

Master Thesis

**Avoidance of Permeability
Reduction of Sand Control
Installations caused by Fines and
Sand Invasion from poorly
consolidated Sandstone
Formations**

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Written by:

Sebastian Trummer, Bsc
m0835046

Adviser:

Univ.-Prof. Dipl.-Ing. Dr.mont. Herbert Hofstätter
Dipl.-Ing. Robert Maier

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Acknowledgement

First of all, I would like to thank my parents, my grandparents, my brother and all of my family for all they have done for me over the last 25 years. Raising me has not always been easy and it may have seemed as if I took them for granted; yet I never did. Their mentoring and unconditional support in many ways greatly helped me, especially through the years of my bachelor and master program.

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Kurzfassung

„Verhinderung der Permeabilitätsreduktion von Sandkontroll- installationen verursacht durch Feinteil- und Sandinvasion verursacht durch schlecht konsolidierte Sandsteinformationen“

Diese Diplomarbeit vergleicht und evaluiert verschiedene chemische Systeme zur Verbesserung der Feinteil- und Sandzurückhaltung in schlecht konsolidierten Sandsteinformationen. Weiters wird evaluiert, ob exzellente Sortierung und Sphärizität des Gravel Pack Materials die Feinteil- und Sandzurückhaltung verbessern und die Leistungsfähigkeit des Gravel Packing Systems positiv beeinflussen.

Kommerziell verfügbare chemische Systeme, die benutzt werden um entweder das Gravel Pack Material oder die Sandkörner der Formation zu beschichten, werden auf ihre Effizienz und ihren Wert in der praktischen Anwendung evaluiert. Diese Chemikalien sollen die Zurückhaltung feiner Teile durch die Sandkontrollenheiten verbessern oder die bohrlochnahe Zone der Formation konsolidieren, um zu verhindern, dass Sand- oder Feinteile den Gravel Pack erreichen. Dadurch soll verhindert werden, dass Sand- oder Feinteile in die Gravel Pack Installation eindringen und den Porenraum, sowie die Durchlässigkeit des Filtermaterials reduzieren. Es wird jedoch erwartet, dass die chemischen in-situ Konsolidierungssysteme die Permeabilität der Formation leicht reduzieren. Die Anwendung und Effizienz dieser Chemikaliensysteme wird im Labor getestet.

Als Alternative oder zusätzlich zu chemischen Methoden zur Verbesserung von Sand- und Feinteilzurückhaltung werden Glasperlen mit nahezu perfekter Sphärizität und besserer Sortierung, die bei geringeren Mediandurchmessern gleiche Permeabilitäten wie herkömmliche Filtermaterial zeigen, evaluiert.

Die durch Labortests gewonnen Resultate zeigen, dass diese neuen Filtermaterialien für Gravel Pack Installationen geeignet sind, da sie leicht verbesserte Sand- und Feinteilrückhaltung liefern. Weiters konnten erfolgreiche Ergebnisse durch die Harzbeschichtung des Gravel Pack Filtermaterials gewonnen werden, wobei die Kombination aus Harzbeschichtung und den neuen Filtermaterialien die besten Resultate lieferte. Künstliche Ausfällungen als in-situ Konsolidierungsmechanismus zeigten ebenfalls Erfolge. Andere Methoden wie Polymer-Konsolidierung oder Nano-Partikel Beschichtung des Gravel Pack Materials zeigten nur ungenügende Resultate und waren nicht in der Lage das Eindringen zu verhindern. Die Anwendung von acrylischen Harzen als in-situ Konsolidierungsmechanismus andererseits, stoppte die Sand- und Feinteil Migration, resultierte aber in einem völligen Verlust der Formationspermeabilität.

Abstract

“Avoidance of Permeability Reduction of Sand Control Installations caused by Fines and Sand Invasion from poorly consolidated Sandstone Formations”

This thesis compares and evaluates the potential of chemical systems to improve the sand and fines retention in poorly consolidated sandstone formations. Furthermore, it is evaluated if excellent sorting and sphericity of the gravel pack material will improve sand and fines retention and positively influence the performance of gravel packing systems.

Commercially available chemical systems, which are used to either, coat the gravel pack material or sand grains of the formation, are evaluated for their efficiency and practical value in well operations. These chemicals are claimed to improve the retention of finer particle sizes by sand control installations or to consolidate the near wellbore formation, avoiding that finer particles reach the gravel pack (GP). As a consequence, sand and fines should not invade the GP installation and therefore not reduce the pore space and finally the conductivity of the filter material. It is expected that the chemical in-situ consolidation systems will slightly reduce the permeability of the formation. The application and efficiency of the chemical systems is tested in a laboratory setup.

As an alternative or addition to chemical means to improve the sand and fines retention of GP installations, glass beads filter material with near-perfect sphericity and better sorting, which demonstrated equal pack permeability as common proppants at lower median grain diameters, are evaluated.

The results obtained by the laboratory tests indicate, that these new filter materials are indeed suitable for gravel pack installations since they provide slightly improved sand and fines retention. Furthermore, successful results could be obtained by resin coating of the gravel pack filter material, whereas the combination of resin coating and new filter materials showed the best results. Artificial scaling as an in-situ consolidation mechanism proved to be successful as well. Other methods, such as consolidation by polymers or nano-particle coating of the gravel pack material showed insufficient results and were not able to stop the sand and fines invasion. The application of in-situ consolidation of the formation by an acrylic resin on the other hand was able to stop sand and fines migration but resulted in the complete loss of formation permeability.

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1 Introduction

Sand and fines particle production is a problem that can be encountered in many reservoirs worldwide. The produced particles do not have any kind of economic value but lead to severe technical problems in production and to additional costs for disposal.

1.1 Problem Definition

Finer particles of poorly consolidated sandstone formations are often mobilized during production due to their low mechanical failure resistance. This highly undesirable effect results in excessive sand production, destabilizing the formation, eroding well equipment and in severe cases even in well kills.

To protect the formation, well installations, and surface equipment from the damaging effects of sand and fines production, sand control methods such as gravel packs, frac packs and high rate water packs are installed in wells producing from poorly consolidated formations. While these sand control units will protect the wellbore from damage if designed properly, they are often subjected to impairment of themselves. The migration tendency of fine material will lead to plugging the sand control installations resulting in a reduction or total loss of conductivity and so, deteriorating the well's performance. Frequent workovers that are required to minimize the damage caused by fines invasion are cost-intensive and may lead to elongated, uneconomic down-times.

To improve the fines and sand retention of the sand control installations, either the filter material itself or the near wellbore area can be treated chemically to stabilize fines and sand and so avoid their mobilization. Alternatively to the chemical treatments, new and innovative filter materials claimed to allow for smaller grain sizes at the same or higher pack conductivity could provide the improved material retention, prolonging the efficiency of the sand-control installation.

1.2 Objective

The objective of this thesis is the evaluation of commercially available chemical methods and innovative filter materials for gravel packs, high rate water packs and frac pack installations in order to improve sand and fines retention capabilities. Furthermore, successfully tested chemical methods will also be evaluated for their applicability with the new and innovative filter materials to prove that in combination with these new filter materials, the positive sand retention effects can be maximized.

2 Literature Review

2.1 Definition of Sand, Fines and Sandstones

Siliciclastic sediments like sandstones, conglomerates and shales consist mainly of silicate particles, which have been formed by weathering breakdown of older rocks followed by diagenesis and by pyroclastic volcanism. 20-25 percent of these siliciclastic sediments are sandstones that are based on a framework of sand particles with a diameter of 0.063 to 2mm. [1]

The exact definition is thereby met by the phi scale [2] and the Wentworth range [3], classifying the framework grains of clastic sediments as, either boulder, cobble, gravel, sand, silt, clay or colloid by their diameter size (Figure 1). This is also the basis for the grain size definition in the ISO norm. [4]

ϕ scale	size range	Wentworth range	name	other names
-8 to $-\infty$	256- ∞ mm	10.1- ∞ in	boulder	
-6 to -8	64-256 mm	2.5-10.1 in	cobble	
-5 to -6	32-64 mm	1.26-2.5 in	very coarse gravel	pebble
-4 to -5	16-32 mm	0.63-1.26 in	coarse gravel	pebble
-3 to -4	8-16 mm	0.31-0.63 in	medium gravel	pebble
-2 to -3	4-8 mm	0.157-0.31 in	fine gravel	pebble
-1 to -2	2-4 mm	0.079-0.157 in	very fine gravel	granule
0 to -1	1-2 mm	0.039-0.079 in	very coarse sand	
1 to 0	0.5-1 mm	0.020-0.039 in	coarse sand	
2 to 1	0.25-0.5 mm	0.010-0.020 in	Medium sand	
3 to 2	125-250 μ m	0.0049-0.010 in	fine sand	
4 to 3	62.5-125 μ m	0.0025-0.0049 in	very fine sand	
8 to 4	3.9-62.5 μ m	0.00015-0.0025 in	Silt	mud
∞ to 8	1/ ∞ -3.9 μ m	1/ ∞ -0.00015 in	clay	mud
∞ to 10	1/ ∞ -1 μ m	1/ ∞ -0.000039 in	colloid	mud

Figure 1: Phi Scale and Wentworth Range Sedimentary Grain Size Classification [5]

The phi scale is defined by

$$\phi = -\log_2 D/D_0 \quad (1)$$

where D is the particle diameter in mm and D₀ is the reference diameter, which is equivalent to 1mm. [2]

Since the framework grains of sediments are hardly ever within one single range window, sediments as well as sedimentary rocks are subdivided by the percentual content of grains (Figure 2) as well as by their mineralogical and matrix material content. Sediments with a matrix content of below 5% are thereby subdivided into different types of arenites (depending on their mineralogy) whereas a matrix content of 5-50% defines a wacke. Matrix contents of more than 50% indicate a mudrock. (Figure 3)

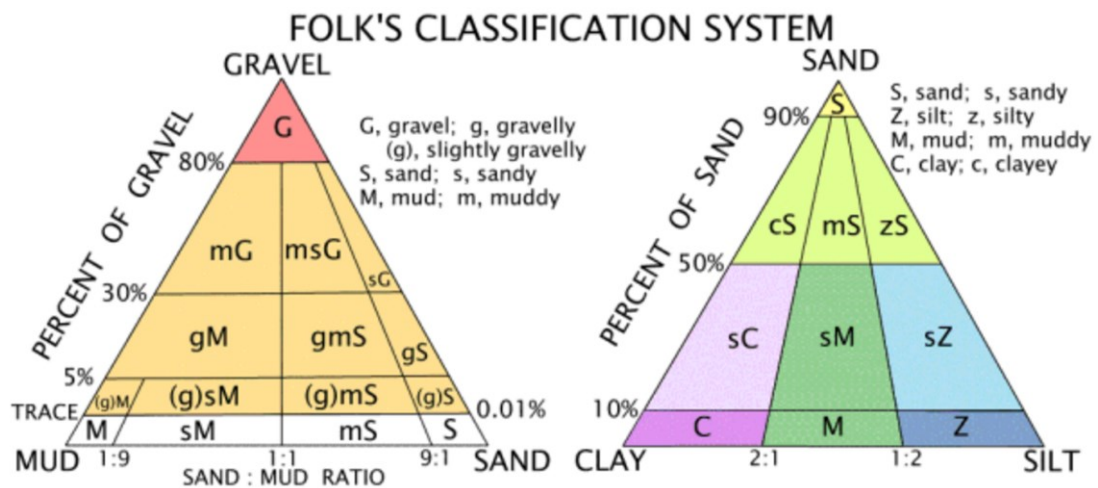


Figure 2: Classification of Sedimentary Rocks by Grain Size [6]

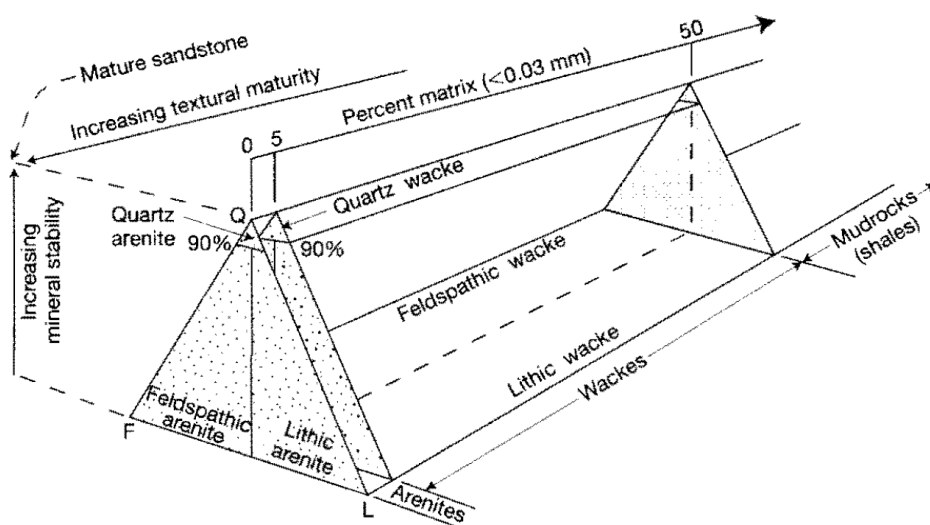


Figure 3: Classification of Sandstones by Mineral Components [1]

The major minerals found in sandstones are Quartz (avg. 65%), different types of feldspars (10-15%) as well as rock fragments (10-15%). These rock fragments are of igneous, metamorphic or sedimentary (mostly fine sandstone, siltstone shale and chert) origin that have not yet fully disintegrated. Their content is highly variable in sandstone frameworks while at the same time they are rarely be found in other siliciclastic sediments such as shale.

