tests only water was present. The pretests under *vacuum* have two outliers and the pretests with overpressure and stirrer on have one. However, as expected there is a steep slope in all three lines, which symbolizes the filtration time. The filtration time is named ∆t. The pretests with vacuum have a longer filtration time than that with overpressure. That means that the filtration is slower under vacuum.

Vacuum

As the measured signals are in volts a calibration is needed to convert these volt signals into volume values. The calibration is given by the following equation

$$V = 543.39 * U - 1681.1 \quad (5.14)$$

with volume V in milliliter and voltage U in volts.

These values are plotted against time. From Figure 14 the filtration time span can be read. The horizontal line shows the time until the filtration starts. Once all the water has passed the filter cloth, it is possible that air bubbles enter the filtration vessel. These air bubbles can cause weight differences and can be regarded as outliers. It can be concluded that all vacuum tests provide similar results. The results are included in appendix 2. The resistance of the filter cloth is calculated with equation (5.11).

Overpressure without stirrer

The tests are carried out the same way as the vacuum tests. The only difference is that the weight is measured continuously. This weight is then transformed into volume by its density ($\varrho$ = 998 g/m³). As seen in Figure 14 the overpressure filtration has hardly any outliers. The reason for that can be that there were no air bubbles and that the filtration vessel does not vibrate. The setup is also a bit different than that for the vacuum tests In the setup for the pretests with overpressure the filtrate is gathered in a bowl that stands on a scale. In the setup for the pretests with vacuum the filtrate is gathered in a vessel that can rotate. This vessel is connected to a computer and volt signals are collected. These signals are than transformed into volume values.

Overpressure with stirrer

For these tests the same setup is used as for the tests without the stirrer. The stirrer is run at two different speed rates: 600 and 300 rpm. As the suspension is tab water there should not be any differences concerning the two speed rates. The graph looks similar to the one without stirrer. So it can be said that the use of the stirrer does not

make any difference as there are no solids in the suspension. The $R_T$ is calculated with equation (5.11).

## 5.5 Tests with the chamber filter press (main tests)

Some tests are carried out to test the functions of the designed test chamber filter press. The first tests are done with tab water. These tests are just taken into account qualitatively. In the next step the test is carried out with the limestone suspension that was also used for the pretests. The concentration is varied as well as the pressure and the filter cloth. There are three different *"operation modes"* as well. The first set was carried out with "*constant pressure"*. That means that the starting pressure was equivalent to the end pressure. The second set was carried out with *"constant filling rate"*. Therefore, a pressure value was taken that guaranteed a constant filling rate from the vessel into the chamber filter press. The third set was carried out with *"constant filtration rate"*. The *constant filtration rate* was realized by a stepwise increase of the pressure difference. Table 8 shows the conditions for every test with limestone suspension.

**Table 8: Test conditions – main tests**

x…"constant pressure" y…"constant filling rate" z…"constant filtration rate"

| Test number | Δp [bar] | Filter cloth | Operation mode | Filtration rate [ml/s] |
|---|---|---|---|---|
| **MT1** | 2 | SK045 | x | 4.63 |
| **MT2** | 3 | SK045 | x | 11.32 |
| **MT3** | 4 | SK045 | x | 11.52 |
| **MT4** | 1 | SK045 | x | 9.71 |
| **MT5** | 1 | SK045 | x | 5.18 |
| **MT6** | 2 | SK045 | x | 4.75 |
| **MT7** | 2 | SK045 | x | 2.69 |
| **MT8** | 3 | SK045 | x | 16.72 |
| **MT9** | 3 | SK045 | x | 7.58 |
| **MT10** | 3 | SK045 | x | 6.87 |
| **MT11** | 4 | SK045 | x | 7.29 |

| | | | | |
|---|---|---|---|---|
| **MT12** | 4 | SK045 | x | 10.23 |
| **MT13** | 4 | SK045 | x | 9.69 |
| **MT14** | 2 | SK030 | x | 5.42 |
| **MT15** | 1 | SK030 | x | 5.91 |
| **MT16** | 1 | SK030 | x | 3.68 |
| **MT17** | 1 | SK030 | x | 5.51 |
| **MT18** | 2 | SK030 | x | 4.73 |
| **MT19** | 2 | SK030 | x | 2.37 |
| **MT20** | 3 | SK030 | x | 5.71 |
| **MT21** | 3 | SK030 | x | 4.67 |
| **MT22** | 3 | SK030 | x | 5.29 |
| **MT25** | 4 | SK030 | x | 6.75 |
| **MT26** | 4 | SK030 | x | 6.99 |
| **MT27** | 4 | SK030 | x | 8.55 |
| **MT28** | 1 | SK030 | x | 5.83 |
| **MT29** | 3 | SK030 | y | 16.06 |
| **MT30** | 3 | SK030 | y | 58.18 |
| **MT31** | 3 | SK030 | y | 66.64 |
| **MT32** | 3.5 | SK030 | z | 3.17 |
| **MT33** | 5.5 | SK030 | z | 38.26 |
| **MT34** | 6.5 | SK030 | z | 56.00 |

The two tests MT23 and MT24 are not included in the data evaluation because some obvious experimental mistakes happened.

## 5.6 Interpretation of the deviations from a horizontal line

According to equation (5.13) the measured values should be located on a horizontal line. However, as seen in Figure 15, these data points can hardly be approximated by one horizontal line. First it drops sharply, finds a minimum plateau and finally it seems that it raises again.

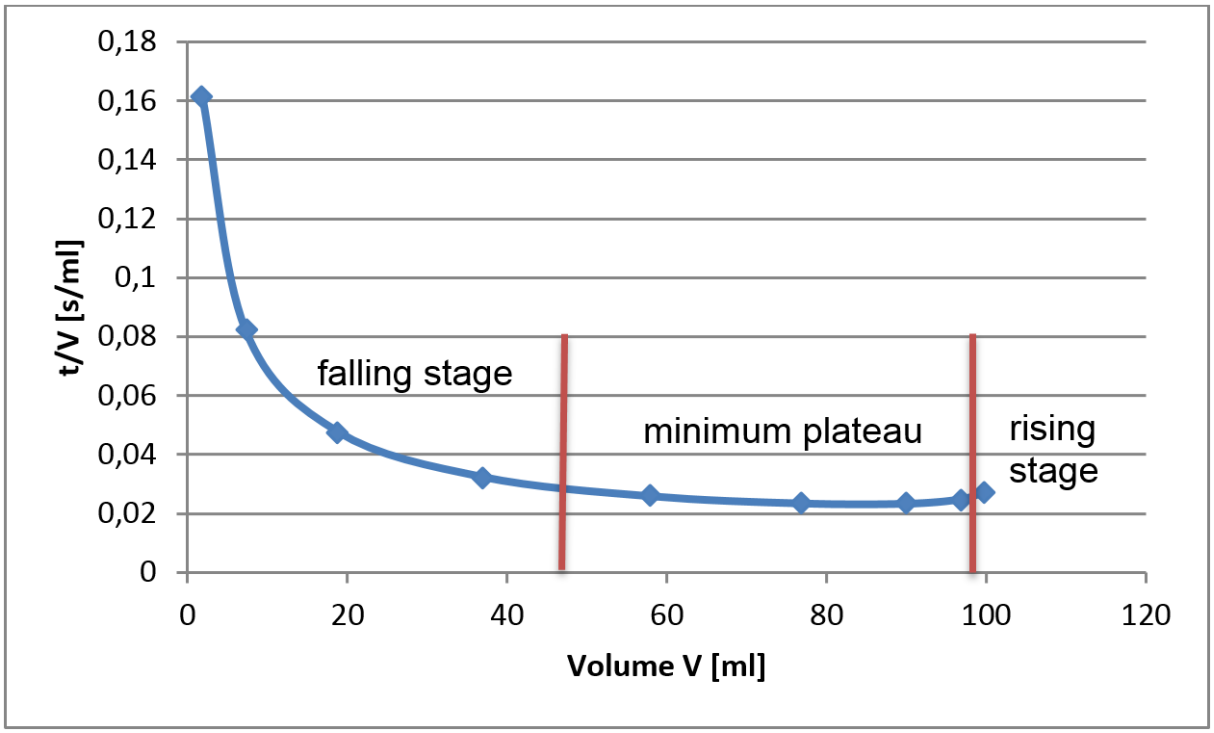


**Figure 15 : t/V versus volume curve MT33**

These deviations may exist due to:

- Partial sedimentation before the beginning of the experiment. The settled layer increases the apparent resistance of the filter medium and therefore, the filtration will become slower.
- Premature sedimentation of all the solids: the thickness of the cake increases quickly at first but does not increase anymore towards the end, and the curve inclines itself towards the right.
- Selective sedimentation of large particles. Finer and finer particles are deposited during filtration and the resistance increases progressively.
- Clogging of the filter medium due to fine particles that migrate through a formed cake of big particles during the experiment.
- Error in the determination of the beginning and end of the filtration process. [44].

The above listed reasons are not all true for every experiment. In the case that is shown in Figure 15 a deviation from the straight line can clearly be seen at the beginning. After some time the line becomes horizontal. A reason for this deviation can be that there is sedimentation in the hose before the experiment starts. Sedimentation in the vessel is not a problem in the special case as a stirrer is used.

The main reason is, however, that the measured volume of the filtrate does not correlate exactly with the measured time as the measurement of the volume is a bit late.

# 6. Results

This chapter presents the results gained from the laboratory tests. First the results of the pretests are presented shortly. A more detailed interpretation of these pretests can be found in [42]. Afterwards the results of the main tests are shown. The main tests are divided into series. These series are grouped according to their *operating mode*: *constant pressure, constant filling rate* and *constant filtration rate*. The results are presented chronologically. The first step is the choice of the filter cloth. Therefore, two test series with *constant pressure* with different filter cloths are performed. With the chosen filter cloth the following series are performed. The next step is the calculation of the solid concentration in the filtrate to analyze the water quality. The last steps are the calculations of the resistance of the filter cloth and the cake resistance. Two different *"cases"* are distinguished. If the resistance of the filter cloth is much smaller than that of the cake, it is set to zero and therefore neglected. And then an easy way of calculation can be done. This way is referred to as *"case 1".* In "*case 2"* the calculation of the resistance of the cake is done with the EXCEL SOLVER®. In that case the resistance of the filter cloth is not neglected.

## 6.1 Choice of filter cloth

The first test series with *constant pressure* is carried out with two different filter clothes, with the one that was used for the pretest and a special one for chamber filter presses with the code name 05-1550-SK030. This filter cloth is specially calendared and consists of satin weave. Its air permeability accounts to 90 l/(m²*s) [45]. The performances of these two filter clothes are compared and the better one is taken for all further measurements. Figure 16 shows the solid fraction (TS) in the filter cake after the filtration process for all main tests. For every pressure level the mean value and the standard deviation is calculated. The standard deviation is shown with error bars.

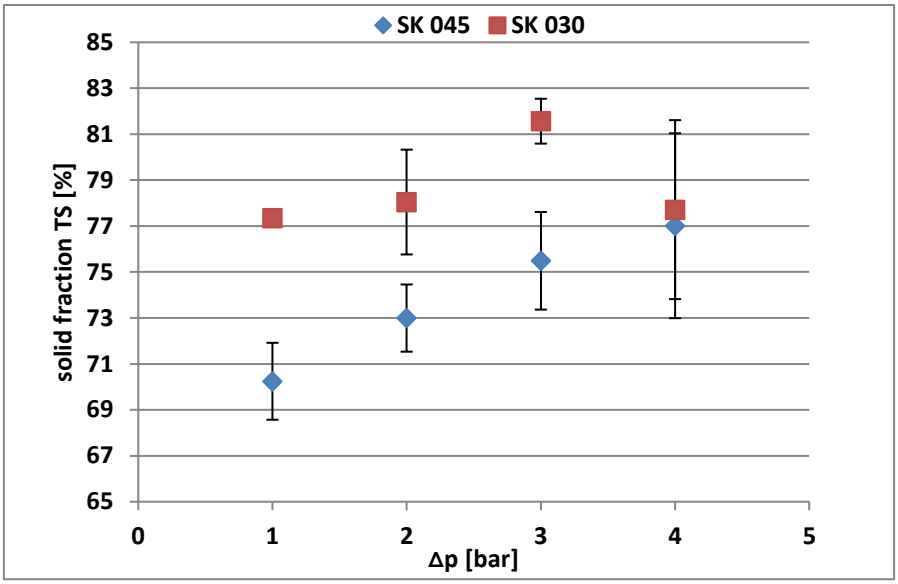


**Figure 16: Solid fraction of the two filter cloths**

At all tested pressure differences the performance of the *special filter cloth SK030* is better than that of the *filter cloth SK045*. That means that the filter cake contains less water (Figure 16) and more of the recycled material (Figure 17). Therefore, the *special filter cloth* is preferred from that point of view.

The third criterion is the pureness of the filtrate. Therefore, the solids content in the filtrate is analyzed. Figure 17 shows the solid concentration in the filtrate against the pressure difference.

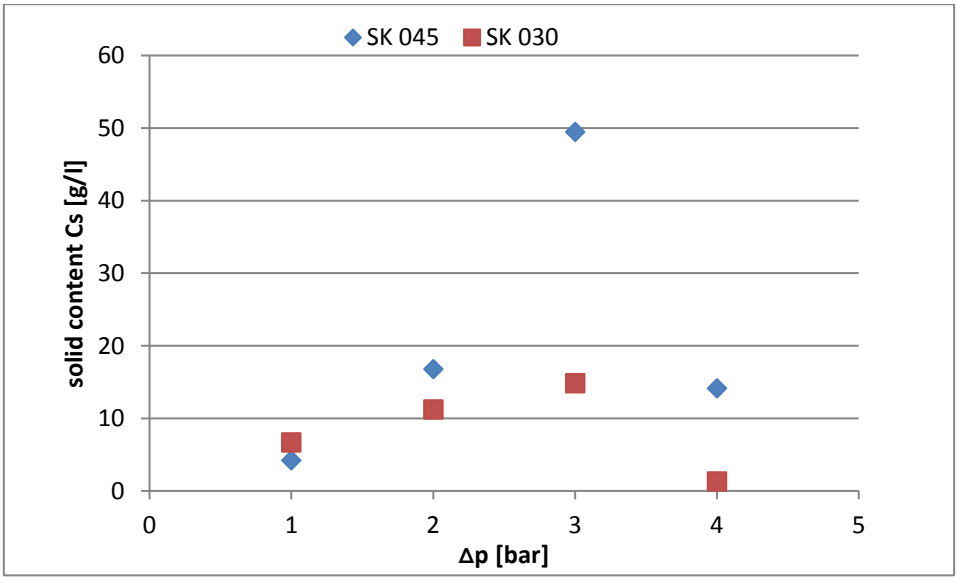


**Figure 17: Solid concentration of the two filter cloths**

Also from this point of view the *special filter cloth* is the better one because the solid concentration is generally lower. Only at a pressure difference of 1 bar the performance of the *normal filter cloth* is better. However, there the difference is very small. As the *special filter cloth* is better on both criteria the tests with *constant filling rate* and *constant filtration rate* are just performed with this filter cloth.

Figure 18 shows the solid fraction of the three different operating modes: *constant filling rate*, *constant filtration rate* and *constant pressure*.

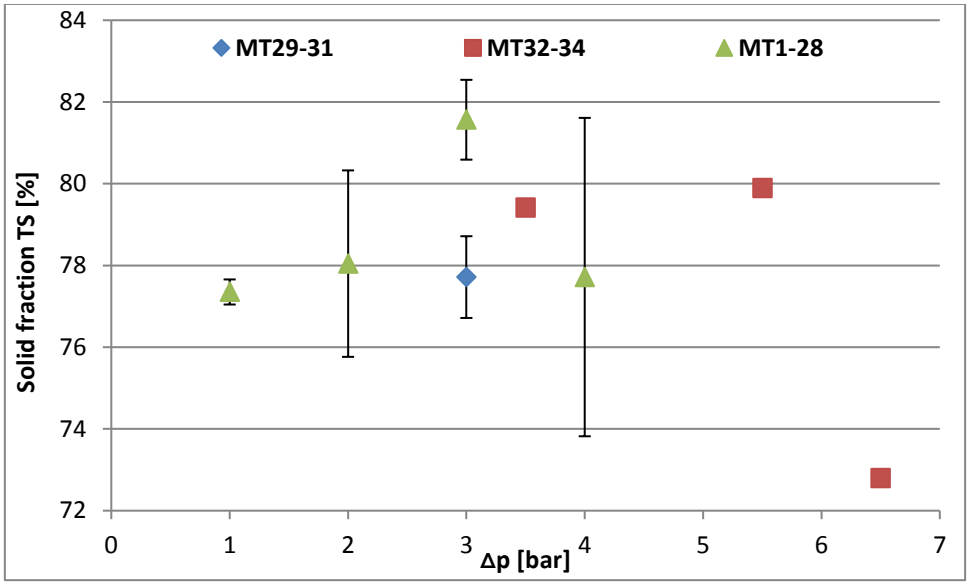


**Figure 18: Solid fraction of the different operating modes**

As expected and irrespective of the operation mode the solid fraction of the filter cake increases with increasing pressure difference though except for the experiment at 6.5 bar. There is no clear evidence whether the kind of operation mode has an influence on the solid cake fraction at all. Generally, the solid fraction is rather low, especially with the filter cloth SK045. Once it is even below 70%, which means that there is more than 30% water in the filter cake. A high value of solid fraction would be more than 90% as this means that there is hardly any water left in the filter cake. However, such good values are just reachable with high pressure. With the *special filter cloth SK030* this value lies between 72 and 82%. However, to have a usable recycling material downstream thermal drying is always necessary.

The tests with *constant filling rate* are just carried out at a pressure difference of 3 bar. The tests with *constant filtration rate* are carried out at three different pressure differences and the tests with *constant pressure* are carried out at four different pressure levels. These test conditions are shown in Table 8.