Other accessory minerals that can be found in lower abundances in sandstones contain coarse micas and heavy minerals with a specific gravity of more than 2.9. These heavy minerals are subdivided in stable non-opaque minerals, metastable non-opaque minerals, stable opaque minerals and metastable opaque minerals.

The interstitial space between the framework sand grains can be filled with grains smaller than 0.03 mm in diameters that are called matrix material and support the framework of sandstone in terms of mechanical stability. In mineralogical terms, these small particles are classified as fine size micas, quartz, feldspar and mostly clays like illite, smectite, kaolinite and chlorite.

The abundance of these fine matrix grains in the interstitial space is highly variable and determines the classification of the sandstone. Sandstones with a matrix material content of less than 5% are called arenites while those with a matrix content of 5-50% are called wackes with their characteristic grey color.

Another essential part for the rock composition are chemical cements with variable abundance. These cements may consist of silicate (mainly quartz but also cherts, opal, feldspars and zeolite), carbonate (mainly calcite but also aragonite, dolomite and siderite), iron oxide (hematite, limonite, goethite) and sulfate minerals (anhydrite, gypsum, barite). Thereof, silicate minerals and especially quartz are the most common types of cement minerals that can be found in sandstones. [1]

The definition of fines within sedimentary rocks on the other hand is not as precise and of purely mechanical nature. While many engineers regard 45 μm as the borderline (since there are no finer commonly available sieves), others tend to take a more relative approach, defining fines as particles smaller than the median grain size of the sandstone divided by 6.5 (Figure 4). In many medium sandstones, this calculation results in a definition of fines being smaller than approximately 50 μm . [5]

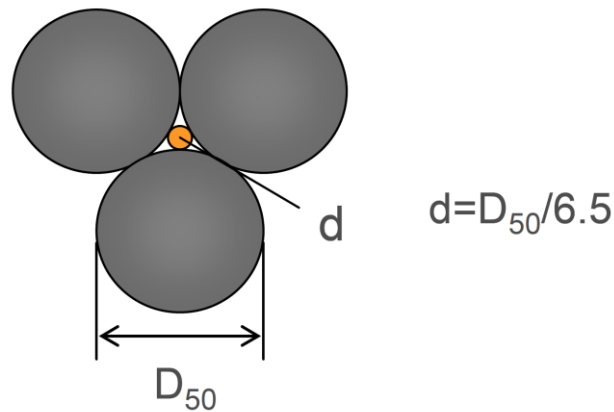


Figure 4: Spheres arranged in a hexagonal Packing [5]

2.2 Sandstone Diagenesis

The formation of a sandstone rock starts with the weathering of the source rock involving chemical, biological and physical processes. These processes affect the mineralogical composition of the final rock since some mineral of the original weathered rock are destroyed or altered, while other more stable minerals are not affected by the decomposition. Chemical processes are generally the most common type of weathering processes, whereas physical processes are the most important ones in terms of sandstone, conglomerate and mudrock formation.

Altogether, these processes result in three products that ultimately form the new sedimentary rock: Source rock residues e.g. from granite consisting of chemically stable minerals, secondary minerals that have been formed in situ by chemical recombination and crystallization and soluble constituents that have been formed by hydrolysis and simple solution from the source rock.

Especially source rock residues by physical weathering processes are of importance since they consist of silicate minerals such as quartz and feldspar as well as other types of rock fragments that are altogether crucial for the formation of sandstone.

The next step in the process is the transport of the weathered material by different means such as wind, ice or water. As soon as the particles have reached their destination area (subsiding basins) the sediments form unconsolidated deposits of gravel, sand or mud. Commonly they are loosely packed, show a high degree of porosity and are uncemented with high interstitial water content. Over time, these sediments are buried by younger sediments triggering the process of diagenesis, whereas chemical and physical processes start occurring due to the overload the sediments experience as well as the changed temperature, pressure and pore water environment. [1]

Generally, the process of diagenesis can be defined as a series of post-depositional effects and processes of either, chemical, physical or biological nature and is taking place before the beginning of metamorphosis. Metamorphosis, taking place at higher depths and therefore higher pressures and temperatures, may be differentiated from diagenesis by several mineral and thermal-history indices. Usually, a temperature range of 180-250 °C (depending on burial depth and therefore the pressure conditions) is regarded as the borderline between diagenesis and metamorphosis (Figure 5). [7]

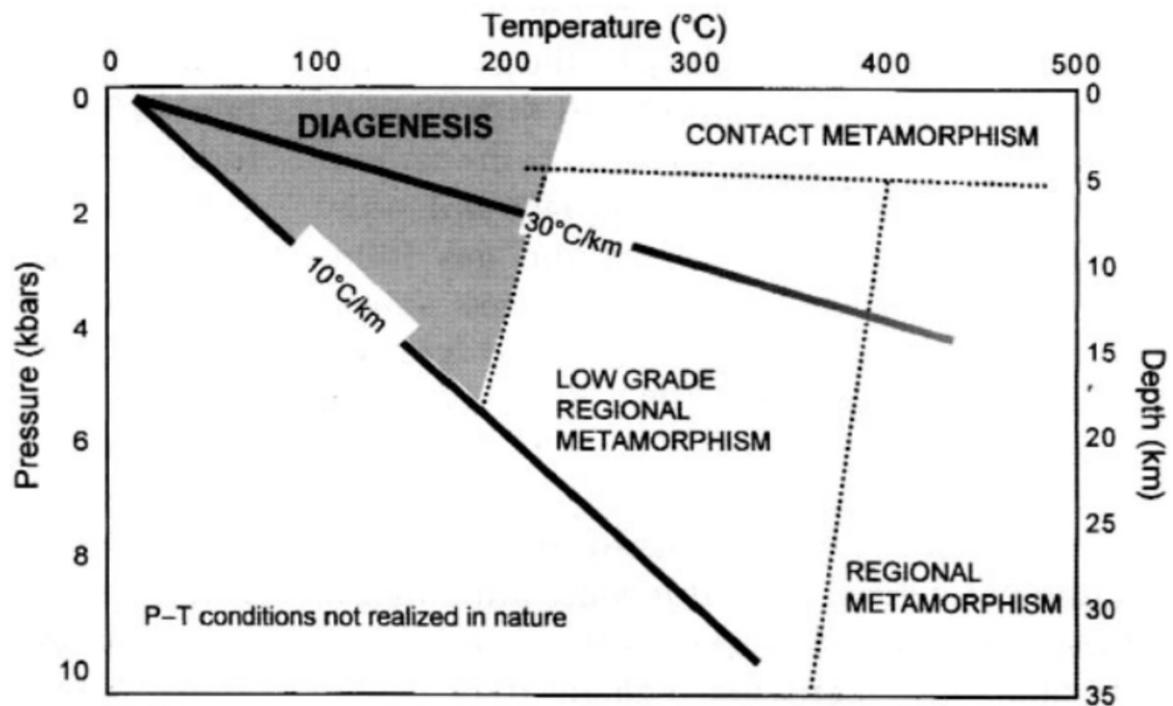


Figure 5: Diagenesis vs. Metamorphism [7]

The main process to form reservoir rock is diagenesis, which leads to the compaction of the sediments and lithification, whereas sand turns into sandstone. The process is accompanied by the reduction of porosity due to compaction as well as mineralogical changes.

Compaction may occur by different mechanisms such as mechanical ones like simple rearrangement of grains or ductile deformation. Chemical compaction on the other hand occurs due to grain dissolution and reprecipitation of the dissolved minerals, whereas the presence of an aqueous pore fluid is essential.

In terms of sand production and formation integrity, the cementation process initiated by diagenesis is very important since it is the main mechanism restraining the grains during hydrocarbon production. Moreover cementation is an essential part of the lithification, occurring by authigenic (in-situ-grown) minerals being precipitated in the pore space.

Essential chemical processes occurring during the process of diagenesis are recrystallization, neomorphism and replacement. Recrystallization of grains alters the grains'

shape and size, while the process of neomorphism involves replacement and recrystallization of a mineral by another related mineral. Especially the process of neomorphism must be regarded as crucial for this thesis since it influences the degree of cementation generated during the process of diagenesis. The conversion of aragonite into low magnesium calcite cement can be seen as a frequently occurring example of neomorphisms in sandstones. Both of these chemical processes, recrystallization as well as neomorphism can only take place in the presence of an aqueous pore fluid and have to be strictly differentiated from the replacement process in which a new autigenic mineral dissolves a former mineral and precipitates in its old place. An example for this dissolution-precipitation process is the replacement of detrital quartz by carbonate cements.

Note that diagenesis is not a single-stage uniform process but rather takes place in different steps (Figure 6). Different systems like the Russian catagenesis and epigenesis classification have been introduced over the last decades but still, the classification introduced by Choquette and Pray in 1970 is most commonly applied nowadays. It was originally supposed to describe the diagenetic process of limestone but it is also applicable to clastic diagenesis since the same fundamentals apply. [7]

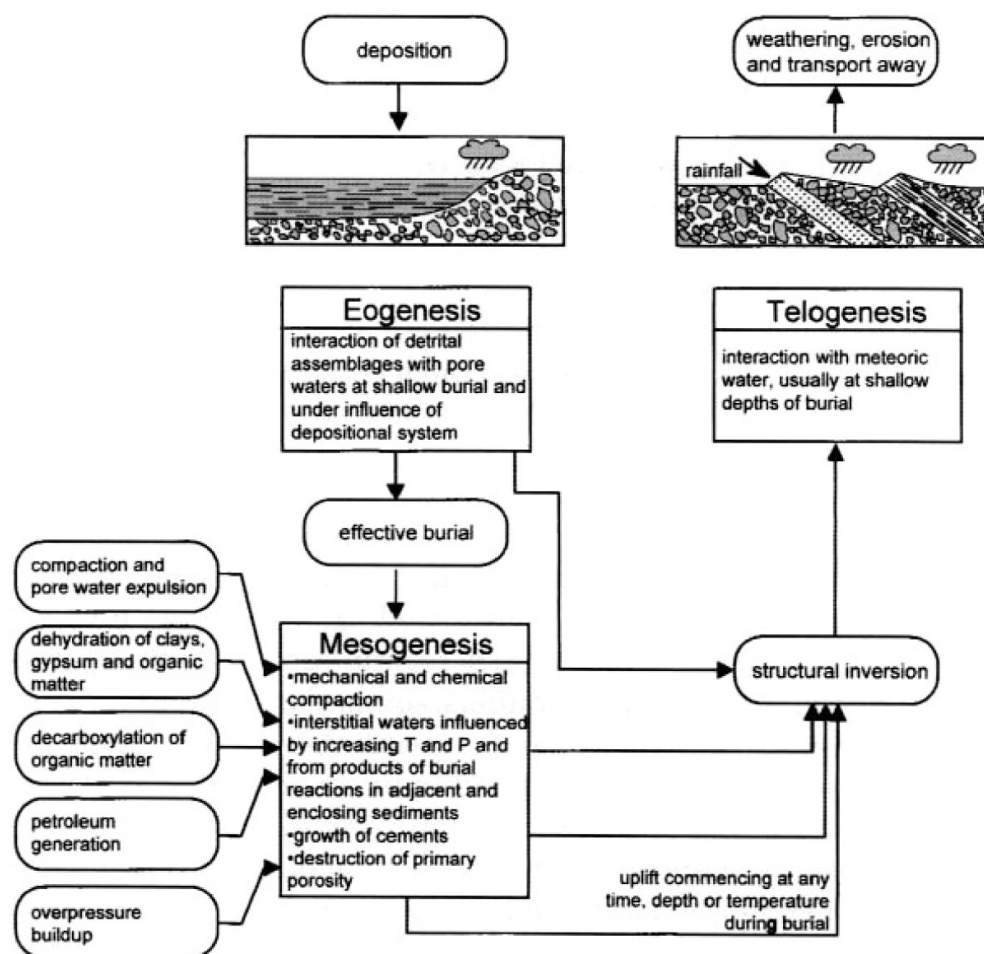


Figure 6: Stages of Diagenesis [7]

This classification subdivides the process of diagenesis into three different stages. Eogenesis or earlier diagenesis occurs near the surface in shallow burial depths soon after the deposition of the sediments. The process is strongly dependent on the pore water composition and therefore also the sedimentation environment. The extent of eogenesis is thereby strongly influenced by aquifers and porosity and may range from a few to several thousand meters below the sediment surface. Eogenesis occurs in a burial depth of up to 1 to 2 kilometers and a temperature range of 30 to 70 °C at common geothermal gradients.

Mesogenesis follows at deeper burial depths between the stages of eogenesis and beginning metamorphosis. More precisely, it begins at depths of depths of 1 to 2 kilometers and temperature conditions of 30 to 70 degrees and ends at temperatures of 200 to 250 °C where low grade metamorphosis begins. The phase of mesogenesis is an important step in the consolidation of the sandstone formation since compaction and cementation mainly take place in this part of the diagenetic process, consolidating the rock and destroying much of its original permeability. Furthermore, the generation of petroleum, dehydration and overpressure buildup occur in the phase of mesogenesis.

Telogenesis as the third phase of diagenesis occurs when the consolidated formation experiences uplift and gets in contact with surface influences again, especially with meteoric water. It is not related to the conditions of the original depositional environment. The contact with surface water leads to oxidation as well as changes in feldspar, converting it to clay. The cements formed during the different phases of diagenesis will differ in mineralogical terms. Most commonly quartz, carbonate minerals and clays can be found in sandstones. [7]

Quartz cement is a simple form of sandstone cement occurring in different forms in sandstone formations ranging from overgrowth cements to extensive replacement cements. They are commonly formed in burial depths of 2000-3000m with temperatures of over 80°C and may be a main factor in the destruction of porosity. The source of quartz cementation varies (internal and external) very much like its abundance, that is not only dependent on temperature but also on other factors such as pressure or clay coating of grains. [7] [8]

Carbonate cement on the other hand is formed during the stages of eogenesis and mesogenesis. It mainly consists of calcite, dolomite, ankerite and siderite, whereas the depositional setting, organic matter content and the host sediment play a significant role. Carbonate cements may have internal as well as external sources and are subjected to alterations and dissolution during telogenesis. [9]

Clay cements differ from carbonate and quartz cements not only in mineralogical but also in volumetric terms. While they only make up a small portion of the sandstone's volume, they may significantly influence its permeability. The most common clay minerals within sandstone cement are kaolinite, illite and chlorite. Clays can be regarded as problematic in many ways. In drilling operations they may swell due to exposure to water, while during production they may provide a significant source for fines migration. [10]

2.3 Sand Production and Rock Failure Principles

Sand production is an undesirable byproduct of oil and gas production in many fields worldwide. The produced sand does not have any kind of economic value but may interfere with production operations (Table 1) and damage the producing wells by plugging, erosion and settling of sand in the surface facilities. [11]

Area	Problem	Effect
Reservoir	Wellbore Fill	<ul style="list-style-type: none"> • Restricted access to production interval • Loss of productivity • Loss of reserve
Subsurface Equipment	Sand Fouling	<ul style="list-style-type: none"> • SSSV not operating • Difficult wire line operations
	Erosion	<ul style="list-style-type: none"> • Equipment replacement • Equipment failure
Surface Installation	Sand accumulation	<ul style="list-style-type: none"> • Malfunctioning of control equipment • Unscheduled shut down
	Erosion	<ul style="list-style-type: none"> • Deferred production • Sand separation and disposal

Table 1: Effects of Sand Production [11]

Sand production in oil and gas wells starts occurring when the formation stress exceeds either, the formation's compressive, tensile or shear strength, resulting in rock failure. The type of rock failure occurring is thereby dependent on rock lithology, rock microstructure and the applied stresses. [11] [12]

Especially unconsolidated and poorly consolidated formations with little cementation are very susceptible to sand production. While consolidated sandstone formations show an average compressive strength of over 16000 psi (Figure 7), this value drops to less than 1000 psi for poorly consolidated formations [13]. Even more significant is the impact of lacking cementation on the cohesive strength of an unconsolidated formation that drops to almost zero. These factors combined make unconsolidated formations very prone to different types of rock failure. [14]

Properties	Sandstone	Siltstone	Sandy mudstone	Mudstone
Density (g/cm ³)	<u>2.47-3.47</u> 2.76	<u>2.43-2.63</u> 2.56	<u>2.64-2.98</u> 2.72	<u>2.05-2.97</u> 2.68
Compressive strength (MPa)	<u>50.60-281.3</u> 111.50	<u>67.2828-130.1</u> 94.54	<u>13.50-112.1</u> 53.46	<u>9.81-81.5</u> 42.75
Tensile strength (MPa)	<u>1.77-10.67</u> 6.66	<u>1.20-9.2</u> 5.20	<u>0.70-8.70</u> 4.39	<u>0.30-7.29</u> 1.91
Cohesion (MPa)	<u>1.91-13.07</u> 6.30	<u>1.25-2.40</u> 2.33	<u>4.00-11.9</u> 6.22	<u>0.14-8.4</u> 3.95
Internal friction angle (°)	<u>33.41-39.15</u> 36.49	<u>39.00-40.03</u> 39.52	<u>31.90-38.4</u> 34.14	<u>31.8-41.52</u> 36.72

Note, $\frac{Min - Max}{Ave}$

Figure 7: Density, Compressive Strength, Tensile Strength, Cohesion and Friction Angle of different Sedimentary Rock Type Samples [12]

Compressive failure occurs if the compressive strength of the rock is exceeded. The uniaxial compressive strength (UCS) of a rock can thereby be easily assessed by a uniaxial compression test in which only one stress is applied on a rock sample axially until the sample fails. Typical results of compressive failure are depicted in Figure 8 and Figure 9. [15]

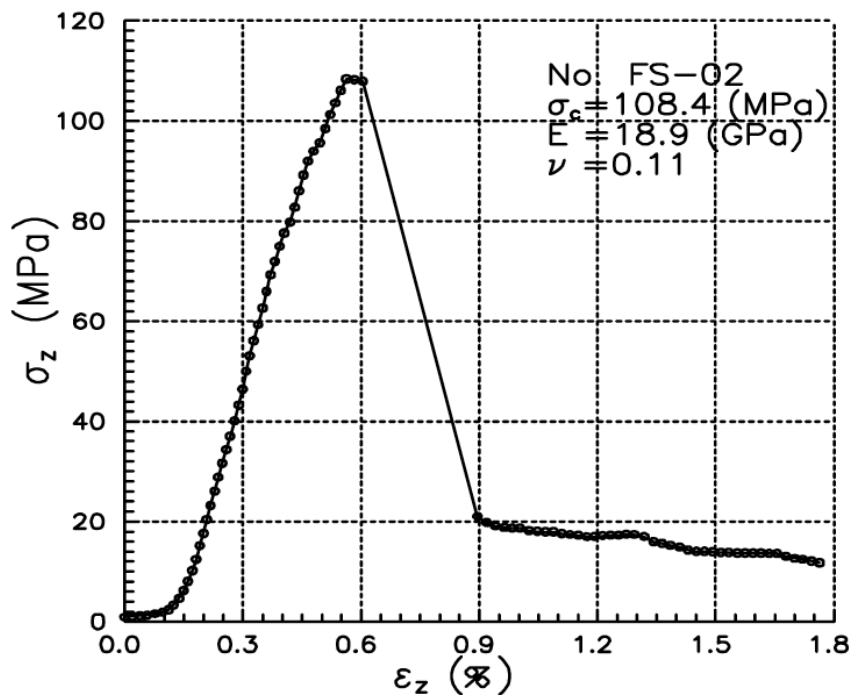


Figure 8: Stress-Strain Diagram of a fine-grained Sandstone obtained by a Uniaxial Test [12]



Figure 9: Rock Compressive Failure resulting in Splitting [12]

Shear failure occurs when shear stresses exceed the shear strength of a material. Since the shear strength is depending on cohesion and friction (Figure 10), it is very low for unconsolidated formations resulting in solids deteriorating from the failure plain due to stress fields around perforation. The shear strength of a formation can be calculated by

$$\tau = c + \sigma_n * \tan \phi \quad (2)$$

(Mohr-Coulomb Failure Criterion)

where τ is the shear stress [Pa], c is cohesion [Pa], σ_n is the normal stress [Pa] and ϕ is the friction angle [°]. [14]

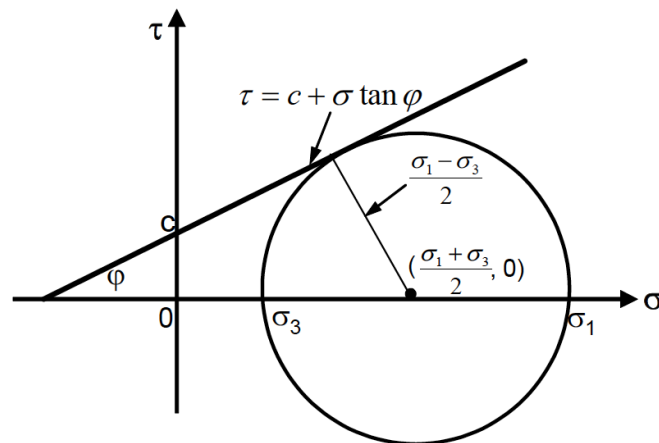


Figure 10: Mohr's Circle for Failure Criterion for Shear Failure [12]

To solve this equation, several factors have to be determined before it can actually be applied on a specific rock. Most commonly, triaxial compressive tests are used to evaluate the uniaxial compressive strength as well as the failure envelope by a series of tests. The major principal stress (σ_1) is thereby applied along the axis of a cylindrical rock sample, while the minor principal stress (σ_3) is applied on the curved surface by a fluid confining pressure. The envelope, defining the Mohr circle is generated by a series of tests (Figure 11) that allow

to determine the slope of the envelope (depending on the friction angle) as well as the cohesive strength of the rock (tensile strength at zero normal stress) [15]. Typical results of shear failure are shown in Figure 12.