In Figure 19 the solid concentration in the filtrate is shown for the different operating modes.

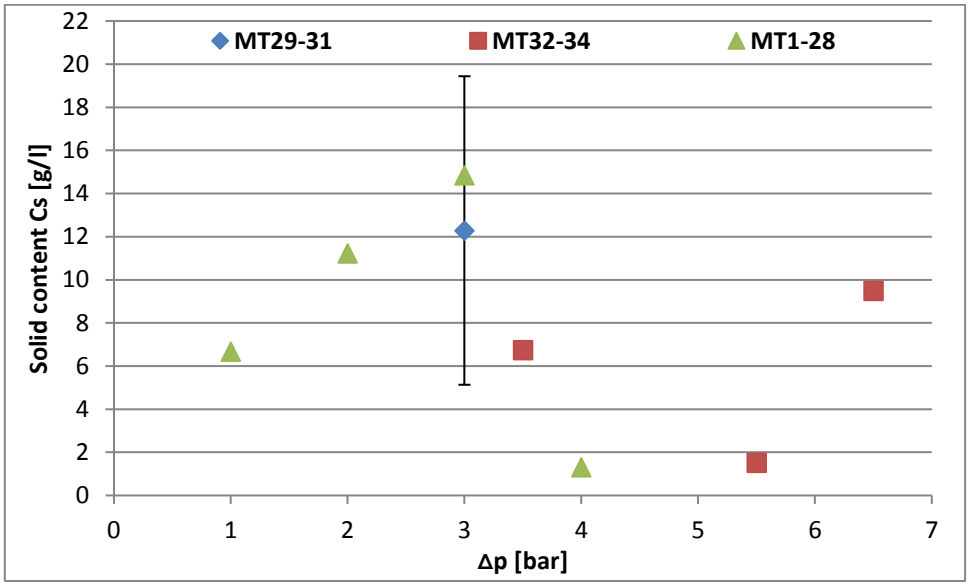


**Figure 19: Solid concentration of the different operating modes**

The solid content in the filtrate has a range from 1 to 15 g/l and it is also depending on the operation mode. Especially high values are reached with *constant filling rate* and *constant pressure* at low pressure differences. For this parameter higher pressure differences deliver normally better results. However, these results are not satisfying, as the water has to be treated before reuse in all tested cases. However, the target is reusing the filtration water without any treatment.

If the target concentration were in the order of 2 g/l, only two experimental settings could meet this request whereas all the others show considerably higher concentrations. Both data points are at a moderate pressure range of 4 to 6 bar. In general, solid filtrate concentration shows remarkable scatter and a clear trend in terms of applied pressure difference or operation mode can hardly be derived.

## *6.2* Filter cloth and filter cake resistances

Pretests

In Table 9 the results of the water tests are summarized. Each test series is repeated at least three times to get identify possibly outliers and to check upon reproducibility.

**Table 9: Water tests - results**

| | $R_T$ [1/m] |
|---|---|
| **Water tests vacuum** | $4.99*10^7 \pm 0.08$ |
| **Water tests overpressure** | $5.84*10^7 \pm 0.09$ |
| **Water tests overpressure with stirrer** | $5.98*10^7 \pm 0.11$ |

As expected the filter cloth resistance has the same magnitude for vacuum as well as for overpressure. This is due to the fact that the pressure difference is taken and this value does not distinguish between vacuum and overpressure. The obtained values are only approximate values because the pressure measurement is not very precise. It is done with an analog manometer. All further measurements are done with a digital measurement program which gives more exact data. A further discussion about these tests is included in [42].

The next section deals with the pretests with overpressure. To obtain the slope of the filter curves two different *"methods"* are used. *"Method 1"*, which is the generally used method, just takes the slope of the correlation line. In Figure 20 the used filtration curves can be seen. PT21 and PT22 are analyzed with *method 1*.

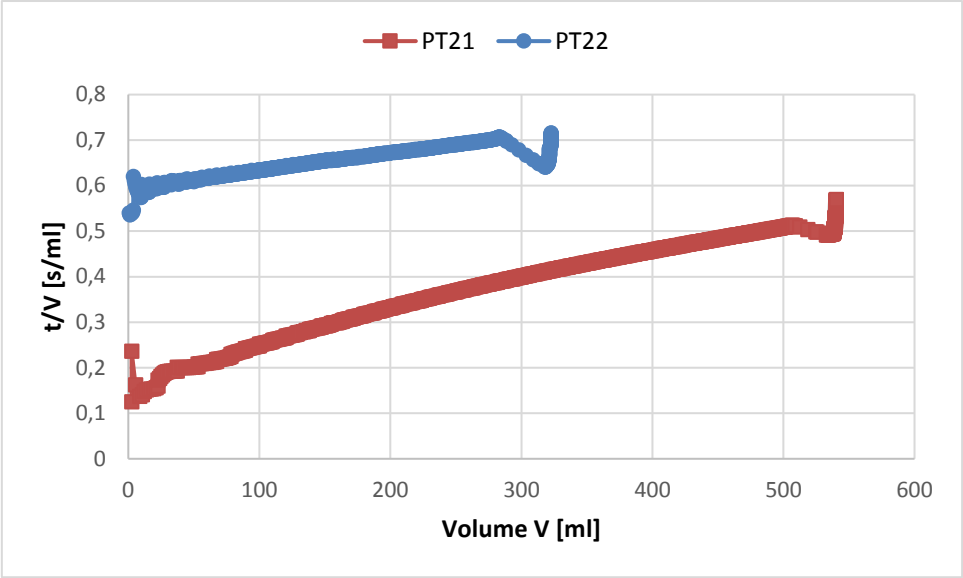


**Figure 20: $R_K$ from pretests - method 1**

*"Method 2"* is chosen if the filtration time span is too short to neglect the outliers at the beginning. PT20 and PT23 are analyzed with *method 2*. In Figure 21 the used filtration curves can be seen.

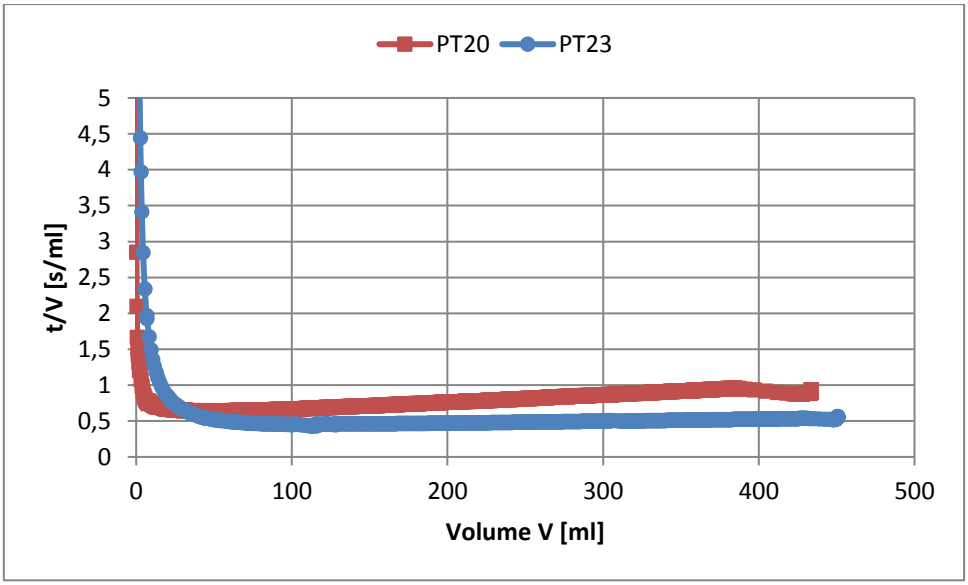


**Figure 21: $R_K$ from pretests - method 2**

Table 10 shows the values of the slope *b* for all measurements with overpressure. The tests PT17-PT19 are not analyzed, as these tests are carried out under vacuum conditions. The values correlate well. However, there is a difference of one magnitude between the two *methods*. The coefficient of the resistance of the filter

cake is calculated with equation (5.12). The filter area is $A = 1.96 * 10^{-3}\ m^2$. The filter cake resistance is calculated with equation (1.4).

**Table 10: Calculation of $R_K$ – pretests with overpressure**

| | Δt [s] | ΔV [ml] | Δp [bar] | b [s/m⁶] | H [m] | $\alpha_H$ [1/m²] | $R_K$ [1/m] |
|---|---|---|---|---|---|---|---|
| **PT20** | 378 | 391.71 | 0.3 | $2.15*10^9$ | 0.006 | $8.25*10^{11}$ | $4.95*10^9$ |
| **PT21** | 262 | 510.92 | 0.3 | $6*10^8$ | 0.007 | $4.53*10^{11}$ | $3.17*10^9$ |
| **PT22** | 261.3 | 401.42 | 0.3 | $3*10^8$ | 0.006 | $8.73*10^{11}$ | $5.24*10^9$ |
| **PT23** | 216.6 | 432.48 | 0.3 | $1.25*10^9$ | 0.008 | $3.96*10^{11}$ | $3.17*10^9$ |

Main tests

The first evaluation step is to plot the filtration time span versus the pressure. This graph is shown in Figure 22. As expected the trend shows that the filtration time is decreasing with increasing end pressure difference.

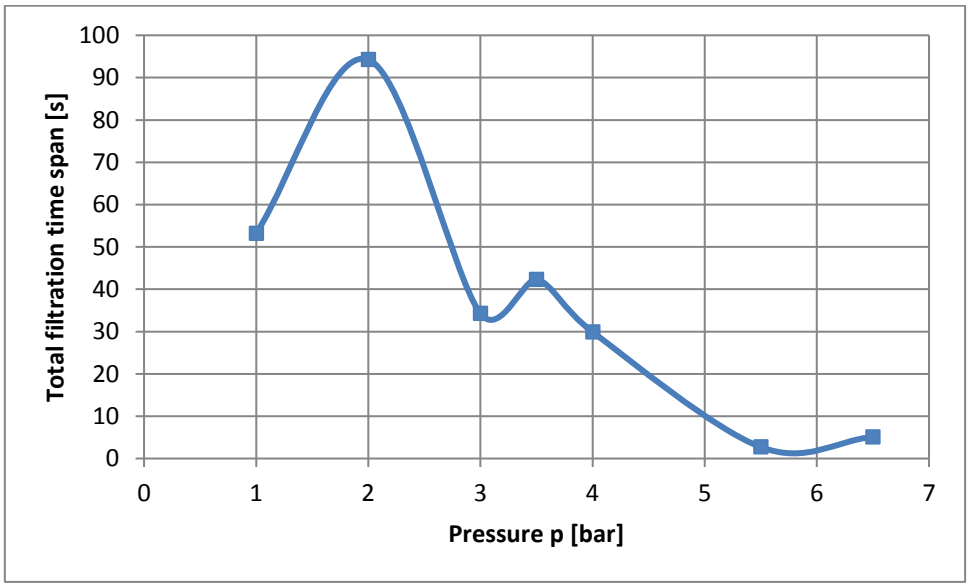


**Figure 22: Total filtration time span versus pressure**

The graph in Figure 22 has two outliers at 1 and 3 bar. These two values are too small to follow the trend of a decreasing filtration time span. However, to be completely sure about the outliers some more tests have to be performed, as it could also be that the value at 2 bar is an outlier, too.

The next step is the calculation of the resistance of the filter cake. This data evaluation is carried out in two different ways (*case 1* and *case 2*). In *case 1*, the resistance of the filter cloth is neglected and set to zero. It is believed that this resistance is very low compared to the resistance of the cake and so it has hardly any influence. To get the coefficient of the resistance of the cake the following formula is used. Appendix 2 shows how equation (6.1) is derived.

$$V = \sqrt{\frac{A^2 * k_1}{\alpha_H * \bar{c} * \eta}} * t \tag{6.1}$$

After rearranging equation (6.1) it can be solved for the coefficient of the resistance of the cake, like the equations (6.2) to (6.4) show.

$$D \equiv \sqrt{\frac{A^2 * k_1}{\alpha_H * \bar{c} * \eta}} \tag{6.2}$$

$$\alpha_H = \frac{A^2 * k_1}{D^2 * \frac{A * H_e}{V_e} * \eta} \tag{6.3}$$

$$\alpha_H = \frac{A * k_1 * V_e}{D^2 * H_e * \eta} \tag{6.4}$$

This equation is then solved with the help of EXCEL® like the following example shows: First, a volume versus time diagram is produced for the filtration period. The starting time and starting volume are set to zero. Then a calibration line is calculated. The slope of this line gives the value for D which is needed in equation (6.4).

Figure 23 shows an exemplary volume versus time diagram with the calibration line. The value accounts in this example to $D = 3.1657\ m^3/s$.

This routine of data evaluation is applied to all main tests though it is only applicable for the situation of a constant pressure difference increase rate. This situation is only present during a restricted time span of the total filtration test, for example at the start.

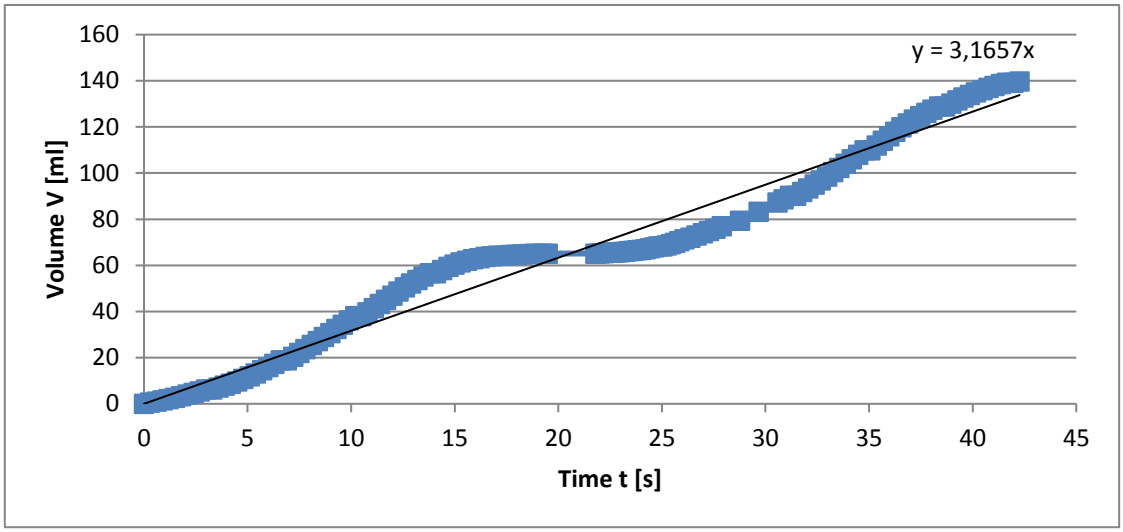


**Figure 23: Volume versus time-diagram of the filtration period MT32**

The end volume is calculated with the equation of the calibration line. To get the value for $k_1$ the same procedure is done with the pressure line. In the tests the pressure is increased gradually in different rates. For MT32 the pressure is increased every 30 seconds by 0.5 bar. For MT33 the pressure is increased every 15 seconds by 0.5 bar and for MT34 the pressure is increased every 15 seconds by 1 bar. This stepwise pressure increase is approximated by a linear overall rise of pressure as depicted in Figure 24. The slope of this fit line gives the value for $k_1$. In the example it lies at $k_1 = 0.0391\ bar/s$. In Figure 24 the line is shown graphically. In appendix 3 the volume versus time and pressure versus time diagrams are shown for all laboratory tests.

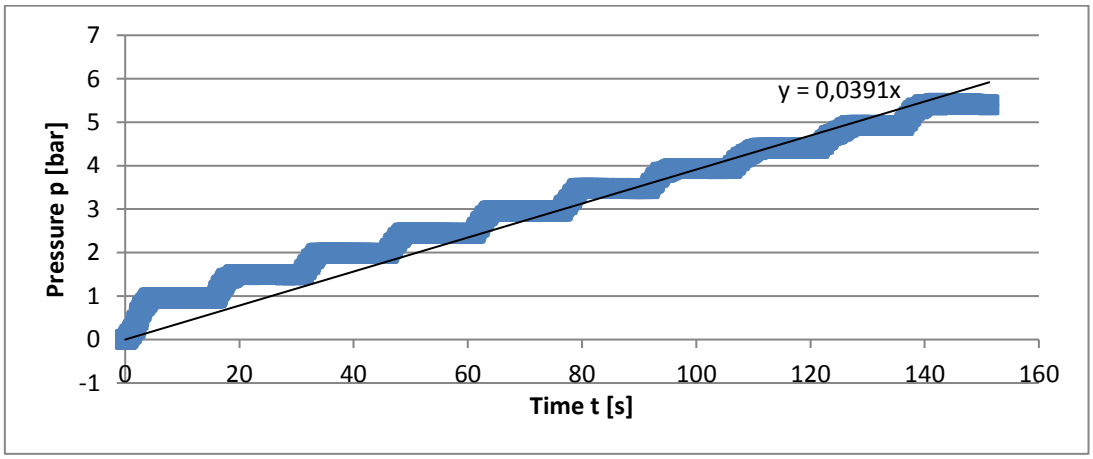


**Figure 24: Pressure versus time-diagram of the filtration period MT33**

With the fixed values of the filtration area (A=0,0064m²), the height of the cake at the end ($H_e$=0,06m) and the viscosity ($\eta=10^{-3}$ Pa*s) equation (6.4) can be used to calculate the coefficient of the resistance of the filter cake.

$$\alpha_H = \frac{0{,}0064 * 0{,}0391 * 10^5 * 103{,}287 * 10^{-6}}{(38{,}265 * 10^{-6})^2 * 0{,}06 * 10^{-3}} = 2{,}942 * 10^{10}\ m^{-2}$$

Afterwards, the volume stream can be calculated with equation (1.3). In this case the resistance of the filter cloth is set to zero.

$$\dot{V} = \frac{0{,}0064 * 5{,}5 * 10^5}{10^{-3} * 1{,}765 * 10^9} = 1{,}994 * 10^{-3}\ {}^{m^3}/_{s}$$

For the *first case*, it is believed that the filter cloth has an influence and therefore its resistance is not set to zero. To solve this *case* the following quadratic equation is used. Appendix 2 shows how this equation is derived.

$$V^2 + V * \left\{\frac{R_T * 2 * A}{\alpha_H * \bar{c}}\right\} - \left\{\frac{A * k_1 * t^2 * 2 * A}{2 * \eta * \alpha_H * \bar{c}}\right\} = 0 \qquad (6.5)$$

Equation (6.5) is solved with the known values for the filtration area, the height of the cake and the viscosity. How equation (6.5) is solved in detail can be seen in appendix 2.