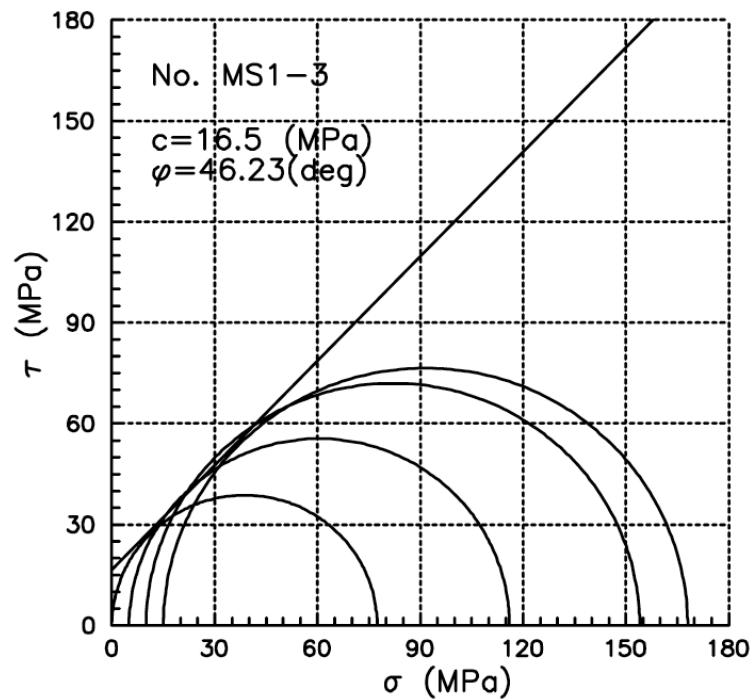


Figure 11: Series of Triaxial Test Results for medium grained Sandstones [12]

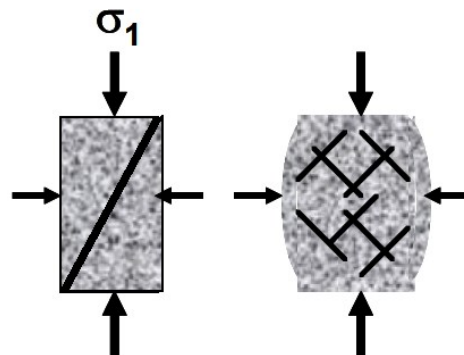


Figure 12: Shear stresses resulting in Shear Failure (left) and multiple Shear Fractures (right) [13]

Note that for practical applications, pore pressure has a significant impact on the effective stress acting on the rock that can be calculated by the Terzaghi's effective stress concept

$$\sigma'_{ij} = \sigma_{ij} - \delta_{ij}p \quad (3)$$

where σ'_{ij} is the effective stress tensor, p is the pore pressure and δ is the Kronecker delta (1 if $i=j$, else 0).

This effective pore pressure only affects normal, but not shear stresses, resulting in a shift of the circle in the Mohr-Coulomb Failure criterion over the failure envelope causing rock failure (Figure 13). [12]

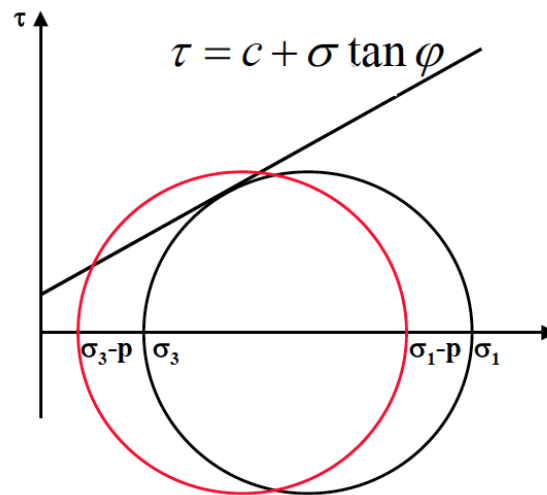


Figure 13: Mohr's Circle with and without Pore Pressure [12]

Other than shear failure, tensile failure is caused by stresses due to pressure differential in the near wellbore zone. If abrupt pressure changes exceed the tensile strength of the formation this will result in rock failure and cause sand production. In particular, this happens often at the tip of the perforation.

Tensile failure of the rock can be measured by uniaxial tension tests, yet they are not commonly performed. Tensile strength is generally low in sedimentary rocks and can be described by the Griffith Criterion

If $\sigma_1 + 3\sigma_3 > 0$

$$(\sigma_1 - \sigma_3)^2 = 8T_0(\sigma_1 + \sigma_3) \quad (4)$$

If $\sigma_1 + \sigma_3 < 0$

$$\sigma_3 = -T_0 \quad (5)$$

If $\sigma_3 = 0$

$$UCS = 8T_0 \quad (6)$$

where σ_1 is the major principal stress, σ_3 is the minor principal stress, UCS is the uniaxial compressive stress and T_0 is the tensile strength of the material. Types of tensile failure are depicted in Figure 14. [12]

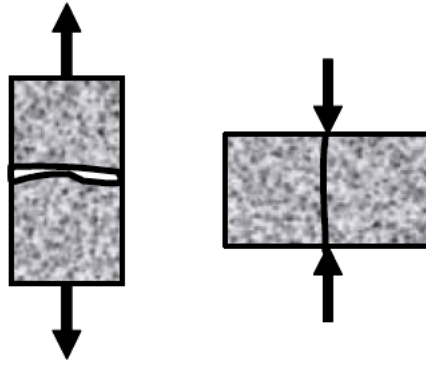


Figure 14: Tensile Failure (left) and Tensile Failure induced by Point Loads (right) [12]

Last, the problem of shear-enhanced compaction has to be addressed. This type of rock failure describes the loss of porosity by plastic deformation that a formation experiences when pore collapse occurs. The acting forces causing the pore collapse are excessive confining or shear stress, whereas the necessary magnitudes are strongly dependent on the formation porosity, as is depicted in Figure 15. Each envelope describes the maximum stress magnitude required for shear-enhanced compaction failure at a certain porosity.

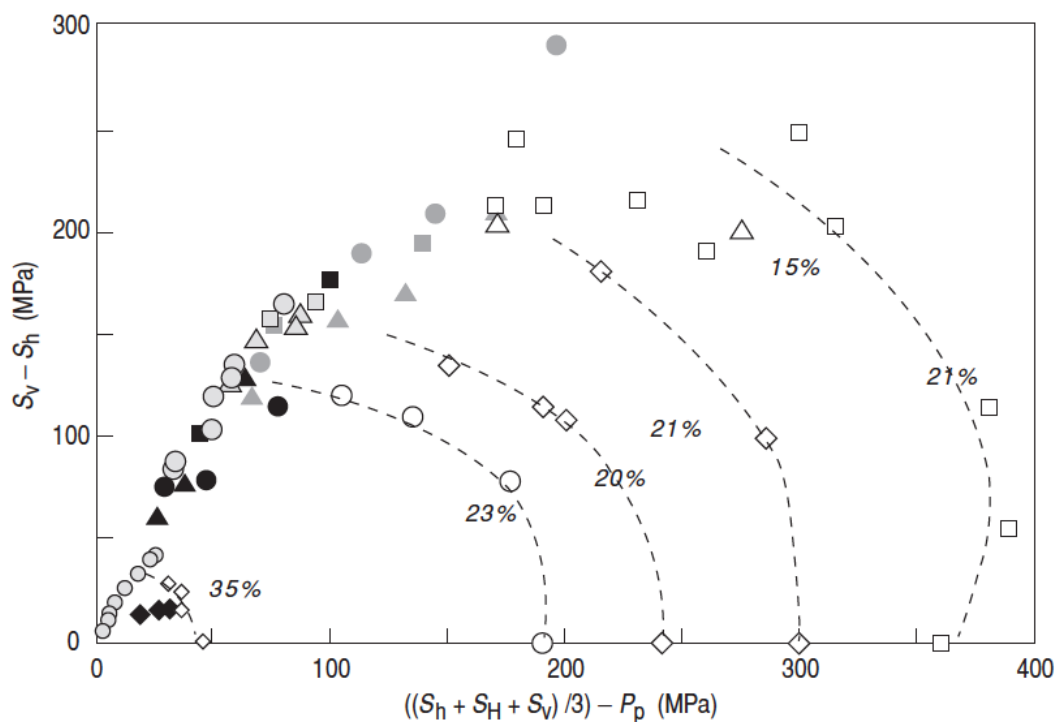


Figure 15: Average Effective Stress (x-axis) vs. Differential Stress (y-axis) Failure Envelopes for different Sandstones [15]

This type of failure is commonly associated with the depletion process of reservoirs, resulting also in subsidence and permeability loss. In poorly cemented sandstones, inelastic factors such as grain rearrangement may play an additional role in compaction. [15]

2.4 Sand Production Influence Factors

Sand production may occur due to many causes, yet high production rates, the onset of water production including the problems associated with it and the reduction of pore pressure are regarded as the most important influence factors. [13]

2.4.1 Production Rate

The forces acting on the formation are highly influenced by the production rate and the fluid viscosity. The pressure difference between the wellbore and the reservoir leads to stress acting on the formation and induces sand production if the formation strength is exceeded.

Note that formations are not only sensitive to the absolute production rates but also to fluctuations of the same. At stable production rates, migrating formation grains may form a stable semicircular sand arch in front of the perforation tunnels (Figure 16), stopping them from invading into the wellbore. Variations in production rates and therefore stresses acting on the formation may cause the sand arch to collapse, resulting in sand production until a new arch is formed. Especially the compacted zones formed at the surfaces of perforation tunnels (Figure 17) are very sensitive to changes in production rate and tend to fail at fluctuating rates. [16]

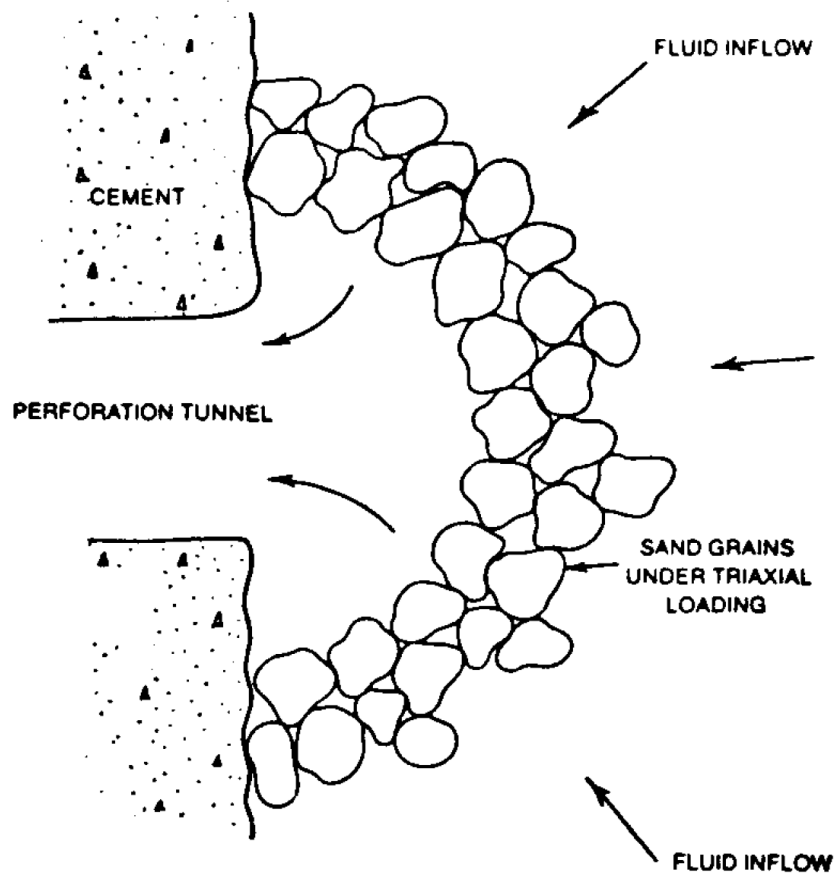


Figure 16: Geometry of a Stable Sand Arch surrounding a Perforation [17]

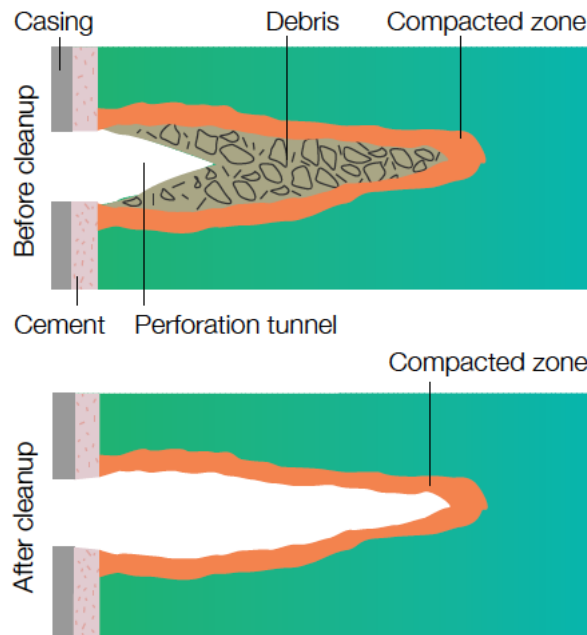


Figure 17: Perforation Zone Before and After Cleanup [16]

2.4.2 Water Production

Another factor to be considered is the beginning of water production from the reservoir. This may lead to the dissolving of cement, an increase in fluid friction, as well as the loss of capillary pressures holding the sand grains in place and start sand production. [13]

Capillary pressure is thereby defined as the pressure difference at the interface of two immiscible phases as it occurs in hydrocarbon reservoirs between oil, water and gas. Capillary pressure has to be overcome first, before fluids can start flowing through a porous medium. It is strongly dependent on the interfacial tension between the fluids, the wettability of the rock (Figure 18) and the capillary radius. The capillary pressure can be calculated by the formula [18]

$$P_c = \frac{2 \cdot \sigma \cdot \cos \theta_c}{r_t} \quad (7)$$

where P_c is the capillary pressure [Pa], σ is the interfacial tension [$\frac{N}{m}$], θ_c is the wetting angle [$^\circ$] and r_t is the capillary radius [m].