In Figure 25 the average values for the coefficient of the cake resistance are plotted against the pressure difference. On the left axis the values where the resistance of the filter cloth is set to zero are plotted. On the right axis the values where the resistance for the filter cloth is unequal zero are plotted.

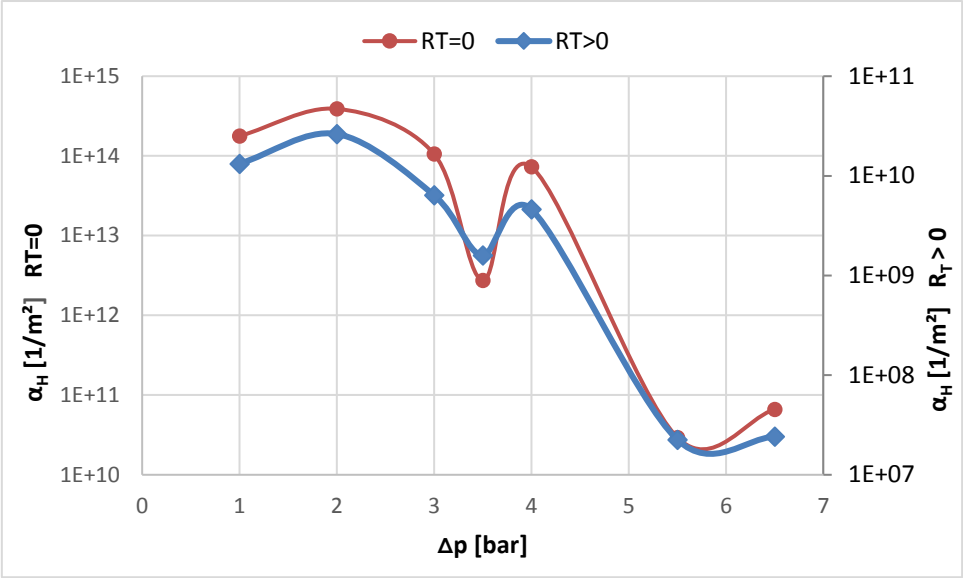


**Figure 25: $\alpha_H$ with and without the resistance for the filter cloth MT1-MT34**

Both graphs show a similar curve shape though the magnitudes are quite different. The values without the resistance of the filter cloth are three to four magnitudes higher than those with the resistance of the filter cloth. The highest cake resistance is reached at a pressure difference of 2 bar. At a pressure difference of 3.5 bar it has a local minimum point. Afterwards it increases again until 4 bar and then there is again a decrease. If these results are compared with the cake formation and filtration velocities (Figure 27), it can be seen that a low cake resistance leads to high velocities.

From the gained information, it can be believed that the resistance of the filter cloth has an influence on the filtration process. In *case 1* the starting value of the resistance of the filter cloth was chosen manually. After some iteration the EXCEL SOLVER® chose the values of the two resistances that fit best. In most of the cases the resistance of the filter cloth stayed constant. So it can be concluded that in *case 1* the calculated value of the resistance of the filter cake is mostly depending on the chosen starting value. Therefore, for further calculations only *case 2* is taken into account.

Figure 26 shows the volume stream plotted against the pressure difference. The volume stream is calculated with equation (1.3).

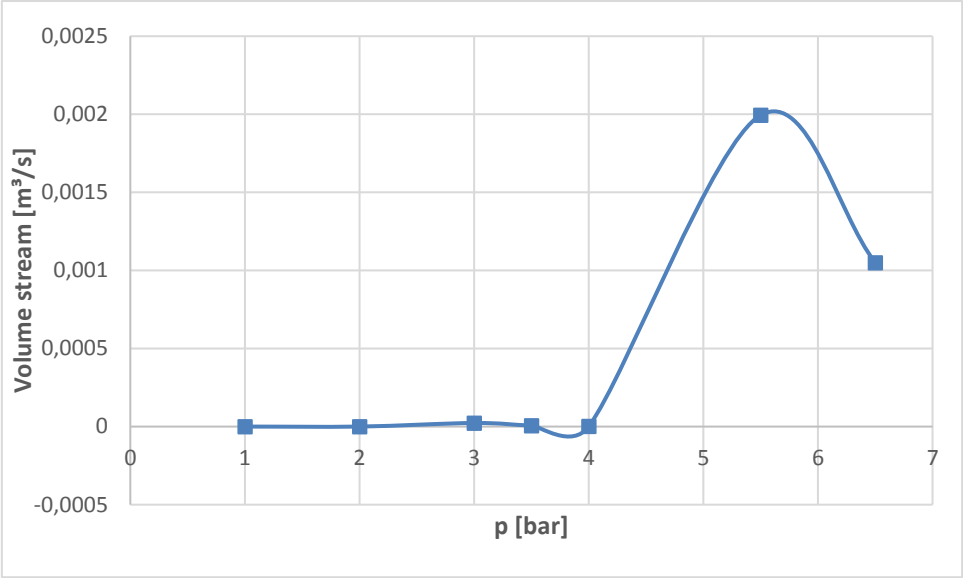


**Figure 26: Volume stream with and without the resistance of the filter cloth**

The largest volume stream is reached at 5.5 bar. At lower pressure differences the stream is very little. The general trend is that lower pressure differences also lead to a smaller volume stream.

Other parameters that are of interest are the filtration velocity and the cake formation velocity. They are calculated with equation (5.4) and (5.5) and plotted against the pressure difference in Figure 27. On the right axis the cake formation velocity is shown and on the left axis the filtration velocity is shown.

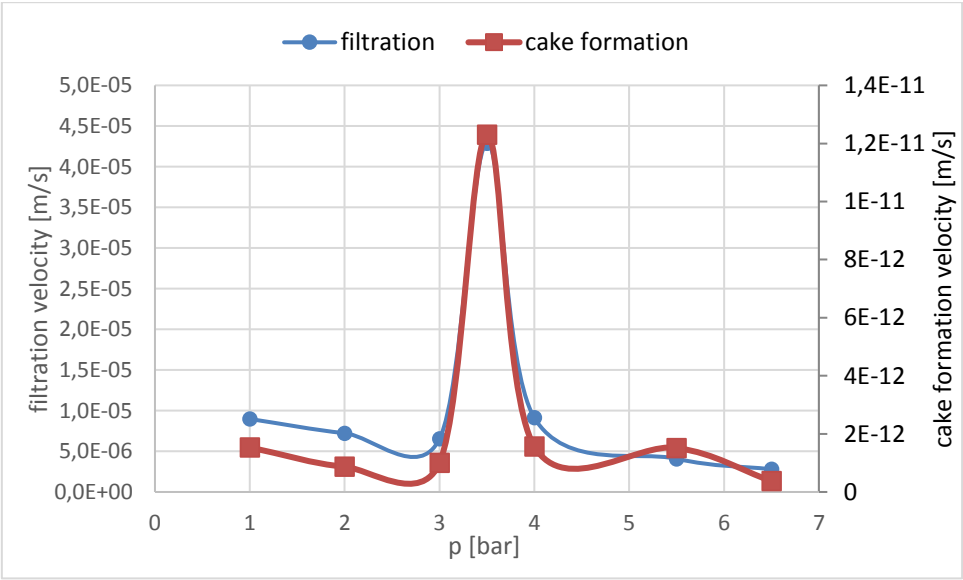


**Figure 27: Filtration and cake formation velocity**

The graph in Figure 27 has its high point at 3.5 bar, where the filtration velocity accounts for $v_F = 4.29 * 10^{-5}\ m/s$. At lower and higher pressure differences the filtration velocity always lies between $v_F = 1 * 10^{-5}\ and\ 2.8 * 10^{-6}\ m/s$. The cake formation velocity is calculated with equation (5.5). The graph of the cake formation velocity has a similar development as that of the filtration velocity. However, the cake formation is much slower. It highest point lies at $v_K = 1.2 * 10^{-11}\ m/s$. Therefore, it is nearly six magnitudes lower than the filtration velocity.

A remarkable fact is that the curves of the both velocities have an outlier at 3.5 bar. This value does not follow the general trend and should be analyzed in more detail in further experiments. However, the filtration velocity is always nearly six magnitudes higher than the cake formation velocity and decreasing slightly with increasing pressure. This is due to the fact that the cake formation velocity is also depending on the height of the cake and the volume stream. As the filter cake represents the highest resistance it is obvious that the cake formation process has to be slower than the filtration process.

# 7. Conclusion and outlook

Further measurements will be necessary of pressures up to 8 bar to really reflect industrial conditions. The change of the operating mode shows that there is no clear trend which mode should be preferred. However, the obtained results show that the pressure difference is important. Therefore, it is recommended to operate the filtration at rather high pressure values which are common in industrial applications anyways.

The designed test chamber filter press has the possibility to be used with two exits. It would be very interesting to make the same tests with two exits to see whether the chamber is filled symmetrically because in large scale operations dewatering occurs at both sides as well. A second scale is needed to document both weights independently.

Concerning the filter cake just the water content was measured. The trend shows that there is no clear difference between the various pressure differences. It is clear that the quality of the filter cake strongly depends on the input material. Therefore some more tests series with different input materials are needed to gain more results.

All the tests were carried out with the same material. However, in further experiments different particle sizes and compositions should be used to broaden the information basis. Another test parameter is to use polluted material and to analyze how much pollutants are found in the filtrate. Contaminants can either be salts or oils for example. Of course, “real-world” samples would be preferred.

The filtration water has to be treated before reusing it, especially if there are contaminants in the sample. However, it is proven that a wet treatment of construction waste is possible. This process may be especially interesting for industries in Asia as there the amount of untreated construction waste is growing fast.

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## List of figures

## List of tables

## List of symbols and abbreviations

| Symbol | Unit | Meaning |
|---|---|---|
| A | $m^2$ | Filter area |
| a | $s * m^{-3}$ | Distance of the horizontal line of formula 5.8 |
| b | $s * m^{-6}$ | Slope of the horizontal line of formula 5.8 |
| $\bar{c}$ | $m^3 * m^{-3}$ | Concentration ratio of cake volume to cumulative filtrate volume |
| $C_s$ | $g*l^{-1}$ | Solid concentration |
| C&D | - | Construction and demolition |
| D | $ml * s^{-1}$ | Slope of the volume line |
| $d_{max}$ | m | Maximum cake thickness |
| EPA | - | Environmental Protection Agency |
| EU | - | European Union |
| $\overline{F}$ | $m * s^{-1}$ | Mean filtration rate |
| H | m | Cake thickness |
| $H_e$ | m | Cake thickness at the end of filtration |
| $k_1$ | $Pa * s^{-1}$ | Slope of the pressure line |
| $M_{s,f}$ | g | Wet weight of the filter cake before drying |
| $M_{s,tr}$ | g | Weight of the filter cake after drying |
| OENORM | - | Austrian Norm |
| RCRA | - | Resource Conservation and Recovery Act |
| $R_K$ | $m^{-1}$ | Resistance of the cake |
| $R_T$ | $m^{-1}$ | Resistance of the filter medium |
| $R_{T(calc)}$ | $m^{-1}$ | Resistance of the filter medium calculated with EXCEL SOLVER® |
| RVS | - | Guidelines and Regulations for the Road Administration |
| PAH | - | Polycyclic aromatic hydrocarbons |
| t | s | Time |
| TS | % | Dry material fraction (weight based) |
| U | Volt | Voltage |
| US | - | United States |
| V | ml | Filtrate volume |
| $\dot{V}$ | $m^3 * s^{-1}$ | Volume flow |

| | | |
|---|---|---|
| $V_c$ | $m^3$ | Total cake volume per cycle |
| $V_e$ | $m^3$ | Filtrate volume at the end of filtration |
| $\propto_H$ | $m^{-2}$ | Coefficient of the resistance of the cake |
| $\Delta p$ | Pa | Pressure difference |
| $\eta$ | Pa * s | Dynamic viscosity |
| $v_F$ | m * s | Velocity of filtration |
| $v_K$ | $m^2$ * s | Velocity of cake formation |

# 8. Appendix

## Appendix 1: Patent analysis

The first key word “demolition waste processing” lists 16 patents; most of them are patented in the United States, followed by South Korea. Table 11 shows ten arbitrary examples of them.

**Table 11: Patents for the keyword "demolition waste processing"**

| ID | Published | Assignees | Title |
|---|---|---|---|
| CN104043635 | 2014-09-17 | BEIJING SIFANGRUGANG | MOBILE COMBINATION TREATMENT STATION AND METHOD FOR REPEATED USE OF DEMOLITION WASTE |
| SG146556 | 2008-10-30 | KIAT | CONTAMINATED SOIL PROCESSING SYSTEM UTILIZING WASTE HEAT |
| KR101396548 | 2014-05-20 | SAMSUNG | THE ESTIMATION DEVICE AND METHOD FOR GENERATION OF CONSTRUCTION WASTE DURING CONSTRUCTION AND DEMOLITION PHASE |
| US2009188844 | 2009-07-30 | ZE GEN | CONSTRUCTION & DEMOLITION DEBRIS (C&D) MATERIALS PROCESSING |
| CN204412345 | 2015-06-24 | HUANG | DEVICE FOR RECOVERING WASTE STEEL BARS IN BUILDING DEMOLITION |
| KR101525592 | 2015-06-03 | SAMSUNG | CALCULATION APPARATUS OF CONSTRUCTION WASTE GENERATED FOR EACH SOURCES USING GENERATION CONSTRUCTION WASTE DB AND METHOD THEREOF |
| JP2011242886 | 2011-12-01 | YOSHIMASA | OCR PATTERN SLIP FOR ELECTRONIC M/CSV REGISTRATION FOR ABUNDANT DISCHARGING OF AN ITEM OF SLUDGE OR DEMOLITION |
| CN103556604 | 2014-02-05 | JIANGSU | METHOD FOR ACHIEVING YELLOW RIVER CLOSURE THROUGH CONSTRUCTION WASTE |
| US2010044278 | 2010-02-25 | HARMON | SYSTEM AND METHOD FOR SEPARATION AND HANDLING OF CONSTRUCTION, DEMOLITION AND GARBAGE MATERIALS |

The second key word “wet processing sand” lists 117 patents from the last ten years. Most of them are registered in China, followed by the United Arab Emirates. Table 12 shows ten arbitrary examples of them.

**Table 12: Patents for the keyword "wet processing sand"**

| ID | Published | Assignees | Title |
|---|---|---|---|
| CN105033872 | 2015-11-11 | ANHUI | WET-SPRAYING SAND MATERIAL DOPED WITH CARBON NANOFIBRES AND USED FOR PUMP BODY CASTING PROCESSING |
| CN202606247 | 2012-12-19 | HENAN | DRY AND WET PROCESSING COMBINED DEVICE FOR RECYCLING OF CONSTRUCTION WASTE |
| CN1807329 | 2006-07-26 | LU DONGXUAN | BONE MATERIAL FOR CONTROLLABLE LOW-INTENSITY BACK-FILLING MATERIAL AND ITS PROCESSING METHOD |
| RU2467809 | 2012-11-27 | MEGRABJAN | METHOD OF MAKING MATERIAL FROM ERODED REEF CORAL SAND |
| CN203281359 | 2013-11-13 | CHENGDU | VERTICAL STARTING SAND MILL |
| CN201482914 | 2010-05-26 | PEIGEN | WATER GLASS WASTE SAND REGENERATION SYSTEM |
| CN102561298 | 2012-07-11 | CONGJIE | GARBAGE PROCESSING METHOD BASED ON SAND COVERING |
| CN203448285 | 2014-02-26 | NOTHERN | WET SCREENING PLANT FOR UNDERSIZE PRODUCTS OF TAILINGS |
| CN101569868 | 2009-11-04 | KUNMING | WET HIGH-EFFECTIVE CLASSIFYING GRINDING METHOD OF PHOSPHORITE |
| CN2925607 | 2007-07-25 | WANG | WETTING GRINDER FOR PROCESSING QUARTZ SAND |

The third key word “wet processing filter press” lists 24 patents from the last ten years. Most of them are registered in China, followed by the United Arab Emirates. Table 13 shows ten arbitrary examples of them.

**Table 13: Patents for the key word "wet processing filter press"**

| ID | Published | Assignees | Title |
|---|---|---|---|
| CN104147878 | 2014-11-19 | CHINA ENFI | WET DUST REMOVAL AND DESULFURIZATION INTEGRATED FLUE GAS PURIFICATION SYSTEM, WET DUST REMOVAL AND DESULFURIZATION INTEGRATED FLUE GAS PURIFICATION DEVICE AND METHOD |
| CN101380510 | 2009-03-11 | ENQING | CHROMIC SLAG WET METHOD DETOXIFCATION AND RESOURCE COMPREHENSIVE UTILIZATION NEW TECHNIQUE |
| CN102210919 | 2011-10-12 | GUANGZHOU | CHROMIUM RESIDUE WET DETOXICATION PROCESSING METHOD |
| CN104058563 | 2014-09-24 | RONG | PROCESSING EQUIPMENT SYSTEM AND METHOD FOR CONVERTING SLUDGE INTO BUILDING MATERIALS |
| CN101353725 | 2009-01-28 | HENAN | NOVEL LIQUID COOLING CLARIFICATION UNDERFLOW PROCESSING UNIT AND METHOD |
| CN103173876 | 2013-06-26 | UNIV | NANOMETER BACTERIAL CELLULOSE ULTRAFINE FIBER |

| | | ZHONGYUAN | PROCESSING METHOD |
|---|---|---|---|
| CN104222756 | 2014-12-24 | SICHUAN | PRODUCTION METHOD OF WET-GROUND GLUTINOUS RICE FLOUR CONTAINING WATER |
| CN101417826 | 2009-04-29 | LE YU | METHOD AND SYSTEM FOR PROCESSING DESULPHURIZATION WASTE WATER |
| CN103230931 | 2013-08-07 | ZHEJIANG | POLLUTED SITE UNDERGROUND WATER PROCESSING-SOIL EX-SITU LEACHING RESTORATION INTEGRAL METHOD |
| UA97902 | 2012-03-26 | DZENZERSKYI | METHOD FOR PROCESSING USED LEAD-ACID ACCUMULATORS AND STORAGE BATTERIES |

The following section presents some of the found patents in detail. These patents are chosen because they are relevant for the wet treatment process of construction waste.

**CN 104043635 – 2014-09-17:**

**Mobile combination treatment station and method for repeated use of demolition waste:**

The invention discloses a mobile combination treatment station and a method for repeated use of demolition waste. The mobile combination treatment station suitable for repeated use of the demolition waste includes a crushing device, wherein the crushing device can be connected to a screening device of the crushing device in a dismantling mode and also can be connected to a waste processing device of the screening device in a dismantling mode; the crushing device includes at least one crusher, the crusher can crush the demolition waste to obtain a crushed material, and the crushed material obtained from crushing is transported to the screening device; the screening device can screen the crushed material according to the particle size, and the crushed material obtained from screening and having a certain particle size and suitable for manufacture of building materials is transported to the waste processing device; the waste processing device includes at least one of the following machines: a ball pressing machine, a brick preparing machine, a foaming machine, and a concrete block molding machine. The mobile combination treatment station and the method for repeated use of the demolition waste can reduce pollution to the environment, make full use of the demolition waste, and reduce the resource consumption and the engineering cost [46].

**CN202606247 – 2012-12-19:**

**Dry and wet processing combined device for recycling of construction waste:**
The utility model relates to a dry and wet processing combined device for recycling of construction waste and aims at solving the problems of land occupation and environmental pollution of the existing construction waste. The technical scheme includes that the device comprises a blanking port, a crusher and a vibrating screen, wherein the blanking port is connected with a feeder through a belt conveyor, the feeder is connected with the crusher through a belt conveyor, the crusher is connected with the vibrating screen through a belt conveyor, the vibrating screen passes through a separation tube and is connected with a dry sand vibrating screen and a washing vibrating screen respectively through belt conveyors, three belt conveyors are arranged on one side of the dry sand vibrating screen, a screw sand washer is arranged under the washing vibrating screen and connected with a wheel bucket sand washer arranged in a pool, a spraying unit is arranged at the upper end of the washing vibrating screen, a belt conveyor is arranged on one side of the wheel-type sand washer, and two belt conveyors are arranged on one side of the washing vibrating screen. The combined device is novel and unique in structure and safe and convenient to use [47].

**CN104058563 – 2014-09-24:**

**Processing equipment system and method for converting sludge into building materials:**
The invention discloses a processing equipment system for converting sludge into building materials. The system comprises at least one wet sludge storage device, at least one ingredient modification device, at least one mechanical dehydration device, at least one dry combustion device and at least one powder making device, wherein the wet sludge storage device is used for containing and diluting sludge and comprises a sludge sealing and storage tank and a stirrer arranged on the sludge sealing and storage tank, the sludge sealing and storage tank is connected with a sludge pump, the ingredient modification device is connected to the sludge sealing and storage tank through a first pumping pipeline and comprises a stirring tank, an automatic feeder and a container for containing modification medicament, the

mechanical dehydration device is connected to the stirring tank through a second pumping pipeline and comprises a filter press which is used for mechanical sludge dehydration to form filter cakes, and a conveying device for conveying the filter cakes in a sealed mode, the dry combustion device is used for receiving the filter cakes conveyed by the conveying device and conducting high-temperature drying, the dry combustion device comprises a rotary type drying cylinder and a combustion furnace arranged at the feeding end of the rotary type drying cylinder, the combustion furnace provides hot air for conducting heat exchange with the filter cakes so as to evaporate water in the filter cakes, then the hot-air dried sludge is placed into the combustion furnace for high-temperature pyrogenic decomposition to form ash residues, and the powder making device comprises a pulverizer used for receiving the ash residues and refining the ash residues. The invention further provides a method for converting the sludge into the building materials [48].

## Appendix 2: Calculations

With the assumption that the filter cloth resistance is negligible compared with the filter cake resistance, $R_T$ gives

$$R_T = 0 \tag{8.1}$$

This schema is donated as *case 2*.

Equation (6.1) with (1.4) and (1.5) in (1.3) gives

$$\frac{dV}{dt} = \frac{A*\Delta p}{\eta*\alpha_H*\frac{\bar{c}*V}{A}} = \frac{A^2*\Delta p}{\eta*\alpha_H*\bar{c}*V} \tag{8.2}$$

For the experiment according to mode *constant filtration rate* the pressure difference was increased linearly with time.

$$\Delta p = k_1 * t \tag{8.3}$$

where $k_1$ denotes the slope.

Equation (8.3) in (8.2) gives

$$\frac{dV}{dt} = \frac{A^2*k_1*t}{\eta*\alpha_H*\bar{c}*V} \tag{8.4}$$

Integrating equation (8.4) gives

$$\int_{V=0}^{V} V * dV = \frac{A^2*k_1}{\eta*\alpha_H*\bar{c}} \int_{t=0}^{t} t * dt \tag{8.5}$$

$$\frac{V^2}{V} = \frac{A^2*k_1}{\eta*\alpha_H*\bar{c}} * \frac{t^2}{t} \tag{8.6}$$

$$V = \sqrt{\frac{A^2*k_1}{\eta*\alpha_H*\bar{c}}} * t \tag{8.7}$$

If the filter cloth resistance $R_T$ is not regarded negligible and the pressure difference $\triangle p$ rises again linearly, equations (1.4), (1.5), (8.3) with (1.3) give

$$\frac{dV}{dt} = \frac{A*k_1*t}{\eta*(R_T+\frac{\alpha_H*\bar{c}*V}{A})} \tag{8.8}$$

or when separating the variables

$$\left(R_T + \frac{\alpha_H*\bar{c}}{A} * V\right) dV = \frac{A*k_1}{\eta} * t * dt \tag{8.9}$$

An integration gives

$$R_T * V + \frac{\alpha_H*\bar{c}}{A} * \frac{V^2}{2} = \frac{A*k_1}{\eta} * \frac{t^2}{2} \tag{8.10}$$

This quadratic equation can be solved for V

$$V = -\frac{R_T*A}{\alpha_H*\bar{c}} + \sqrt{\left(\frac{A*R_T}{\alpha_H*\bar{c}}\right)^2 + \frac{A^2*k_1*t^2}{\eta*\alpha_H*\bar{c}}} \tag{8.11}$$

or

$$V = \frac{R_T*A}{\alpha_H*\bar{c}} * (-1 + \sqrt{1 + \frac{k_1*\alpha_H*\bar{c}*t^2}{\eta*{R_T}^2}}) \tag{8.12}$$

if

$$\frac{k_1 * \alpha_H * \bar{c} * t^2}{\eta * {R_T}^2} \gg 1$$

equation (8.12) approaches equation (8.7).

## Appendix 3: Results

Figure 28 to Figure 59 show the volume versus time and pressure versus time diagrams of all measurements. These diagrams are needed to receive the values for $k_1$ and for D. To gain $k_1$, a fit line of the pressure line is generated. The slope of this fit line gives the value for $k_1$. To gain the value for D, the slope of the fit line of the volume line is taken. This scheme is shown in Figure 28. This calculation method is applied to all measurements though not all of them show a linear increase of pressure. The measurements MT4, MT6, MT9, MT10, MT11, MT12, MT13, MT22, MT26, MT27, MT28 and MT31 do not show a linear increase of pressure and therefore, the used analyzing method is not ideal. As a consequence these values are not convincing.