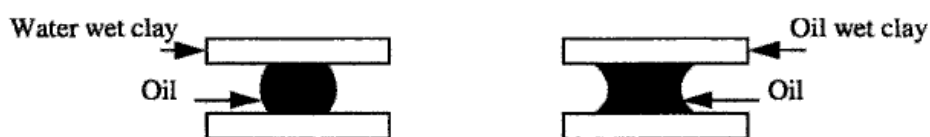


Figure 18: Oil vs. Water Wet Formation [18]

2.4.3 Pore Pressure Reduction

As already mentioned in section 2.3, the reason for sand production can be found in the gradual reduction of pore pressure. Friction forces holding the sand grains in place are strongly correlated to the overburden pressure the formation is exposed to but also to the pore pressure. The relevant factor in this case is the net pressure, which is defined as the overburden minus the pore pressure. While this seems to indicate, that a reduction in pore pressure might lead to reduced fines and sand particle migration, the opposite can be observed in many reservoirs: Decreasing pore pressure during production due to a lack of strong water drive or other pressure conserving mechanisms leads to an increased net pressure acting on the formation, resulting in crushing the rock and increased production of fines particles. [13]

2.5 Sand Production Prediction

Sand production in wells can be subdivided into three different types [13]

- Transient sand production describes a production behavior in which sand production declines under continuous production conditions like after clean-up or after water breakthrough.
- Catastrophical sand production describes a production behavior in which sand production leads to the kill of the well due to a high rate of sand influx and is always unacceptable.
- Continuous sand production describes a production behavior in which sand production results in a constant level of grains being produced. Whether or not continuous sand production is accepted depends on the quantity and type of grains being produced as well as the operational constraints of the wellbore and the surface facilities.

Within most oil companies, sand production of particles with a diameter of below 0.045 mm in an amount that does not fill up the wellbore or plugs flow lines of any kind is regarded to be acceptable.

Although the types of sand production are clearly defined, the exact prognosis of the future production behavior is very difficult, especially with rocks that cannot immediately be classified as very hard or very weak in terms of compressive strength. [17]

Bean-up tests in which the choke size for a well is gradually increased provide answers about the production rate at which a formation starts producing sand. This allows to determine a maximum allowable production rate but this method is very time intensive. [19]

Other possibilities are the use of core samples in laboratory tests or the correlation of logs.

The effect of forces acting on core samples can also be measured with a simple pressure drawdown test apparatus (Figure 19) and shows, that the failure stress of most sandstones lies at around 1.7 times their compressive strength (Figure 20) [17]. The problem of this method lies in the possible alterations to the core that could compromise the results unnoted. [16] This could occur by either, filtrate invasion, fluid expansion and expulsion as well as

physical damage to the rock. Exposure of cores to atmospheric conditions on the well site and different problems such as oxidation, dehydration, bacterial growth and many others during transport require core preservation methods to be applied. Examples for these preservation methods are dry sealing the core (in tight metal cans, plastic bags tubes e.g.), freezing of the core with dry ice or wet conservation in different containers with brine, oil or other fluids. [20]

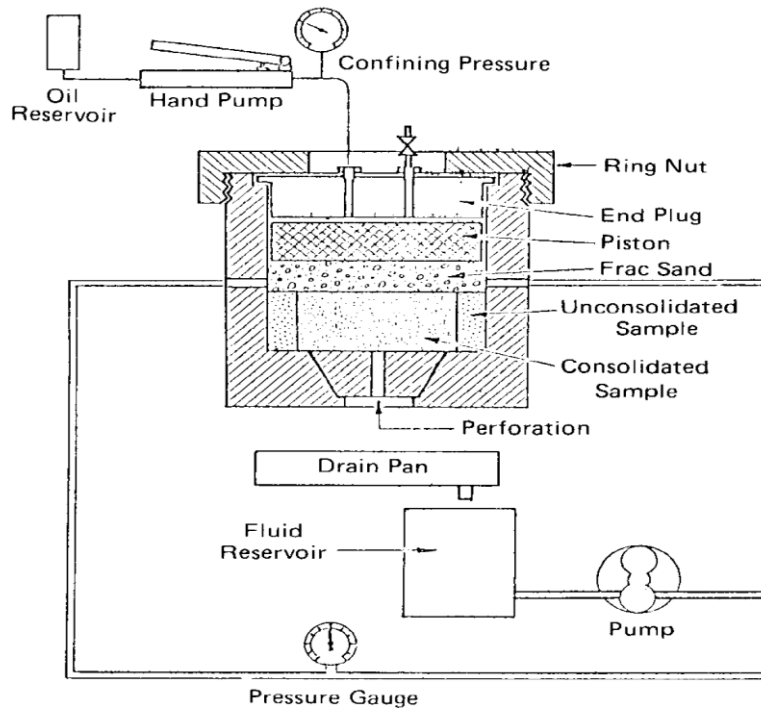


Figure 19: Formation Failure Testing Setup [17]

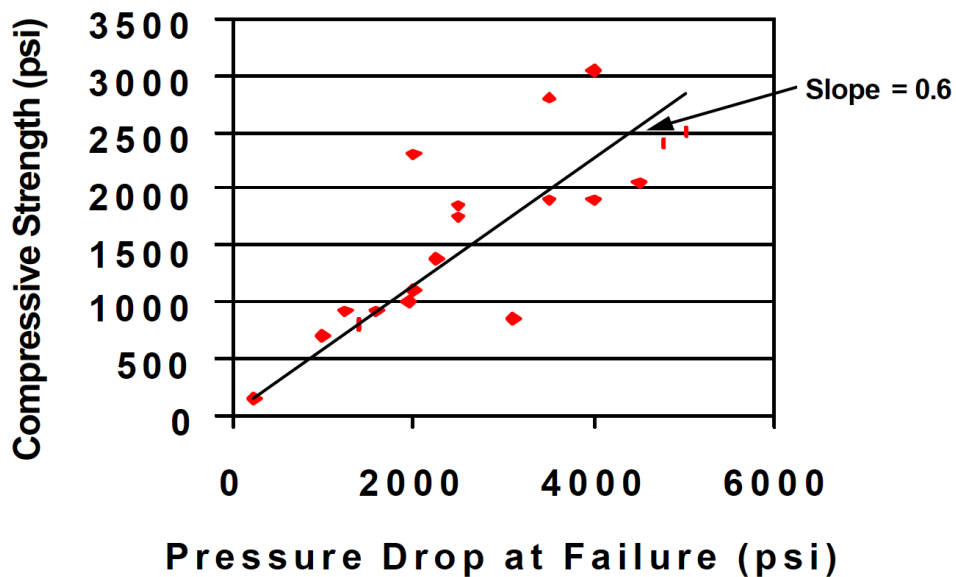


Figure 20: Rock Failure vs. Compressive Strength [17]

Another way of obtaining the rock's compressive strength is by logs. Sonic logs are related to porosity and rock hardness, whereas neutron logs are primarily influenced by the porosity of the formation. Although these logs seem to deliver accurate results, there is no way of directly measuring the rock's compressive strength by logging. Therefore all data obtained have to be interpreted by correlations in order to get meaningful predictions about the rock's compressive strength and its sand production behavior. [17]

Prediction of sand production has a significant impact on the measures that have to be taken. While traditionally methods aim to keep sand out of the wellbore (exclusionary) and thus reduce interference with production downhole, inclusionary methods produce acceptable amounts of sands to the surface where the sand production is handled by different means. [21]

2.6 Sand and Fines Invasion Control

Sand and fines invasion control can be subdivided into mechanical and chemical control methods that use different approaches. While mechanical methods simply aim to keep the grains out of the wellbore, chemical methods stabilize the formation and stop sand and fines from being mobilized in the first place.

2.6.1 Mechanical Control Methods

Different types of mechanical control methods are available for sand and fines control. Which mechanical control method has to be chosen depends on many factors such as formation geology, production rate, the presence of nearby-aquifers, subsurface installations and also the lifetime and economics of the well.

2.6.1.1 Gravel-free Installations

The most simple and generally most economic sand retention system is the installation of a slotted liner or a screen without any further gravel packing across the production interval. By doing so, the cost for the gravel material (either sand or synthetic material) and filter medium installation service can be saved, having a significant impact on the well's economies. The problem with gravel-less installations though is, that they are only applicable in very coarse and well sorted formations since they rely on formation sands bridging over the slots and therefore forming a gravel pack by themselves. As for dimensioning, the slot size should not be greater than 1-2 times the 10-percentile diameter of the formation sands depending on their uniformity. [22]

An essential issue of the slotted liner installation is, that they are usually not considered as long-term solutions for sand control. The mixing of different formation particles bridging over the liner will eventually result in the creation of a low-permeability barrier and reduce the well's productivity. [16]

Wire wrapped screens as another gravel-free sand control unit consist of a triangular shaped wire that is wrapped around a perforated pipe and connected to ribs. The success of this

sand control method is also depending on the formation quality [13], yet the longevity and filter quality is usually superior to slotted liners.

In Expandable sand screens on the other hand the control effect is achieved by overlapping filtration media attached to the inner expanding pipe, being kept in place by an expanding protective shroud [13].

2.6.1.2 Liner-free Installations

Inverting the gravel free approach of sand control, gravel may also be used as a stand-alone mechanical sand invasion control without the insertion of a liner. To do so, 20-25% coarser gravel has to be mixed into the normal gravel in order to create a bridging. This method is not recommended for cased holes where a single insufficiently filled perforation would be sufficient to allow fines influx destroying the gravel's permeability but may work very well in open-hole completions. In this case, the whole lower section of the wellbore is filled up with a cylindrical gravel pack. The total absence of hardware around the perforation is a great advantage since it allows higher infilling pressures resulting in better packing and therefore also improved sand control. [22]

2.6.1.3 Gravel Packs

Although gravel- and liner-less sand control installations may have several advantages in very specific wellbore and formation conditions, gravel packing is still the most common mechanical sand control method. [22]

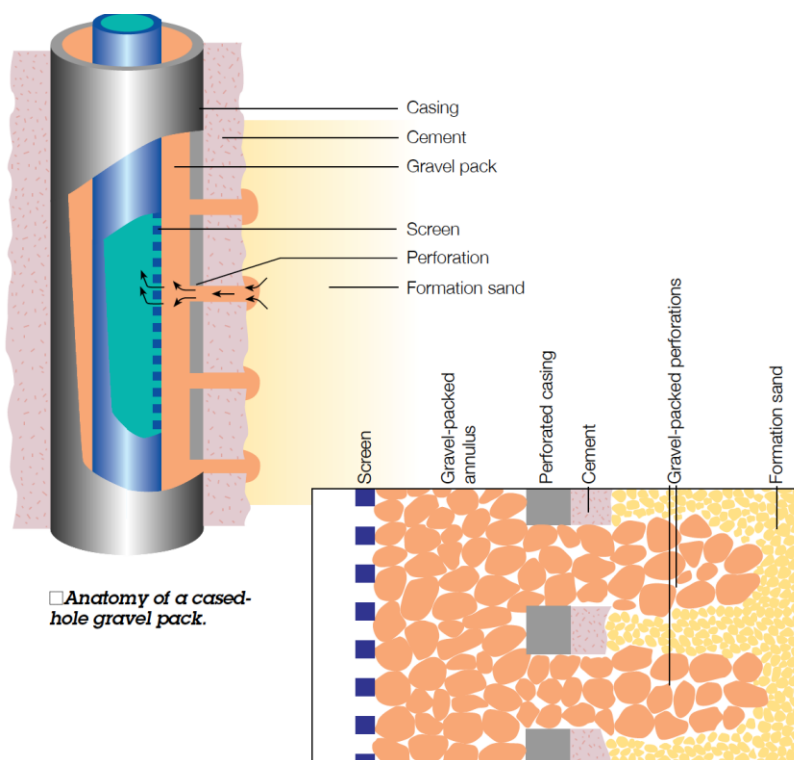


Figure 21: Anatomy of a cased-hole Gravel Pack [16]

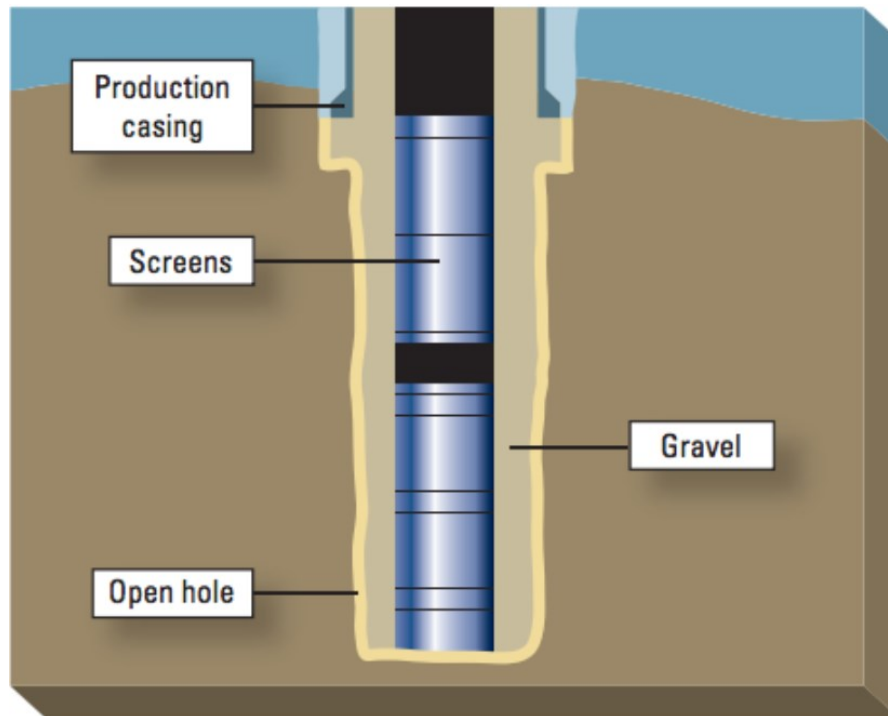


Figure 22: Anatomy of an open-hole Gravel Pack [23]

In gravel packing, a centralized screen is run downhole in order to create an annular space. This annular space is then filled up by proppants being pumped downhole in a carrier fluid at sufficient pressures to ensure proper packing but below formation fracture pressure. In cased hole applications the gravel is supposed to intrude into the perforations and stabilize them (Figure 21) whereas in open hole completions the gravel is supposed to protect the formation interface from erosion (Figure 22).

When placed, the gravel pack itself can be considered as a near-wellbore damage but due to its positive stabilizing effects and the high permeabilities the gravel provides its advantages outweigh its disadvantages by far.

While this technique seems to be very simple, several considerations have to be made to assure proper sand control by gravel packing.

Proper screen/slotted liner dimensioning is crucial for gravel pack design. The openings should be dimensioned in a way to allow maximum flowrates while keeping the gravel in place and avoiding the proppant itself being produced. [22]

For the placement operations the selection of an adequate carrier fluid is important. Conventional circulating gravel packs with gravel concentrations of 0.25-15 lbm/gal commonly use carrier fluids with a viscosity of less than 50 cp like ungelled water. High density circulating gravel packs on the other hand with gravel concentrations of 7-15 lbm/gal use carrier fluids with more than 50 cp in intervals of up to more than 30m. Lower gravel concentrations and higher viscosities generally help control settling, yet lower concentrations

result in more fluid leak-off being required whereas the leak-off rate is lowered by high viscosities. [16]

The most important design consideration for gravel packs though is the adequate choice of filter medium in different terms. An adequate filter medium should provide fines retention over a long production period, withstanding all downhole conditions. While the forces acting on the annular proppant filling are not challenging for most materials, the stress acting on the proppants in the perforations may be significant. To prevent any insufficiencies of the filter medium due to wellbore conditions, often synthetic materials such as ceramic or sintered bauxite proppant with high crush resistance are used. These materials are furthermore less challenged by unfavorable pH conditions downhole. [22]

To provide proper sand control, the dimensioning of the proppant is crucial. Empirical data have shown that dimensioning should be controlled by median grain size diameter ratios. Proppant/formation grains median grain size ratios of 5.7 proved to be sufficient for retention (Figure 23). [24]

While smaller ratios hinder proper bridging, higher ratios of up to 11 lead to fines invasion into the gravel packing resulting in permeability reduction but still good sand control. Ratios of up to 15 only slow sand production while ratios of over 15 do not hinder grains from invading into the wellbore at all. [22]

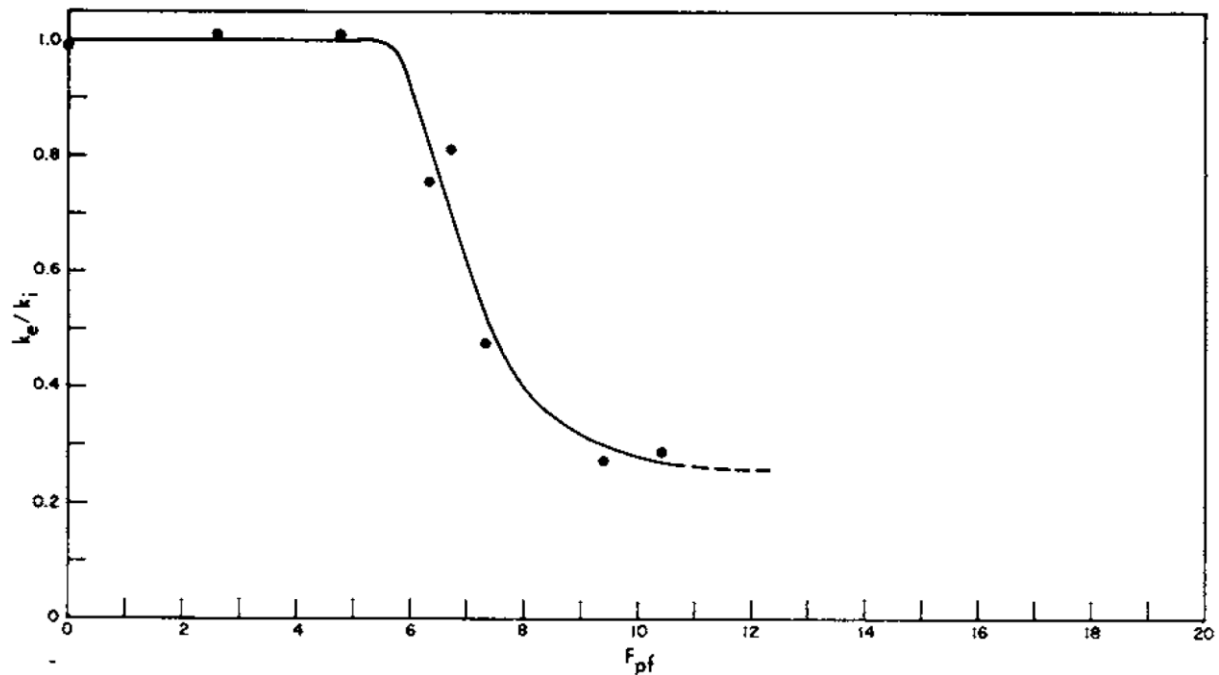


Figure 23: Median Grain Size Ratio (x-axis) vs. Gravel Pack Impairment [24]

2.6.1.4 Frac Packs

Frac packs are designed very similar to conventional gravel packs and combine the advantage of conductivity enhancement with sand control. Unlike normal fracture operations that are usually conducted in low permeability formations, frac packs are set in medium to high permeability regions where fractures are created, inflated and packed. Due to the higher permeability of the formation, fracture length usually does not play a significant role unlike in low permeability fracturing operations. Fracture conductivity is of much higher importance in these formations and therefore the created conductivity highways are enhanced by tip-screen out treatment design and the selection of an adequate highly permeable proppant. Frac Packs are overcoming the near-wellbore damage, connecting the reservoir to the wellbore with highly permeable pathways and therefore significantly reducing the required pressure drawdown. The reduced drawdown results in less stress acting on the formation and therefore reducing sand production tendencies. The flow regime encountered is changed by these operations as well and goes from radial to linear flow (Figure 25) [25]. Although this method has been tested successfully [26], there are some constraints to its applicability such as rock properties and mechanical completion integrity of the wellbore equipment [25]. Frac packs result in a lower positive skin than conventional gravel packs and therefore they are very common in certain areas like the US Gulf of Mexico where more than 65% of all sand control systems used are frac packs. Statistics demonstrate that they also show a low rate of completion failure if carefully operated (Figure 24). [23]

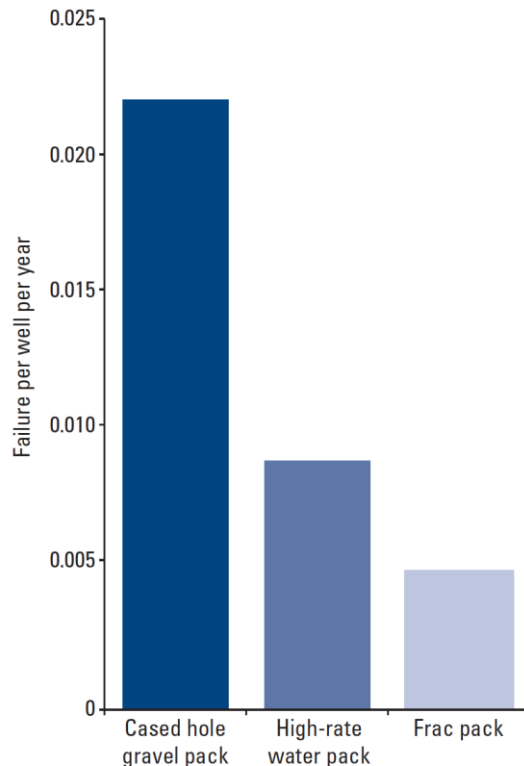


Figure 24: Average Rate of Failure of Gravel Packs, Frac Packs and High Rate Water Packs [23]

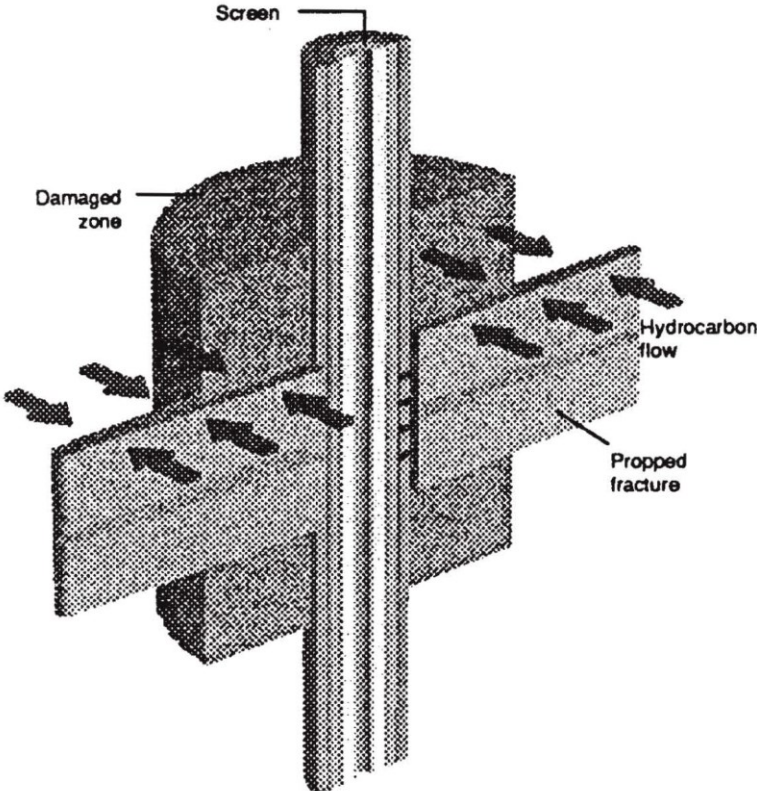


Figure 25: Frac Pack Schematics [25]