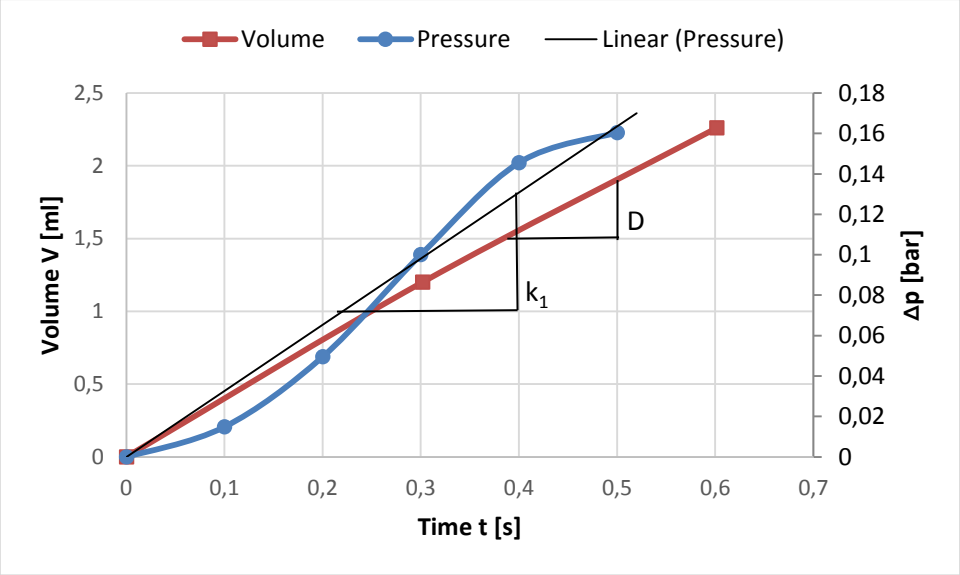



**Figure 28: MT 1**

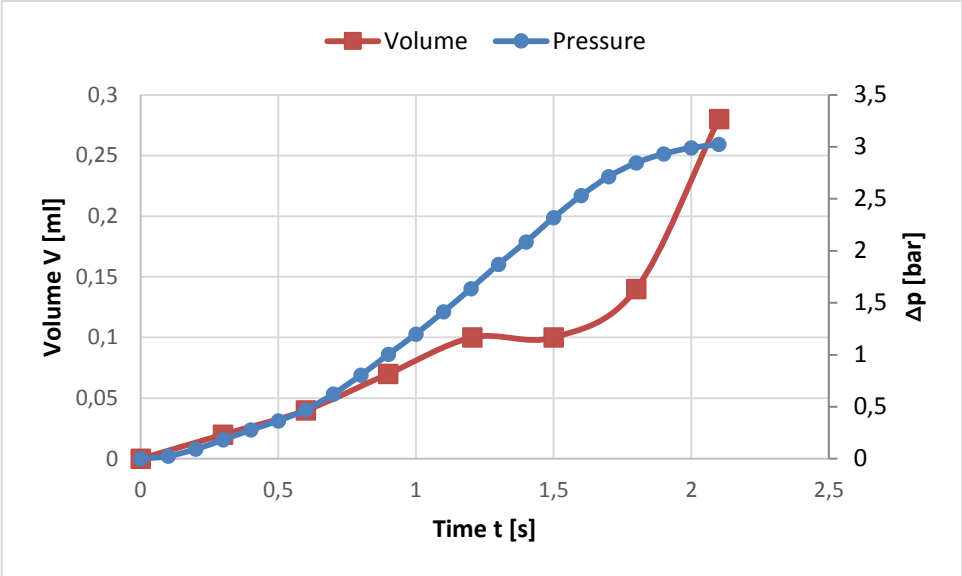



**Figure 29: MT 2**

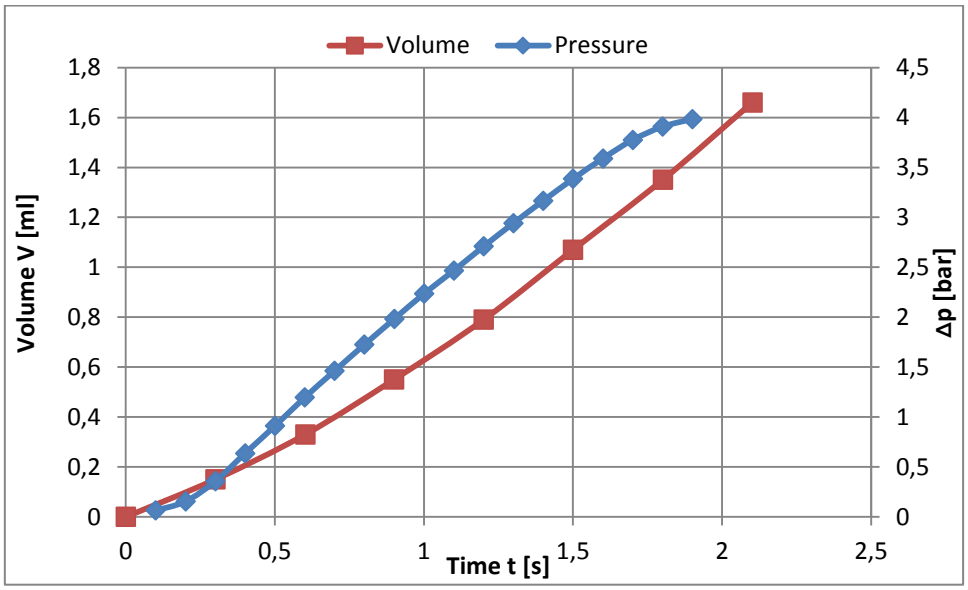



**Figure 30: MT 3**

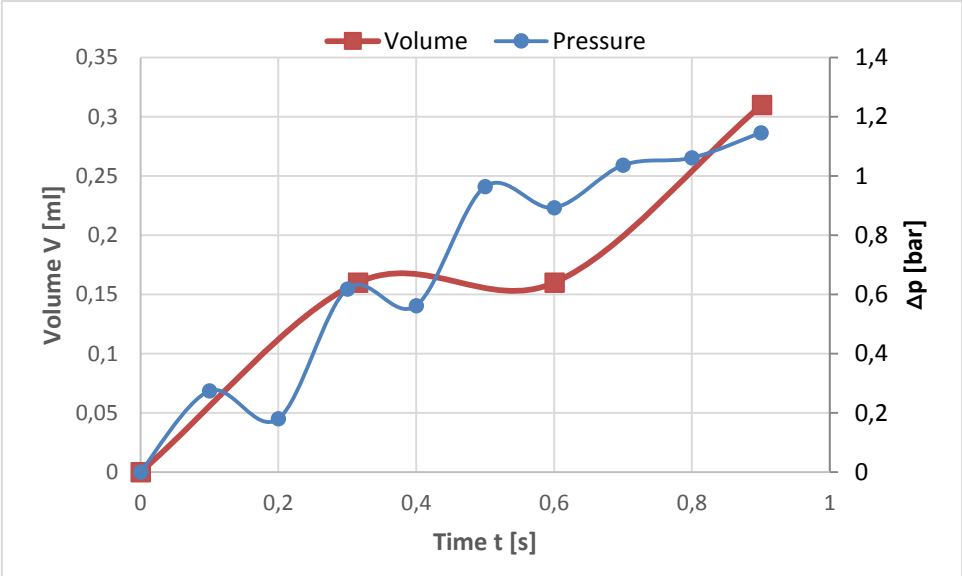



**Figure 31: MT 4**

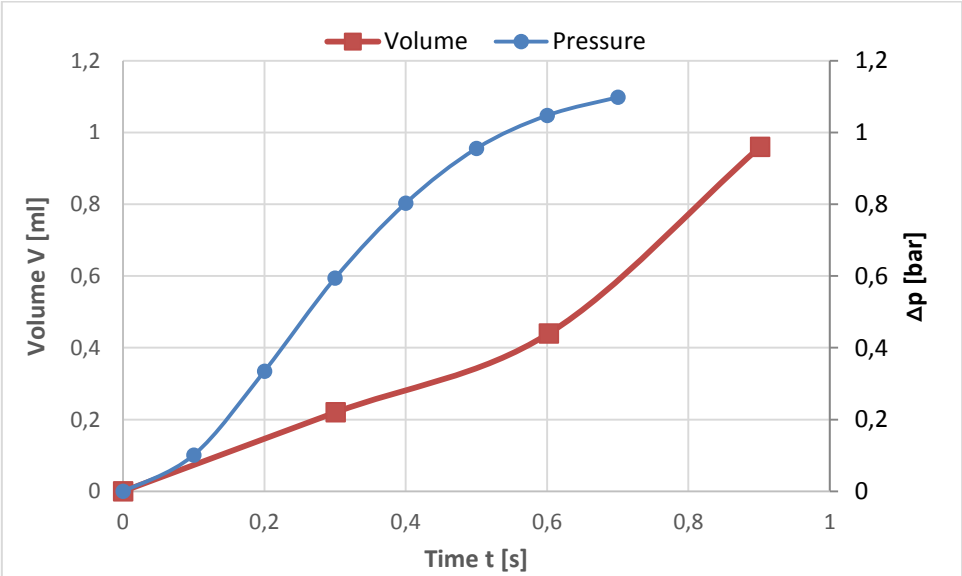



**Figure 32: MT 5**

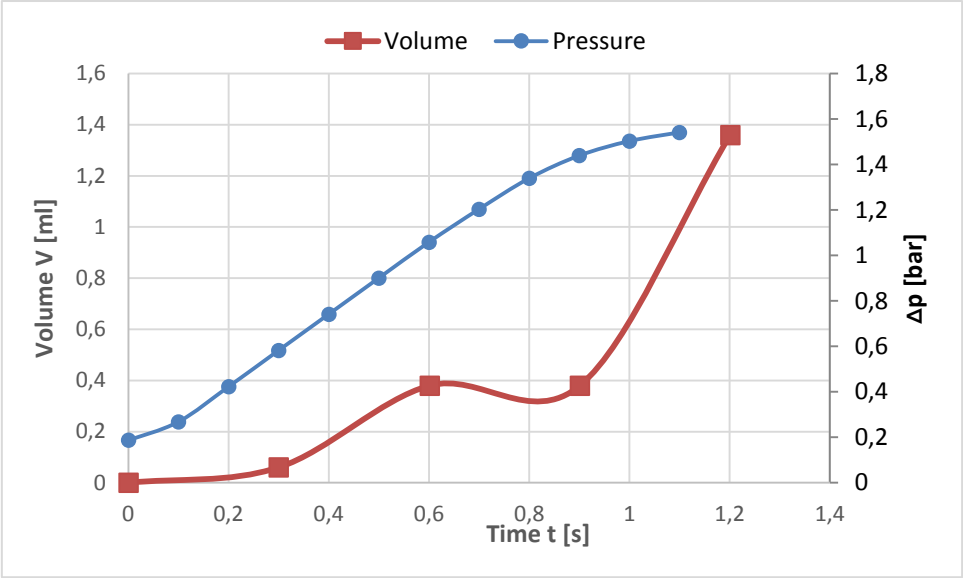



**Figure 33: MT 6**

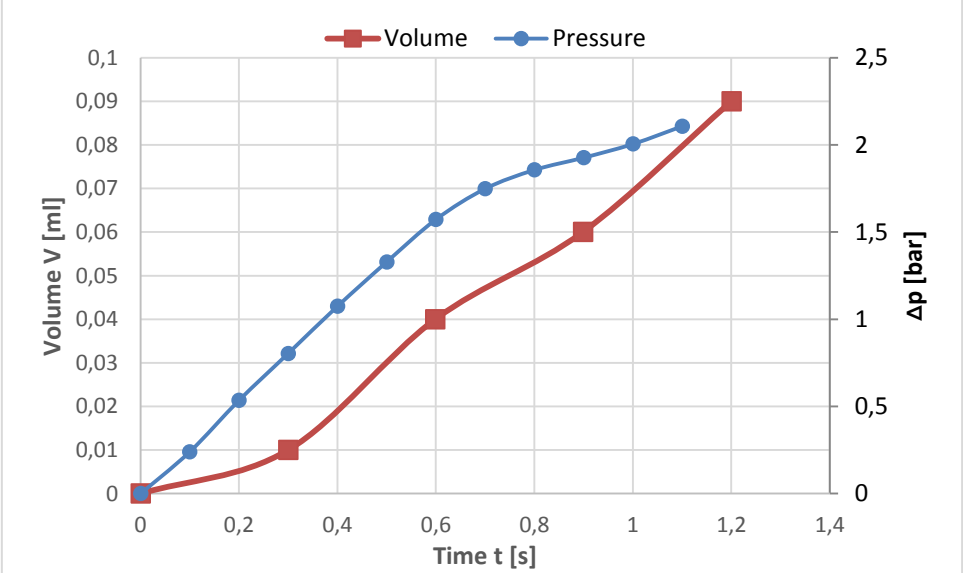



**Figure 34: MT 7**

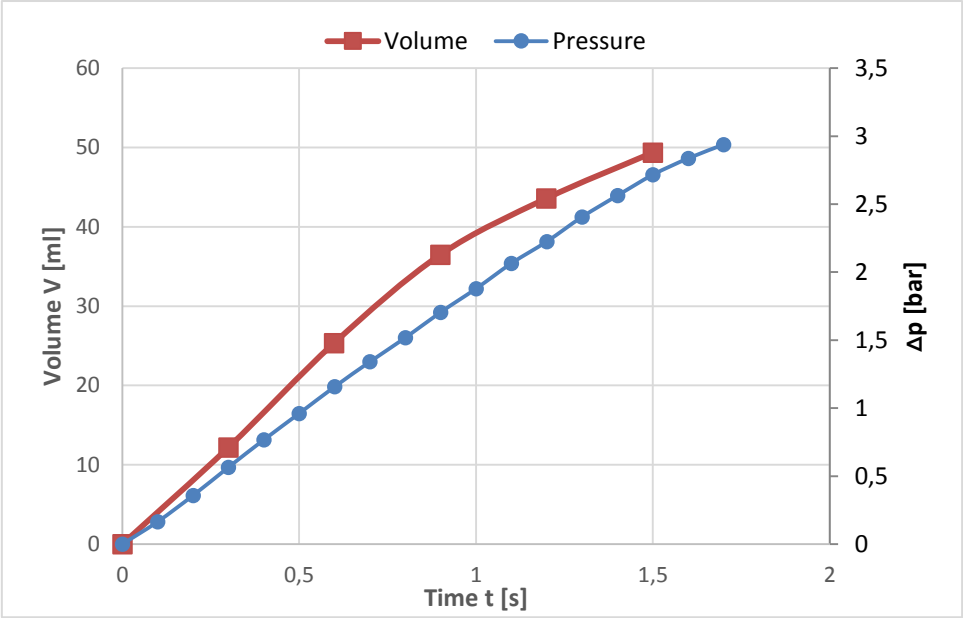



**Figure 35: MT 8**

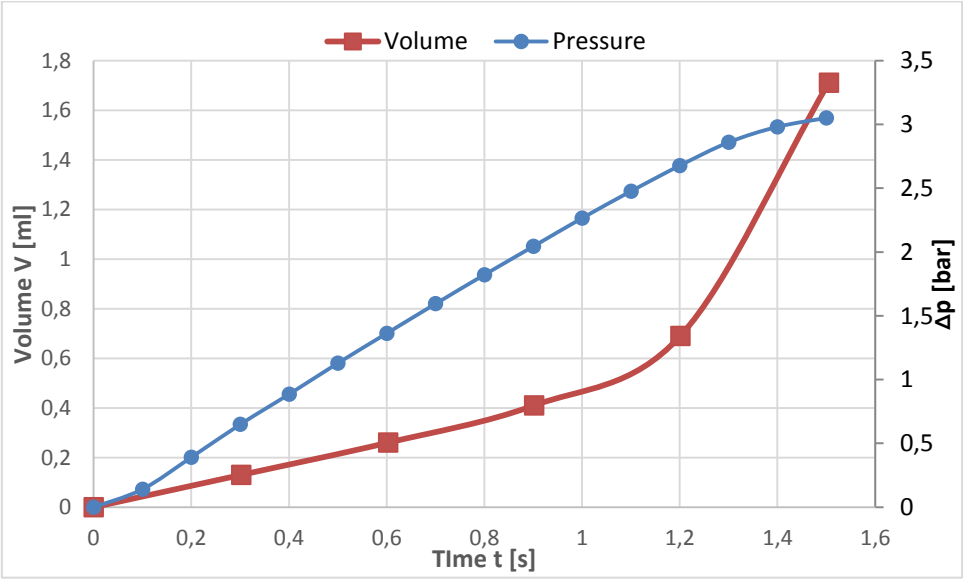



**Figure 36: MT 9**

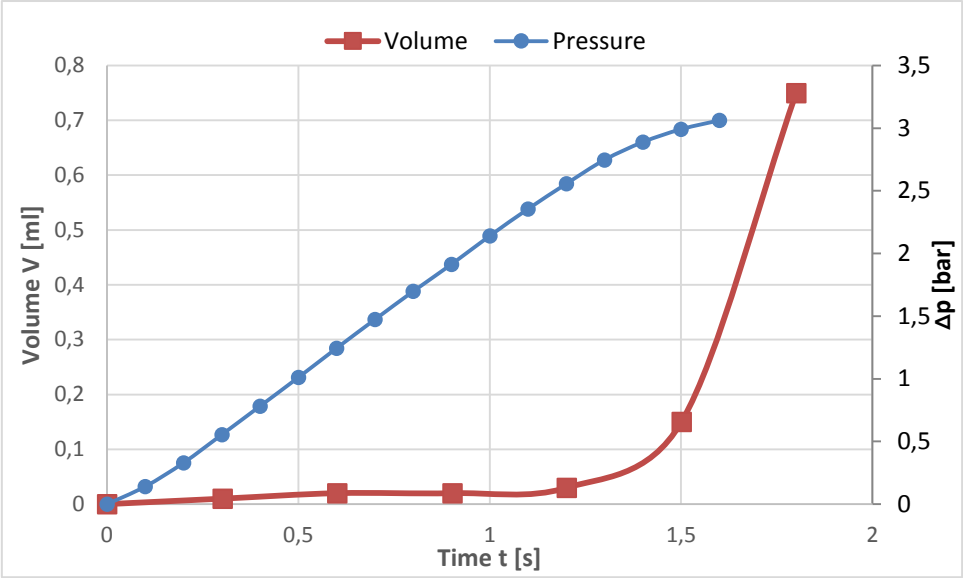



**Figure 37: MT 10**

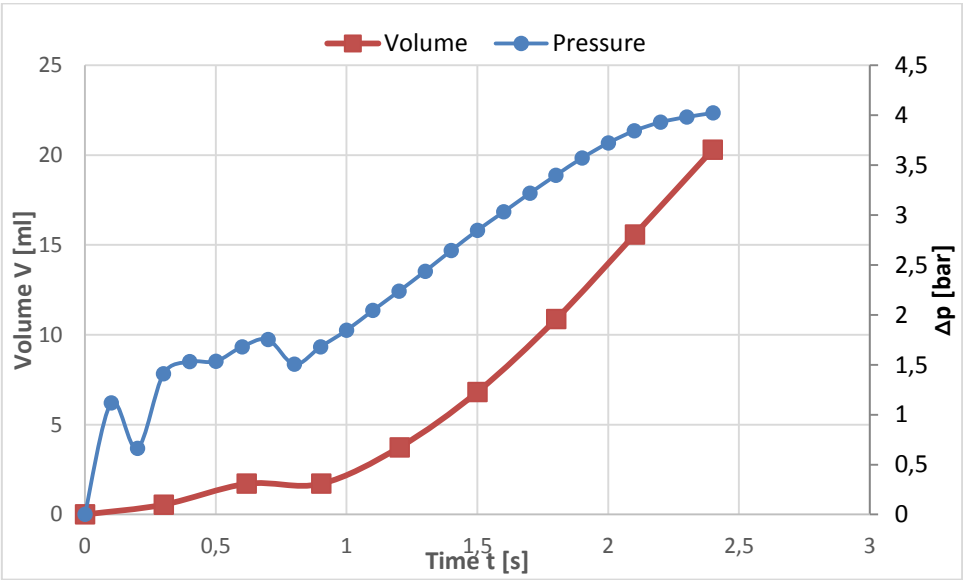



**Figure 38: MT 11**

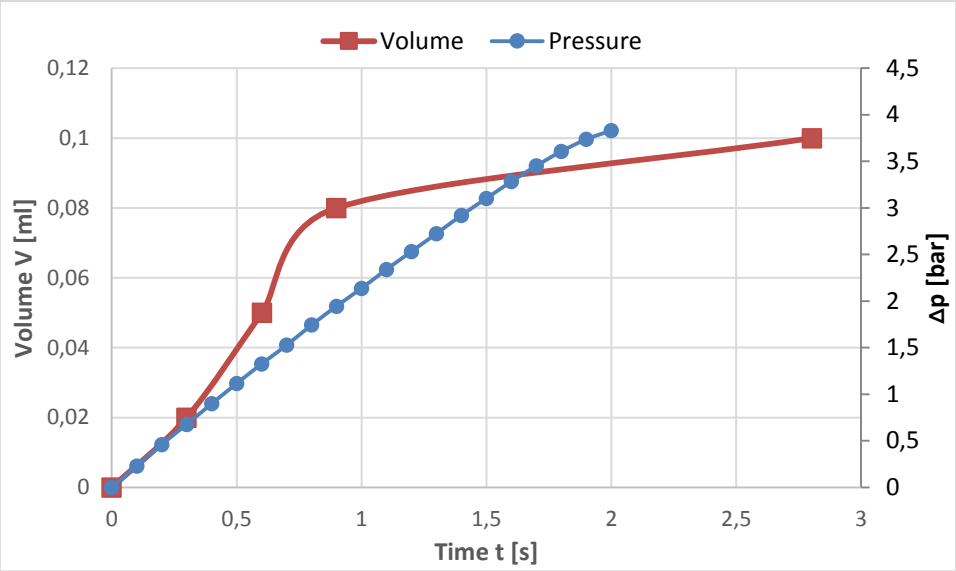



**Figure 39: MT 12**

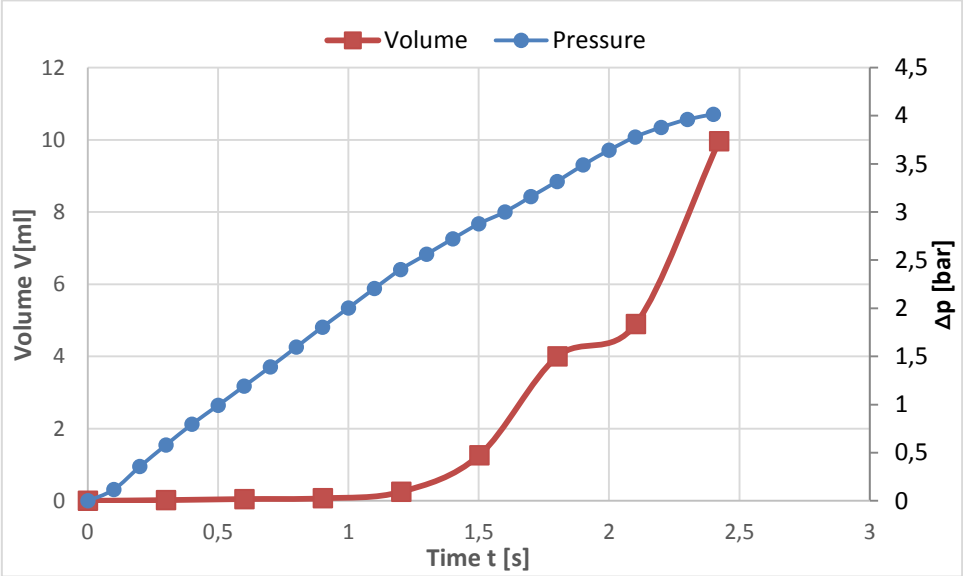



**Figure 40: MT 13**

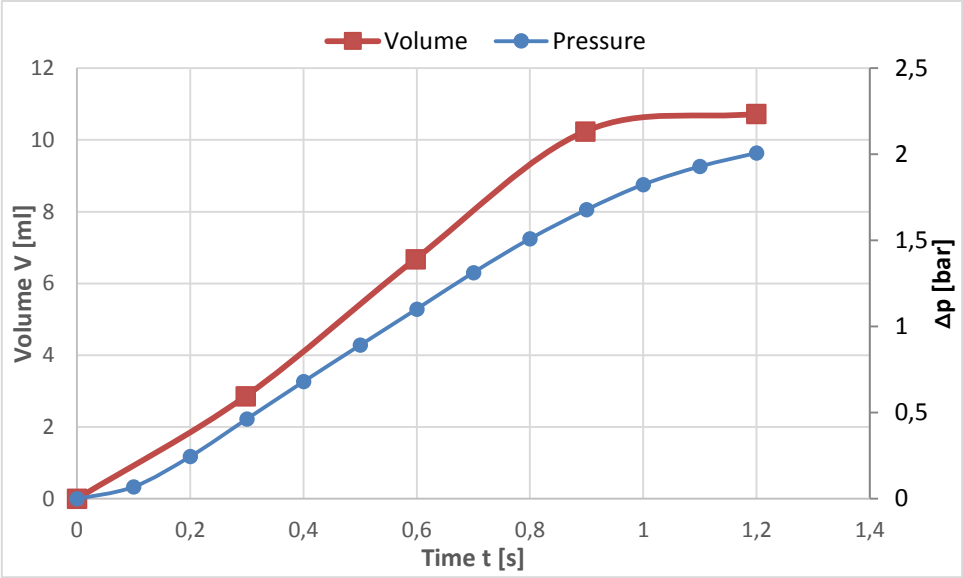



**Figure 41: MT 14**

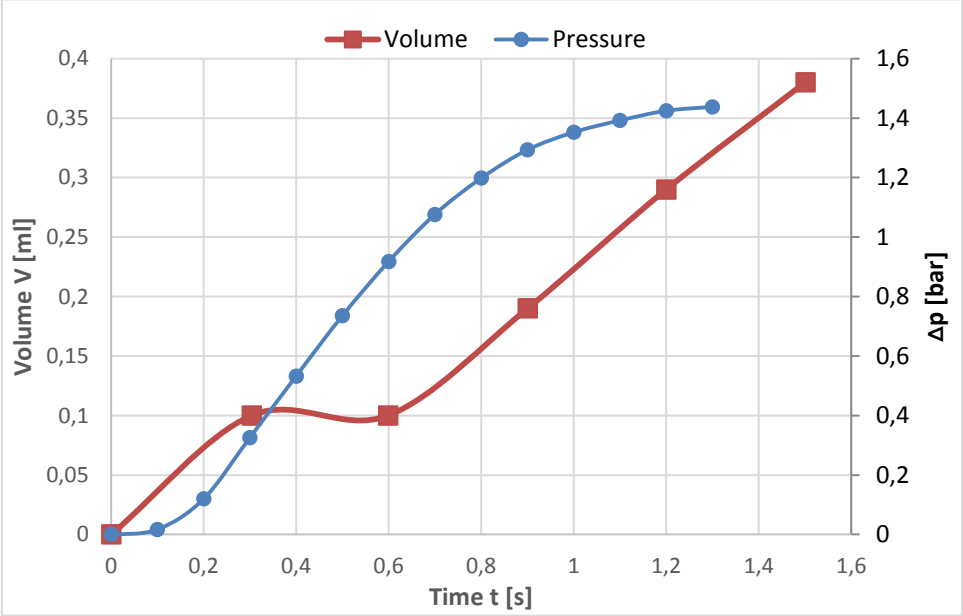



**Figure 42: MT 15**

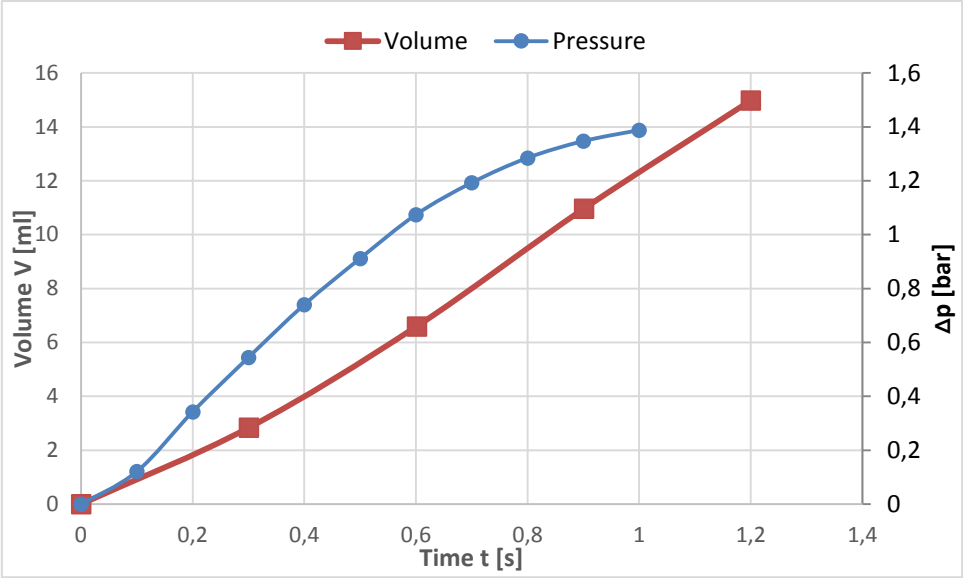



**Figure 43: MT 16**

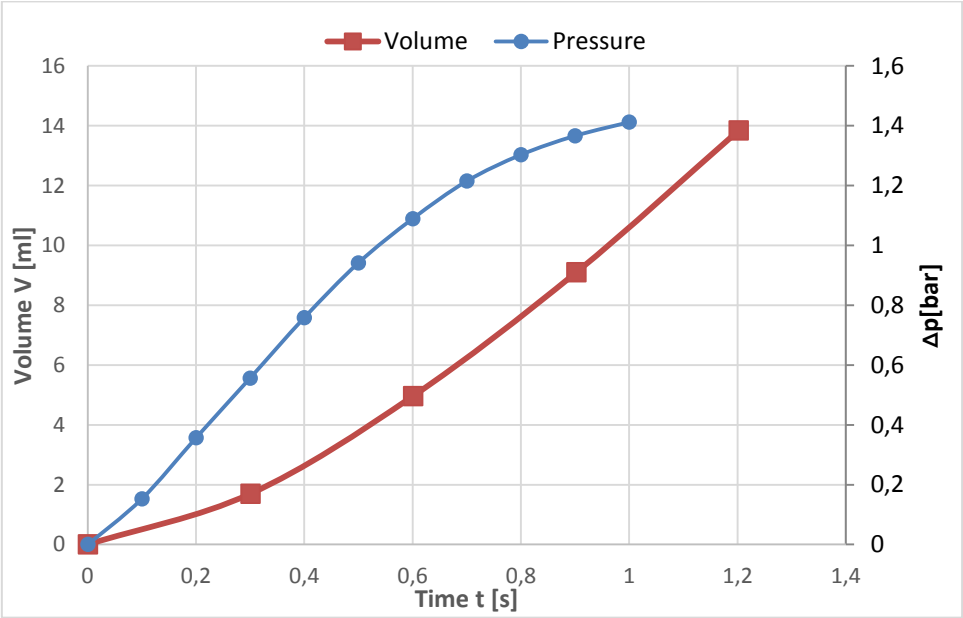



**Figure 44: MT 17**

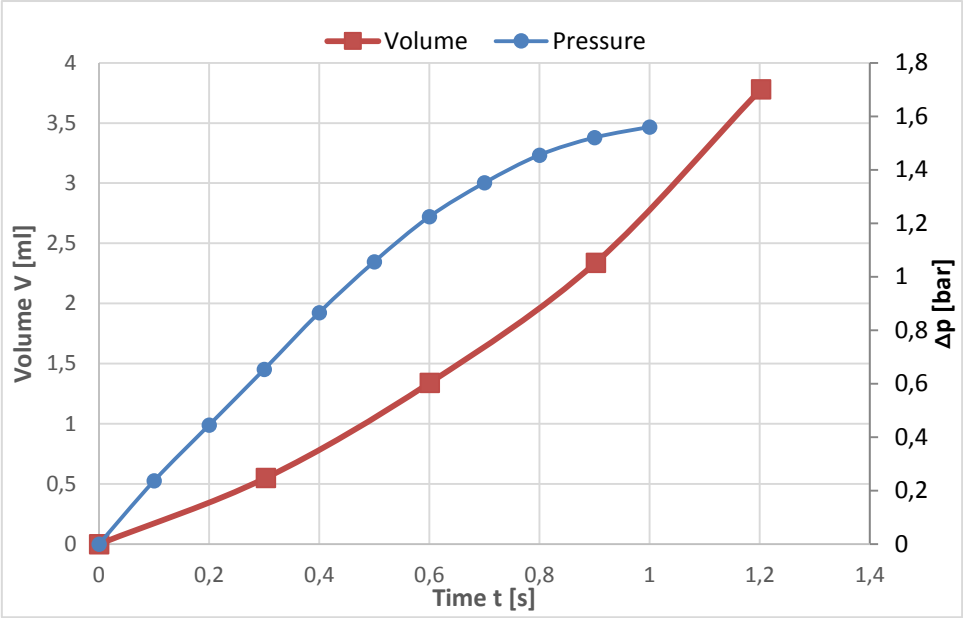



**Figure 45: MT 18**

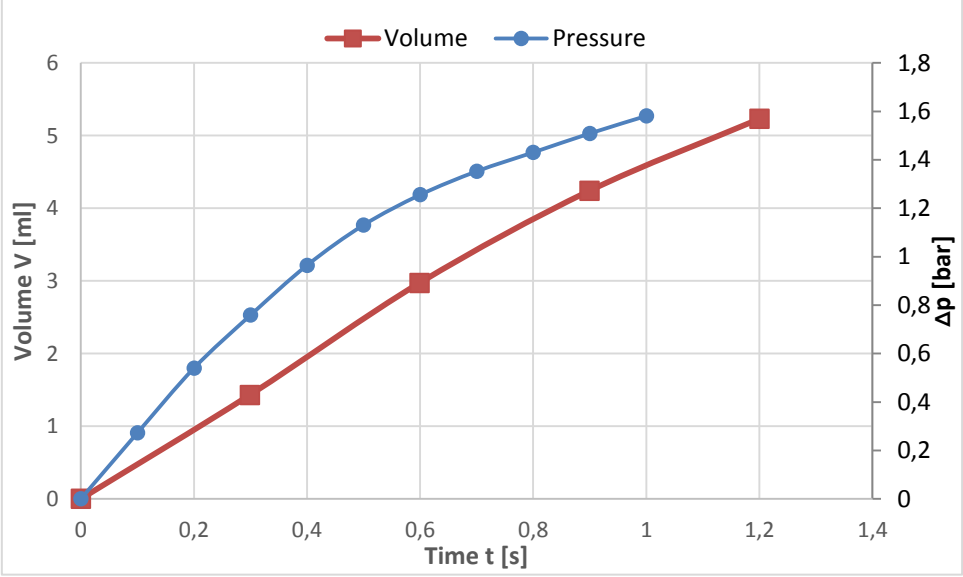



**Figure 46: MT 19**

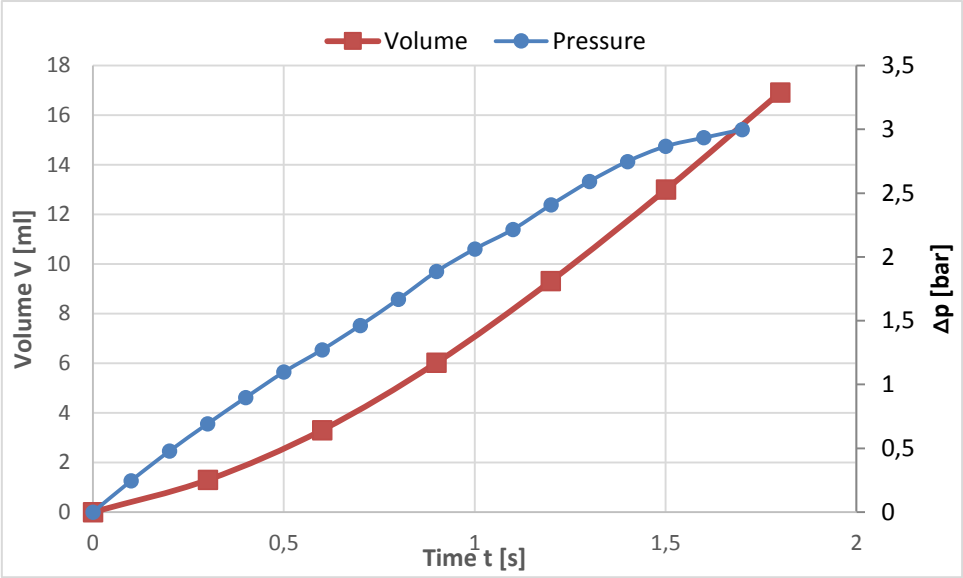