2.6.1.5 High Rate Water Packs (HRWP)

High rate water packs are very similar to frac packs, relying on the mechanisms of fracturing in order to minimize sand production. In terms of proppant invasion depth into the formation, high rate water packs are set between the gravel pack and frac packs (Figure 26). [23]

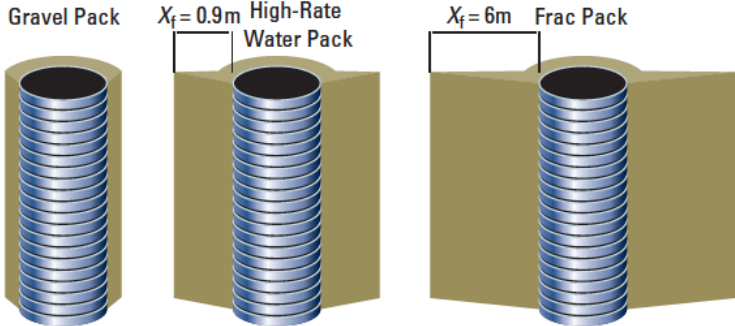


Figure 26: Proppant Invasion Depth of different Sand Control Mechanisms [23]

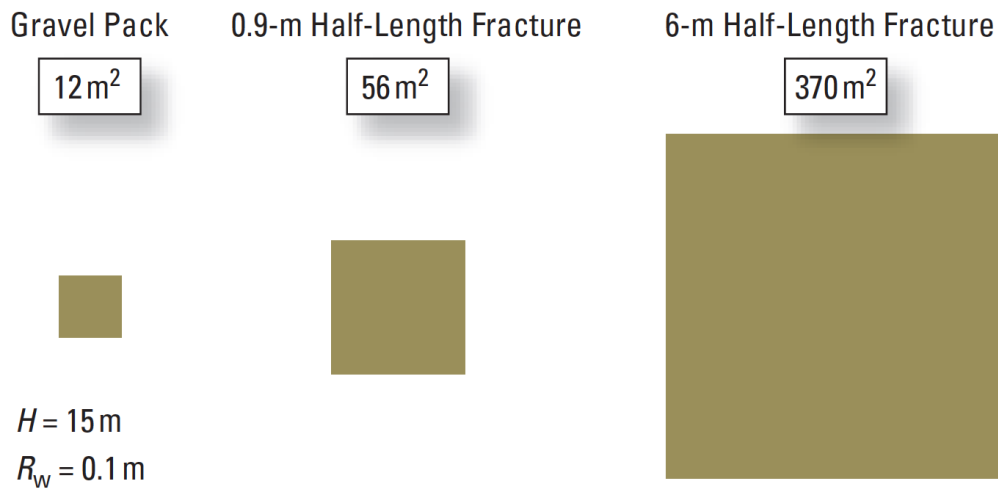


Figure 27: Sand Face Area Comparison of Gravel Packs, High Rate Water Packs and Fracture Packs [23]

Unlike frac packs, high rate water packs are created by using water as a carrier fluid being pumped down the well with a proppant concentration of 1-2 lb/gal at pressures higher than the fracture pressure. Shorter fractures are created since the low-viscosity carrier fluid is quickly leaking off into the formation. Although this method compromises in terms of invasion depth, sand face area (Figure 27) and flow efficiency (Figure 28) it offers a safer stimulation and sand control mechanism in case of near-by aquifers. [23] [27]

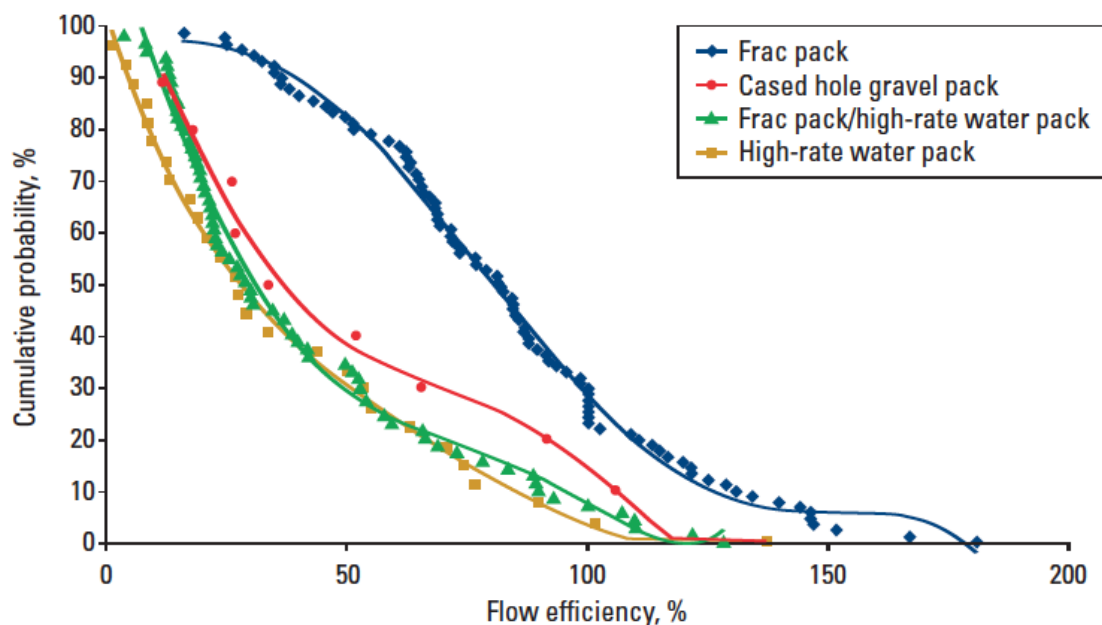


Figure 28: Flow Efficiency of different Sand Control Methods [23]

High rate water packing has proven to be very efficient in deep and deviated wells and especially such where the interval length exceeds 40 feet and common gravel packing methods result in pack voids. Due to the high rates applied, the pack is self-diverting and the low viscosity carrier fluids are usually less formation damaging. Still, one of the major disadvantages of this method is that it can only be applied in wells with a small damage radius due to smaller fracture half-length compared to frac-pack operations. [27]

2.6.2 Chemical Control Methods

Unlike mechanical methods aiming to retain sand production at the wellbore interface, chemical consolidation methods aim to consolidate the formation in situ. Different types of chemical consolidation methods with different working mechanisms are available on the market.

2.6.2.1 Resins

Resin injection into poorly consolidated formations is a common method to mitigate sand production. The rock particles are bound together by mostly phenolic, furan or epoxy resins thus providing an artificial cementation to keep the grains in place. As soon as the resins are injected into the formation, a catalyst is flushed through in order to get the reaction started. The amount of resin used is thereby variable and of special importance since resins reduce permeability and therefore well productivity. A compromise has to be found ensuring sufficient consolidation, yet reducing permeability as little as possible. Formation consolidation using resins has to be carried out very carefully in terms of placement since the resin has to cover all of the sand face in order to provide effective consolidation, limiting its applicability to intervals of 10-15 ft. Therefore only a small percentage of unconsolidated formations is treated with resins. [16]

Chemical resin consolidation systems are often expensive and therefore mostly used in smaller production sections, where they offer the advantage of not having to place additional mechanical equipment. An example for such a resin treatment is Shell's Eposand 9; an epoxy resin that is pumped into the formation diluted in a hydrocarbon solvent. A curing agent separates the phases and the resin is pulled into the pendular rock region by capillary forces where it solidifies and cements the rock. Eposand 112 on the other hand, as an overflush system initially occupies the total pore space and is thereafter displaced, leaving only a residual saturation to be cured behind. Both of these systems may be applied before the unconsolidated formation starts eroding but also as a remedial technique after the beginning of erosion if the formation has been repacked with clean sand. An overflush resin like Eposand 112 was tested for application and will be discussed later on. [28]

A more recently developed consolidation process called "Sanset Process" was introduced by the Esso Production Research Company and serves as another example for resin consolidation. It uses phenol-formaldehyd to provide compressive strengths of 3000 psi to the rock while retaining a permeability of 50%. A curing agent added before pumping controls the curing as well as the placement time.

Note that the resins mentioned only serve as examples of resin systems used in field operations. A great variety of different chemical resin consolidation systems is available on the market whereas

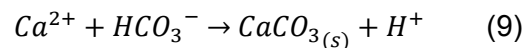
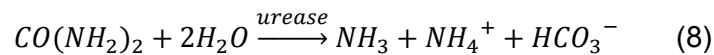
- Minimum preparation time
- Low injection pressure
- Short curing time
- High compressive strength
- Good resistance to well fluid deterioration
- Commonly used treating fluids
- And high permeability retention

are considered to be preferable properties of a resin system. [29]

2.6.2.2 Quasinatural Consolidation (QNC) [30]

Quasinatural Consolidation as a rather new development is based on the in-situ formation consolidation by the formation of calcium carbonate scale. Thereby calcium carbonate forms bridges between the unconsolidated grains resulting not only in a reduction of sand production but also a slight deterioration in terms of permeability.

A mixture of Ca^{2+} combined with urea and urease as a catalyst is pumped and forms calcium carbonate in two steps



This method has been successfully tested in the laboratory and constitutes an environmentally friendly, inexpensive solution for in-situ consolidation. Although this method seems to provide several benefits, there are a few operational constraints associated with this method. In order to efficiently consolidate, reservoir temperature should be in a range of 60 to 70 °C. While at low temperature, urease will take a long time to activate the reaction, temperatures of more than 70 °C will result in a quick deactivation of the catalyst. Furthermore it limits the possibilities of acidizing the well after consolidation since and HCl treatment would lead to a dissolving of the carbonate scale. A chemical of this type was tested for its sand retention capability in the practical part of this thesis.

2.6.2.3 Polymers [31]

Polymers injected into the formation may provide additional compressive strength to the rock by attaching to the pore wall or getting entrapped in capillaries and voids of the formation. The results gained by the application of polymer treatment have been differing. While some tests resulted in the reduction of brine and improvement of oil relative permeability, others led to slug formation and a complete blockage of flow. Similarly, the reported decrease in

permeability after polymer treatment varies greatly as does the gain of compressive strength that is dependent on several factors such as

- Sand particle size and distribution
- Formation chemical elements
- Degree of salinity
- Presence of carbonates and clays

and many other factors. A polymer claimed to reduce migration tendencies and enhance relative oil permeability was tested for this thesis.

2.6.2.4 Surface Forces [32]

Nanoparticles as a type of consolidation treatment rely on the acting of surface active forces calculated by

$$V_T = V_{DLR} + V_{LVA} + V_{BR} + V_{BR} + V_{AB} + V_{HR} \quad (10)$$

where V_T is the total interaction energy, V_{DLR} are the electric double layer forces (repulsive), V_{LVA} are the London-Van der Waals forces (attractive), V_{BR} are the Born forces (repulsive), V_{AB} are the acid base interaction forces (attractive) and V_{HR} are the hydrodynamic forces (repulsive).

A positive total interaction energy leads to repulsion and a negative one results in attraction. For practical applications only London-Van der Waals attraction forces and electric double layer forces are of relevance when suitable nanoparticles like MgO, SiO₂ or Al₂O₃ with their high surface areas and adsorption/conduction properties are being used. Laboratory results proved this method to be effective in terms of fines retention. A proppant coating with its effects based on surface force attraction was tested for this thesis.