**Figure 47: MT 20**

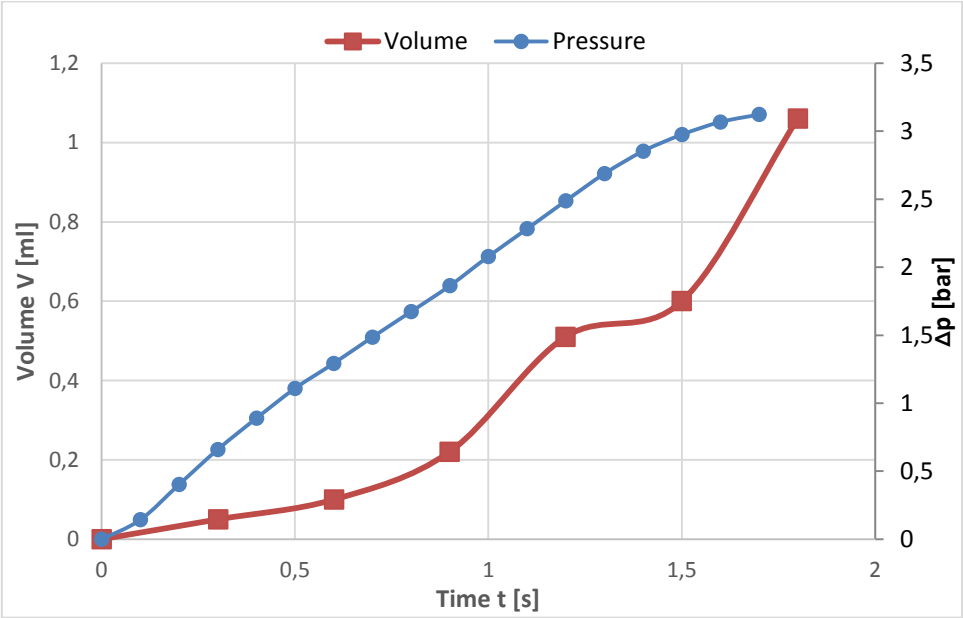



**Figure 48: MT 21**

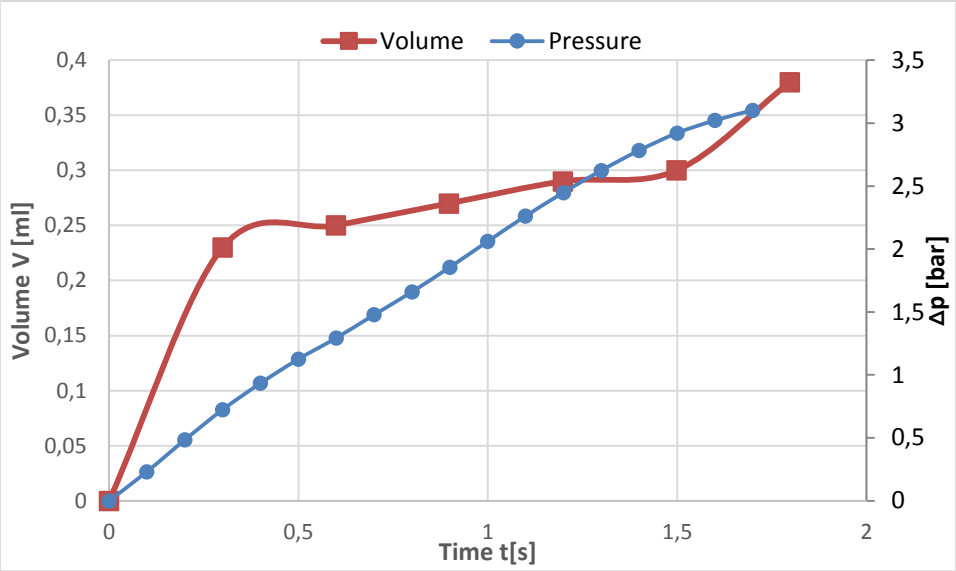



**Figure 49: MT 22**

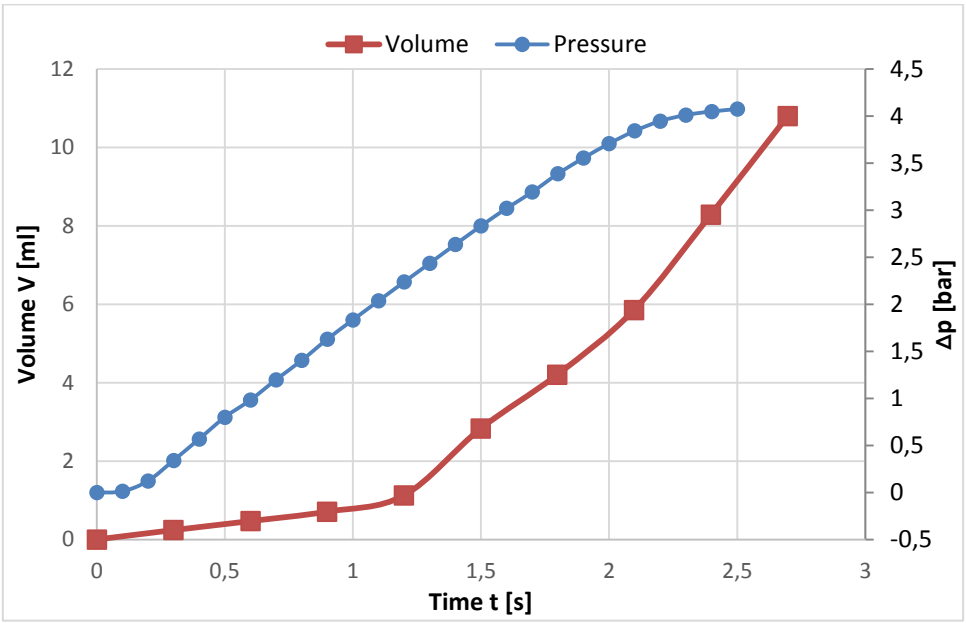



**Figure 50: MT 25**

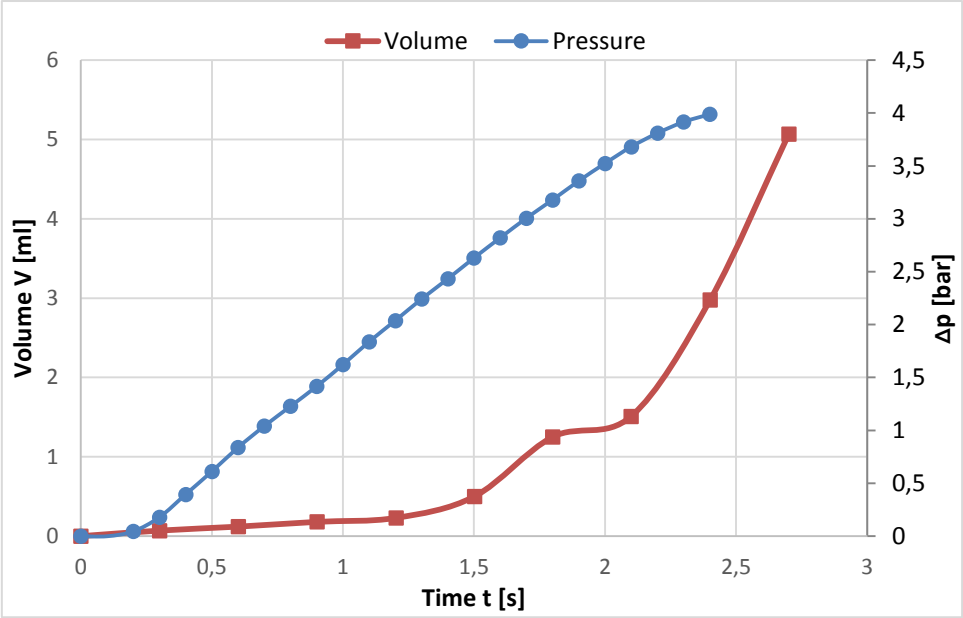



**Figure 51: MT 26**

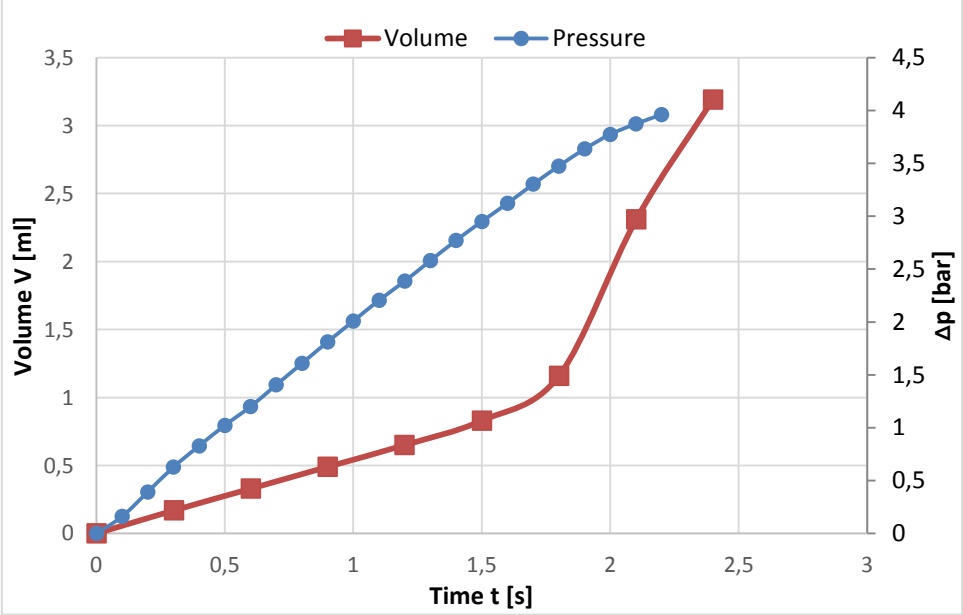



**Figure 52: MT 27**

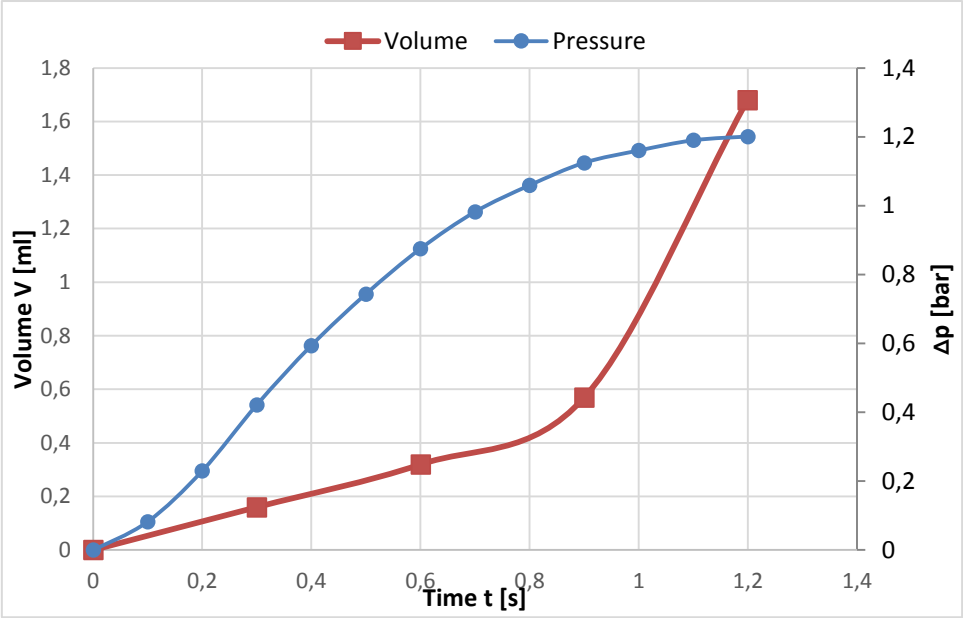



**Figure 53: MT 28**

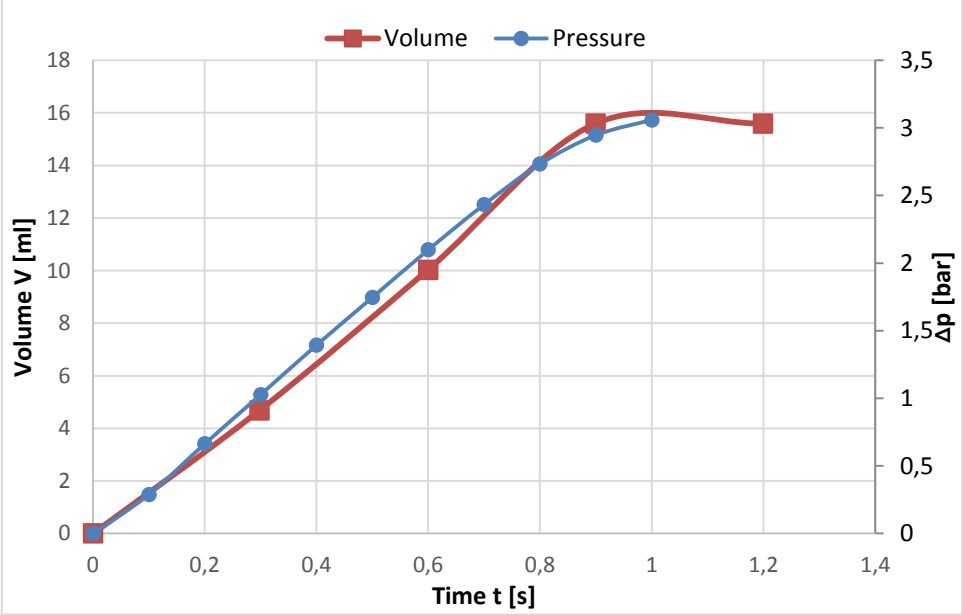



**Figure 54: MT 29**

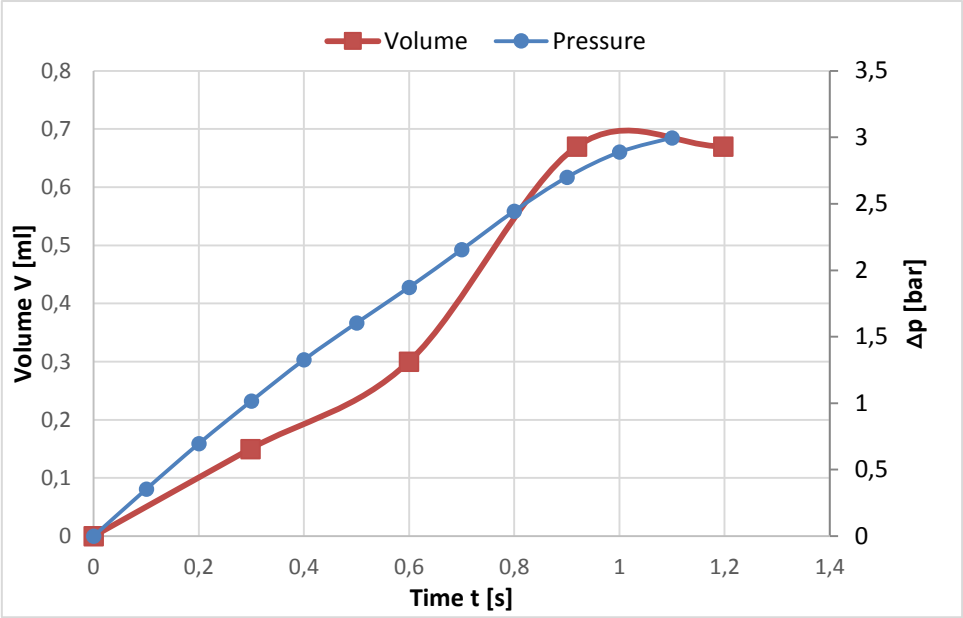



**Figure 55: MT 30**

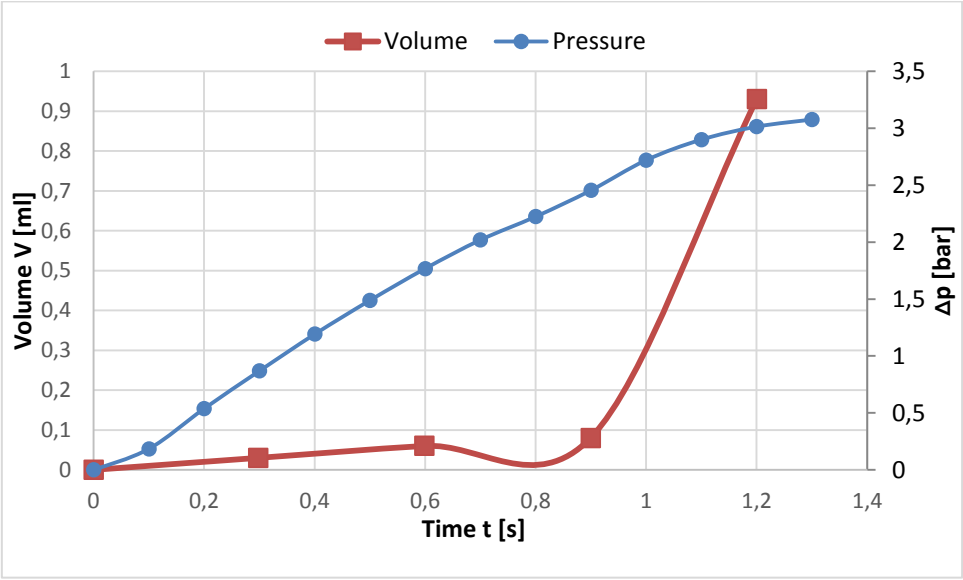



**Figure 56: MT 31**

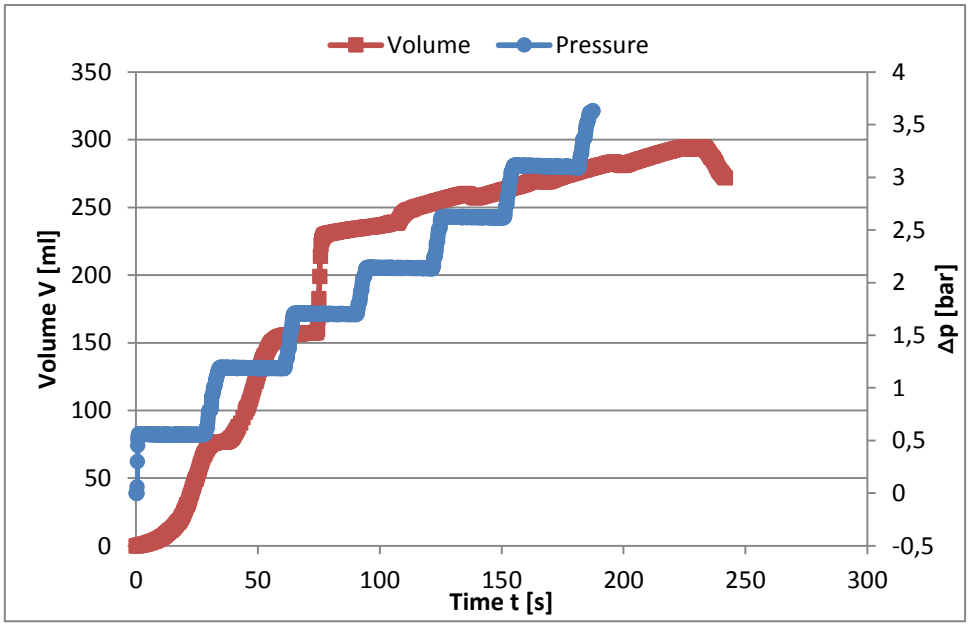



**Figure 57: MT 32**

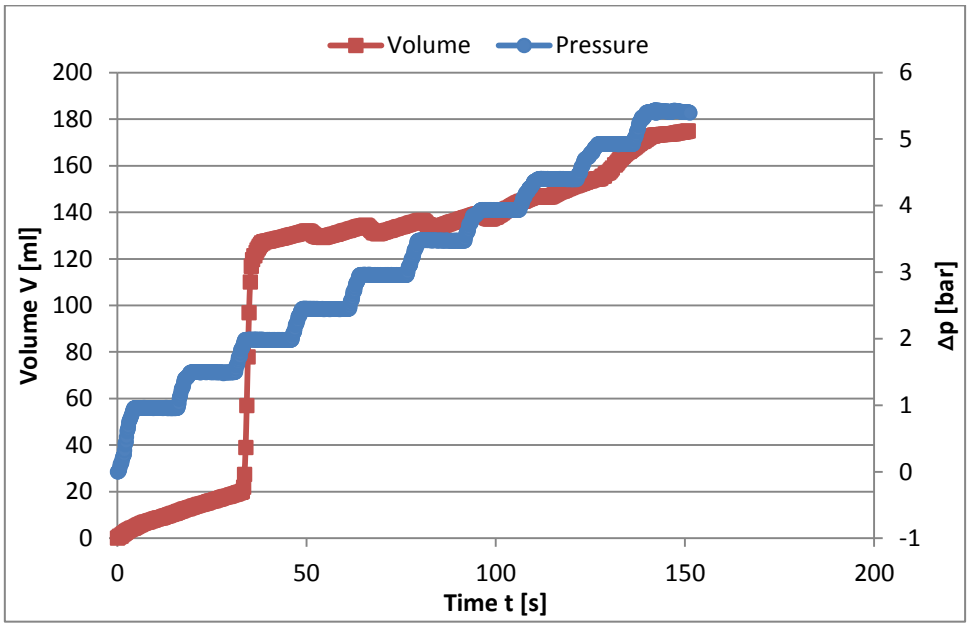



**Figure 58: MT 33**

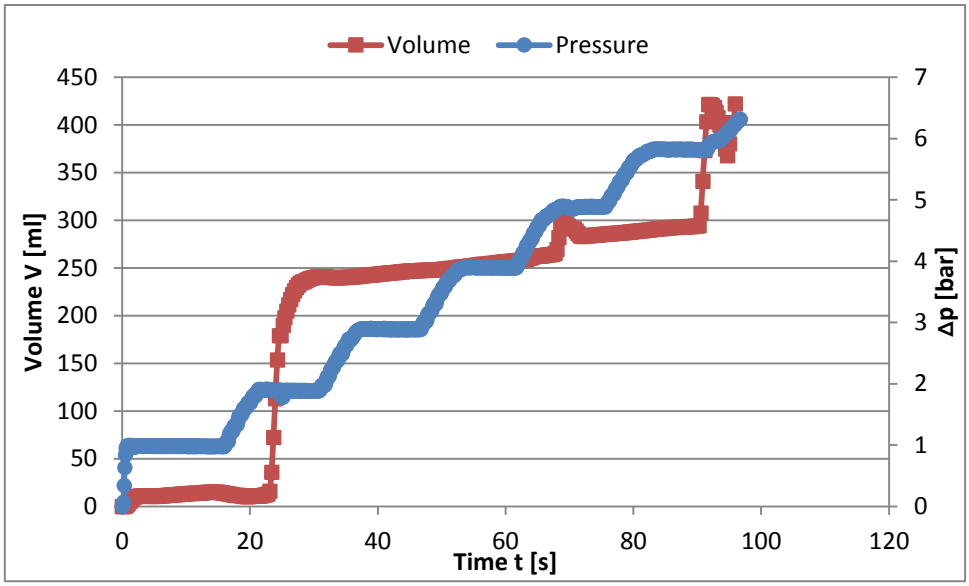



**Figure 59: MT 34**

In Table 14 the results of the main tests MT1-MT34 are summarized. In the first column the pressure difference is shown. These values represent the applied end pressure. In the second column the total filtration time span is shown. Total filtration time span represents the duration of the experiment. In the third column the value D is shown. This value is read from Figure 28 to Figure 59. The deviation of these values is described above. In the forth column the filtration volume is shown. The filtration volume represents the total volume that is gathered in the beaker. In the fifth column the values for $k_1$ are shown. These values are read from Figure 28 to Figure 59. The deviation of these values is described above. In the sixth column the coefficient of the filter cake $\alpha_H$ is shown. $\alpha_H$ is calculated with equation (5.12). In the seventh column the filter cake resistance $R_K$ is shown. $R_K$ is calculated with equation (1.4). In the eighth column the volume stream $\dot{V}$ is shown. The volume stream symbolizes the mass of suspension that passes the chamber filter press per second. In the ninth column the resistance of the filter cloth that is calculated by EXCEL SOLVER® is shown. The starting value for the iteration was $10^8$ $m^{-1}$. In the tenth column the resistance of the filter cloth that is calculated with equation (5.11) is shown. In the eleventh column the filtration velocity $\nu_F$ is shown. This value is calculated with equation (5.6). In the twelfth column the cake formation velocity $\nu_K$ is shown. This velocity is calculated with equation (5.7). In the thirteenth column the concentration ration of cake volume to cumulative filtrate volume $\bar{c}$ is shown. This value is calculated with equation (1.5).