2.7 Gravel Pack Damage Mechanisms

2.7.1 Mechanical Damage Mechanisms [33]

While gravel packs are installed in unconsolidated formations to control sand production, they may be damaged by sand particles. Proper gravel pack design though aims not only to prevent sand migration and maximize permeability but also to avoid damages to the gravel pack that can occur by particle plugging.

If this is not achieved, the invasion of grains into the gravel pack can occur by different mechanisms. Gradual pore blocking occurs in deep distances due to fines migrating through the pore space and finally depositing on the pore walls resulting in a parabolic permeability decline over time. Single particle invasion on the other hand occurs in deep invasion distances as well but leads to a linear permeability reduction over time. Internal cake formation as the third mechanism occurs due to high concentrations of various size particles bridging at a pore throat, resulting in a hyperbolic permeability decline over time.

The actual behavior of the gravel pack when subjected to grains migration essentially on the gravel-sand diameter ratio and the particle concentration whereas fluid velocity does not play a significant role. Depending these factors, five different types of gravel pack reactions can be observed.

- No interaction occurs if the median grain size diameter of the gravel is too big to stop the sand from invading. In this case, the sand is migrating through the gravel pack without causing permeability reduction
- Pore filling is the result of particles gradually invading the gravel pack and decreasing its permeability in a hyperbolic fashion
- Combined internal bridging and single pore blocking results from an initial single pore blocking and leads to a hyperbolic decrease in permeability as well
- Shallow internal bridging occurring in low invasion depths can be removed by backflow
- No invasion into the gravel pack can be seen as the most preferable scenario. Grains are not able to invade the gravel pack, yet external cakes buildup may reduce well productivity

2.7.2 Scaling [34]

Although not directly related to sand and fines invasion into the sand control installation, scaling might also cause mechanical damage to the filter medium by coating and plugging perforations, gravel packs, downhole completions and also surface facilities. The scaling tendency of a well is thereby depending on the thermodynamic conditions downhole and especially alterations of them. As many minerals are water soluble, they might be dissolved in pore water, transported and finally tend to precipitate when changes in thermodynamic conditions lead to oversaturation of dissolved ions in the pore water. Solubility for most minerals increases with pressure and temperature whereas for calcite a decrease can be observed.

Scaling within reservoirs and sand control units may begin with unstable cluster atoms formation called homogeneous nucleation. These first crystals being formed from changed equilibrium conditions may grow by the additions of further ions requiring superheating whereas the free energy required for the growth of the crystal decreases with its increase in size. Heterogeneous nucleation on the other hand occurring on surfaces requires less energy and is commonly formed in sand control units such as gravel packs.

Further mechanisms than self-scaling by changes in thermodynamic conditions are scaling due to incompatibility mixing, evaporation induced scaling and gas flooding. Carbonate scaling as a very common form of scaling in reservoirs may be treated by acid jobs but still represents a major issue since these remedial operations are very time and cost-intensive.

Preventing the formation of scale is therefore preferred over remedial action. Although the focus of this thesis is not on the prevention of scale damage, it shall be noted that new glass beads filter materials that were tested for their fines retention capability also show

improvement in terms of gravel pack scaling tendencies. Due to their smooth surfaces, calcium carbonate scaling reduced as compared to common ceramic proppant materials, whereas further improvement can be reached by hydrophobic coating (Figure 29, Figure 30 and Figure 31).

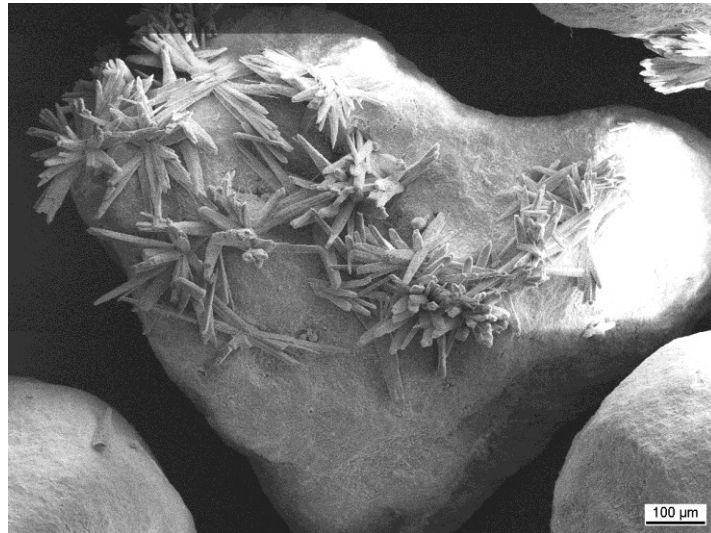


Figure 29: Calcium Carbonate Scale on Ceramic Proppant [34]

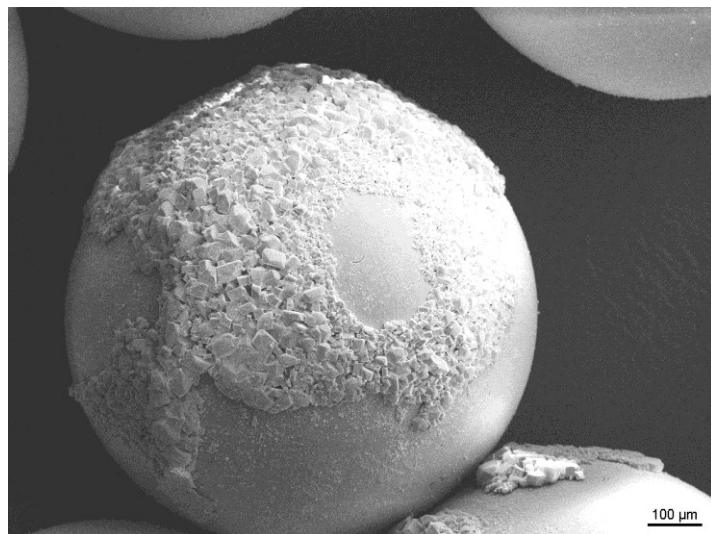


Figure 30: Calcium Carbonate Scale on uncoated Glass Beads [34]

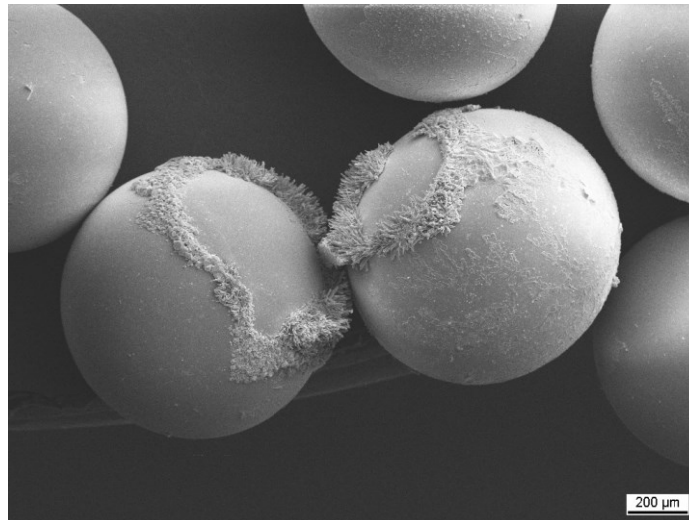


Figure 31: Calcium Carbonate Scale on hydrophobically coated Glass Beads [34]

3 Evaluation Criteria

In order to properly evaluate the effectiveness of sand and fines migration methods, several criteria had to be set up. Since the aim of this thesis is to investigate improved sand control methods, the evaluation criteria were selected according to actual sand production problems.

The sand and fines migration from a simulated artificial formation into the simulated gravel pack, compromising its permeability, should be stopped. Furthermore, sand and fines particles should also be stopped from migrating through the gravel pack material without reducing its permeability.

It was therefore decided to evaluate a method's efficiency by the permeability reduction measured via flow rate and pressure drop and also by the amount of particles that could be filtrated from the efflux. First, baseline tests without any kind of sand or fines invasion should be used to obtain the materials' permeability when not subjected to migration tendencies. Fines migration tests on the untreated material then showed the impact of invasion on the materials' permeability and delivered comparables that were later on used to evaluate the chemical treatments' efficiency during sand and fines invasion.

4 Laboratory Test Setup

The test-setup consisted of the flow tube within a mounting, a set of six pumps in a serial connection, a pressure sensor, a digital amplifier as well as a scale and a PC (Figure 32).

The filter medium to be tested was filled into the flow tube, which then was connected to influx- and efflux lines. The pumps were connected to the influx line in a serial connection while the flow rate was calculated from the weight of the efflux measured by a laboratory scale connected to a personal computer. The differential pressure sensor mounted to the flow tube, measuring the pressure drop over the filter medium was connected to the amplifier, which converted the milliamper signal into a digital one. This digital signal was then transferred to the PC. Data were recorded with a sampling rate of 1 per 10 seconds. To measure the amount of fines or particles travelling through the filter medium into the efflux beaker when the sand retention of the filter medium and/or the consolidation efficiency of the different chemicals were determined, a filtration unit connected to a water-jet pump was used. For the baseline and the chemical-free fines invasion tests fluid was pumped directly with the pumps while for the chemical consolidation tests, in order to avoid direct contact of the pumps and their sensitive valves and seals with potentially aggressive chemicals, displacement containers with a petroleum buffer were installed.



Figure 32: Test Setup with saturated Sample

4.1 Flow Tube

The center-piece of the test-setup was the plexi-glass tube with an inner diameter of 17mm and an outer diameter of 45mm (Figure 33). At the lower end of the flow tube, an o-ring was mounted into a side-groove, providing necessary sealing capacities since the o-ring placed on the lower mounting plate, proved to be impractical and not functional especially because of the material grains' tendency to slip between the o-ring and the sealing surface when filling the flow tube with filter material. With the o-ring in the side groove, the flow tube provided a seal to the lower side of the mounting even without the upper mounting being pressed on top during the filling of the material. On the upper side of the flow tube the problem of grains compromising the integrity of the sealing surface was not given. Therefore the integrated o-ring in the top mounting plate was sufficient to provide the required sealing. Note that on the upper side of the flow tube, the inner diameter had to be extended to 25mm for a length of 2 mm. This was done to connect to the inner space filled with the test material to the openings of the mounting, which would otherwise be placed directly over the plexi-glass edge. This extension of diameter was not required for the lower side of the flow tube since the bottom plate of the mounting provided flow channels engraved into the metal, directly leading to the openings of the lower mounting plate. A connection for the differential pressure transducer was installed at the middle of the flow tube. This was necessary to measure the permeability decline of the gravel pack filter medium when fines invasion from an artificial formation sand was simulated. While for the permeability baseline tests the flow tube was filled with only one type and size of material, it was filled with a combination of gravel pack filter medium on the bottom and artificial formation on the top for the tests to measure fines invasion into the filter medium. Minimum two pore volume of brine to saturate the flow tube's fill was flown from the bottom to the top. In case chemical treatments were simulated, the chemicals were also flown from the bottom to the top, which is the direction from the filter medium to the artificial formation.



Figure 33: Flow Tube with Sidewall Adaption and O-Ring

4.2 Mounting

The mounting itself consisted of two metal plates connected with threaded rods and nuts (Figure 34). The flow tube was mounted in between the metal mounts and the sealing capacity was obtained by applying compression force tightening up the nuts to the threaded rods. This had the effect that the side mounted o-ring was placed correctly into the mount and the upper o-ring was well connected to the sealing surface of the top plate. Although the top and bottom mounting plates provided two openings, only one outlet at each plate was used. Initially, the second opening was used at the bottom to hook up the pressure measurement but it proved impractical because filter grains frequently fell into the opening and blocked the connection to the pressure transducer, resulting in uncertainty and uncertain measurements. Changing the setup that the differential pressure measurement was connected to the effluent line the phenomena occurred less frequently and if so, it was immediately noticed by a massive decrease in efflux rate. Therefore only one opening at each plate was used and connected to a flow line for in- and outflow combined with a valve to shut in the flow tube.