**Table 14: Main tests - results**

| Test no° | Δp [bar] | t [s] | D [ml/s] | V [ml] | $k_1$ [bar/s] | $\alpha_H$ [1/m²] | $R_K$[1/m] | $\dot{V}$ [m³/s] | $R_{T\,(calc)}$ [1/m] | $R_T$ [1/m] | $v_F$ [m/s] | $v_K$[m/s] | $\bar{c}$ [-] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MT 1** | 2 | 172.45 | 4.63 | 799.03 | 0.33 | $1.30*10^{14}$ | $7.79*10^{12}$ | $1.64*10^{-7}$ | $1*10^{8}$ | $5.93*10^{12}$ | $9.94*10^{-6}$ | $4.78*10^{-13}$ | $4.81*10^{-8}$ |
| **MT 2** | 3 | 62.36 | 11.32 | 706.02 | 1.45 | $8.50*10^{13}$ | $5.10*10^{12}$ | $3.77*10^{-7}$ | $1*10^{8}$ | $2.17*10^{13}$ | $7.07*10^{-6}$ | $3.84*10^{-13}$ | $5.44*10^{-8}$ |
| **MT 3** | 4 | 38.40 | 11.52 | 442.25 | 2.19 | $7.78*10^{13}$ | $4.67*10^{12}$ | $5.48*10^{-7}$ | $1*10^{8}$ | $2.95*10^{13}$ | $7.22*10^{-6}$ | $6.27*10^{-13}$ | $8.68*10^{-8}$ |
| **MT 4** | 1 | 26.09 | 9.71 | 253.22 | 1.44 | $4.12*10^{13}$ | $2.47*10^{12}$ | $2.59*10^{-7}$ | $1*10^{8}$ | $6.21*10^{12}$ | $1.00*10^{-5}$ | $1.52*10^{-12}$ | $1.52*10^{-7}$ |
| **MT 5** | 1 | 99.95 | 5.18 | 517.64 | 1.75 | $3.60*10^{14}$ | $2.16*10^{13}$ | $2.96E*10^{-8}$ | $1.*10^{8}$ | $3.31*10^{12}$ | $5.80*10^{-6}$ | $4.30*10^{-13}$ | $7.42*10^{-8}$ |
| **MT 6** | 2 | 77.11 | 4.75 | 365.89 | 1.60 | $2.77*10^{14}$ | $1.66*10^{13}$ | $7.71*10^{-8}$ | $1*10^{8}$ | $6.07*10^{12}$ | $6.89*10^{-6}$ | $7.23*10^{-13}$ | $1.05*10^{-7}$ |
| **MT 7** | 2 | 127.78 | 2.69 | 343.38 | 2.21 | $1.12*10^{15}$ | $6.72*10^{13}$ | $1.90*10^{-8}$ | $1*10^{8}$ | $3.44*10^{12}$ | $4.64*10^{-6}$ | $5.18*10^{-13}$ | $1.12*10^{-7}$ |
| **MT 8** | 3 | 15.60 | 16.72 | 260.88 | 1.83 | $1.82*10^{13}$ | $1.09*10^{12}$ | $1.76*10^{-6}$ | $1*10^{8}$ | $3.21*10^{13}$ | $7.88*10^{-6}$ | $1.16*10^{-12}$ | $1.47*10^{-7}$ |
| **MT 9** | 3 | 39.92 | 7.78 | 302.68 | 2.19 | $1.16*10^{14}$ | $6.99*10^{12}$ | $2.75*10^{-7}$ | $1*10^{8}$ | $1.49*10^{13}$ | $7.72*10^{-6}$ | $9.80*10^{-13}$ | $1.27*10^{-7}$ |
| **MT 10** | 3 | 57.89 | 6.87 | 397.45 | 2.05 | $1.85*10^{14}$ | $1.11*10^{13}$ | $1.73*10^{-7}$ | $1*10^{8}$ | $1.32*10^{13}$ | $6.83*10^{-6}$ | $6.60*10^{-13}$ | $9.66*10^{-8}$ |
| **MT 11** | 4 | 33.58 | 7.29 | 244.79 | 1.86 | $9.13*10^{13}$ | $5.48*10^{12}$ | $4.67*10^{-7}$ | $1*10^{8}$ | $1.87*10^{13}$ | $8.98*10^{-6}$ | $1.41*10^{-12}$ | $1.57*10^{-7}$ |
| **MT 12** | 4 | 25.11 | 10.23 | 256.85 | 2.04 | $5.35*10^{13}$ | $3.21*10^{12}$ | $7.97*10^{-7}$ | $1*10^{8}$ | $2.62*10^{13}$ | $8.88*10^{-6}$ | $1.33*10^{-12}$ | $1.50*10^{-7}$ |
| **MT 13** | 4 | 17.42 | 9.69 | 168.79 | 1.83 | $3.51*10^{13}$ | $2.11*10^{12}$ | $1.22*10^{-6}$ | $1*10^{8}$ | $2.48*10^{13}$ | $1.05*10^{-5}$ | $2.39*10^{-12}$ | $2.28*10^{-7}$ |
| **MT 14** | 2 | 50.99 | 5.42 | 276.22 | 1.78 | $1.79*10^{14}$ | $1.07*10^{13}$ | $1.19*10^{-7}$ | $1*10^{8}$ | $6.93*10^{12}$ | $7.89*10^{-6}$ | $1.10*10^{-12}$ | $1.39*10^{-7}$ |
| **MT 15** | 1 | 48.04 | 5.91 | 283.72 | 1.29 | $1.12*10^{14}$ | $6.73*10^{12}$ | $9.51*10^{-8}$ | $1*10^{8}$ | $3.78*10^{12}$ | $9.28*10^{-6}$ | $1.26*10^{-12}$ | $1.35*10^{-7}$ |
| **MT 16** | 1 | 80.07 | 3.68 | 294.57 | 1.59 | $3.68*10^{14}$ | $2.21*10^{13}$ | $2.90*10^{-8}$ | $1*10^{8}$ | $2.35*10^{12}$ | $6.84*10^{-6}$ | $8.92*10^{-12}$ | $1.30*10^{-7}$ |
| **MT 17** | 1 | 41.41 | 5.51 | 228.19 | 1.61 | $1.29*10^{14}$ | $7.76*10^{12}$ | $8.24*10^{-8}$ | $1*10^{8}$ | $3.53*10^{12}$ | $9.06*10^{-6}$ | $1.52*10^{-12}$ | $1.68*10^{-7}$ |
| **MT 18** | 2 | 51.92 | 4.73 | 245.56 | 1.81 | $2.12*10^{14}$ | $1.27*10^{13}$ | $1.01*10^{-7}$ | $1*10^{8}$ | $6.05*10^{12}$ | $7.84*10^{-6}$ | $1.23*10^{-12}$ | $1.56*10^{-7}$ |
| **MT 19** | 2 | 85.25 | 3.07 | 201.77 | 1.84 | $4.21*10^{14}$ | $2.52*10^{13}$ | $5.07*10^{-8}$ | $1*10^{8}$ | $3.93*10^{12}$ | $6.19*10^{-6}$ | $1.18*10^{-12}$ | $1.90*10^{-7}$ |
| **MT 20** | 3 | 42.87 | 5.71 | 244.90 | 1.95 | $1.56*10^{14}$ | $9.35*10^{12}$ | $2.05*10^{-7}$ | $1*10^{8}$ | $1.10*10^{13}$ | $8.16*10^{-6}$ | $1.28*10^{-12}$ | $1.57*10^{-7}$ |
| **MT 21** | 3 | 66.35 | 4.67 | 310.01 | 2.00 | $3.04*10^{14}$ | $1.82*10^{13}$ | $1.05*10^{-7}$ | $1*10^{8}$ | $8.97*10^{12}$ | $6.64*10^{-6}$ | $8.22*10^{-13}$ | $1.24*10^{-7}$ |
| **MT 22** | 3 | 41.98 | 5.29 | 221.92 | 1.98 | $1.68*10^{14}$ | $1.01*10^{13}$ | $1.91*10^{-7}$ | $1*10^{8}$ | $1.01*10^{13}$ | $8.23*10^{-6}$ | $1.42*10^{-12}$ | $1.73*10^{-7}$ |
| **MT 25** | 4 | 41.68 | 6.75 | 281.46 | 1.79 | $1.18*10^{14}$ | $7.08*10^{12}$ | $3.62*10^{-7}$ | $1*10^{8}$ | $1.73*10^{13}$ | $8.42*10^{-6}$ | $1.15*10^{-12}$ | $1.36*10^{-7}$ |
| **MT 26** | 4 | 34.49 | 6.99 | 241.04 | 1.71 | $9.01*10^{13}$ | $5.41*10^{12}$ | $4.74*10^{-7}$ | $1*10^{8}$ | $1.79*10^{13}$ | $9.26*10^{-6}$ | $1.47*10^{-12}$ | $1.59*10^{-7}$ |
| **MT 27** | 4 | 18.59 | 8.55 | 158.90 | 1.92 | $4.45*10^{13}$ | $2.67*10^{12}$ | $9.58*10^{-7}$ | $1*10^{8}$ | 2.19E+13 | $1.06*10^{-5}$ | $2.57*10^{-12}$ | $2.42*10^{-7}$ |
| **MT 28** | 1 | 23.69 | 5.83 | 138.08 | 1.20 | $5.19*10^{13}$ | $3.11*10^{12}$ | $2.06*10^{-7}$ | $1*10^{8}$ | $3.73*10^{12}$ | $1.29*10^{-5}$ | $3.58*10^{-12}$ | $2.78*10^{-7}$ |
| **MT 29** | 3 | 10.80 | 16.07 | 173.50 | 3.31 | $2.37*10^{13}$ | $1.42*10^{12}$ | $1.35*10^{-6}$ | $1.27*10^{8}$ | $3.09*10^{13}$ | $7.80*10^{-6}$ | $1.73*10^{-12}$ | $2.21*10^{-7}$ |
| **MT 30** | 3 | 1.50 | 58.18 | 87.27 | 2.97 | $8.16*10^{11}$ | $4.90*10^{10}$ | $3.92*10^{-5}$ | $1.91*10^{-4}$ | $1.12*10^{14}$ | $2.68*10^{-6}$ | $1.18*10^{-12}$ | $4.40*10^{-7}$ |
| **MT 31** | 3 | 3.31 | 66.69 | 220.57 | 2.64 | $1.39*10^{12}$ | 8.37*1010 | 2.29*10-5 | 0 | $1.28*10^{14}$ | $2.33*10^{-6}$ | $4.06*10^{-13}$ | $1.74*10^{-7}$ |
| **MT 32** | 3.5 | 42.26 | 3.17 | 133.79 | 0.02 | $2.75*10^{12}$ | $1.65*10^{11}$ | $1.36*10^{-5}$ | 0 | $7.09*10^{12}$ | $4.29*10^{-5}$ | $1.23*10^{-11}$ | $2.87*10^{-7}$ |
| **MT 33** | 5.5 | 2.70 | 38.27 | 103.29 | 0.04 | $2.94*10^{10}$ | $1.77*10^{9}$ | $1.99*10^{-3}$ | 0 | $1.35*10^{14}$ | $4.0*10^{-6}$ | $1.52*10^{-12}$ | $3.72*10^{-7}$ |
| **MT 34** | 6.5 | 5.11 | 56.02 | 286.17 | 0.07 | $6.60*10^{10}$ | $3.96*10^{9}$ | $1.05*^{10-3}$ | 0 | $2.33*10^{14}$ | $2.79*10^{-6}$ | $3.74*10^{-13}$ | $1.34*10^{-7}$ |

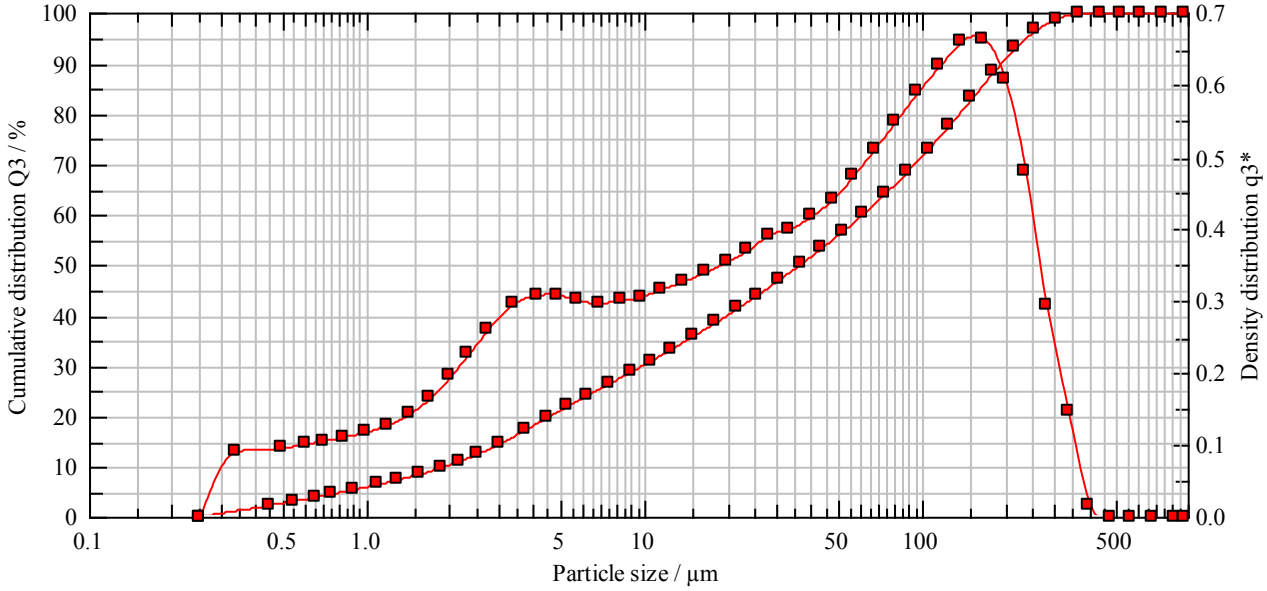
# Appendix 4: Particle size measurement

Sympatec GmbH
System-Partikel-Technik

HELOS-Partikelgrößenanalyse
*WINDOX 5*

**HELOS (H2395) & RODOS, R2+R5**
**Gesteinsmehl** **2017-04-24**

**$x_{10}$ = 1,92 µm** **$x_{50}$ = 36,15 µm** **$x_{90}$ = 193,32 µm** **SMD = 4,67 µm** **VMD = 70,30 µm**
$x_{16}$ = 3,39 µm $x_{84}$ = 155,94 µm $x_{99}$ = 318,92 µm $S_V$ = 1,29 m²/cm³ $S_m$ = 12854,20 cm²/g




**Cumulative distribution**

| $x_0$/µm | $Q_3$/% | $x_0$/µm | $Q_3$/% | $x_0$/µm | $Q_3$/% | $x_0$/µm | $Q_3$/% |
|---|---|---|---|---|---|---|---|
| 0,45 | 2,31 | 3,75 | 17,36 | 30,50 | 47,07 | 255,00 | 96,47 |
| 0,55 | 3,13 | 4,50 | 19,80 | 36,50 | 50,18 | 305,00 | 98,74 |
| 0,65 | 3,87 | 5,25 | 21,86 | 43,50 | 53,36 | 365,00 | 99,87 |
| 0,75 | 4,52 | 6,25 | 24,14 | 51,50 | 56,59 | 435,00 | 100,00 |
| 0,90 | 5,39 | 7,50 | 26,48 | 61,50 | 60,24 | 515,00 | 100,00 |
| 1,10 | 6,41 | 9,00 | 28,86 | 73,50 | 64,19 | 615,00 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 100,00 | | | | | |
| 1,30 | 7,34 | 10,50 | 30,90 | 87,50 | 68,35 | 735,00 |
| | 100,00 | | | | | |
| 1,55 | 8,43 | 12,50 | 33,29 | 105,00 | 73,01 | 875,00 |
| | 100,00 | | | | | |
| 1,85 | 9,70 | 15,00 | 35,88 | 125,00 | 77,74 | |
| 2,15 | 10,97 | 18,00 | 38,56 | 150,00 | 82,96 | |
| 2,50 | 12,45 | 21,50 | 41,29 | 180,00 | 88,21 | |
| 3,00 | 14,51 | 25,50 | 44,02 | 215,00 | 92,91 | |

**Density distribution (log.)**

| $x_m$/µm | $q_3$lg | $x_m$/µm | $q_3$lg | $x_m$/µm | $q_3$lg | $x_m$/µm | $q_3$lg |
|---|---|---|---|---|---|---|---|
| 0,34 | 0,09 | 3,35 | 0,29 | 27,89 | 0,39 | 234,15 | 0,48 |
| 0,50 | 0,09 | 4,11 | 0,31 | 33,37 | 0,40 | 278,88 | 0,29 |
| 0,60 | 0,10 | 4,86 | 0,31 | 39,85 | 0,42 | 333,65 | 0,15 |
| 0,70 | 0,11 | 5,73 | 0,30 | 47,33 | 0,44 | 398,47 | 0,02 |
| 0,82 | 0,11 | 6,85 | 0,30 | 56,28 | 0,47 | 473,31 | 0,00 |
| 0,99 | 0,12 | 8,22 | 0,30 | 67,23 | 0,51 | 562,78 | 0,00 |
| 1,20 | 0,13 | 9,72 | 0,31 | 80,20 | 0,55 | 672,33 | 0,00 |
| 1,42 | 0,14 | 11,46 | 0,32 | 95,85 | 0,59 | 801,95 | 0,00 |
| 1,69 | 0,17 | 13,69 | 0,33 | 114,56 | 0,63 | | |
| 1,99 | 0,19 | 16,43 | 0,34 | 136,93 | 0,66 | | |
| 2,32 | 0,23 | 19,67 | 0,35 | 164,32 | 0,66 | | |
| 2,74 | 0,26 | 23,41 | 0,37 | 196,72 | 0,61 | | |

**Evaluation: WINDOX 5.6.0.0, *FREE***

Revalidierung:
Referenzmessung: 04-24 11:01:05
Kontamination: 0,00 %

**Product: Gesteinsmehl**

Dichte: 1,0000 g/cm³, Formfaktor: 1,000
Disp. Meth.: Standard_Trocken_1.5bar_VC_f..
$C_{opt}$= 5,65 %

**Trigger: Standard_Trocken_tolerant**

Start: c.opt >= 4%
Gültigkeit: 2% <= c.opt <= 15%
Stopp: 10s c.opt <= 2% or 120s real time
Zeitbasis: 100,0 ms

**User paramater:**

Benutzer: Michael Piller
Probe: Mischkalk
Nummer: 0,00
Nummer: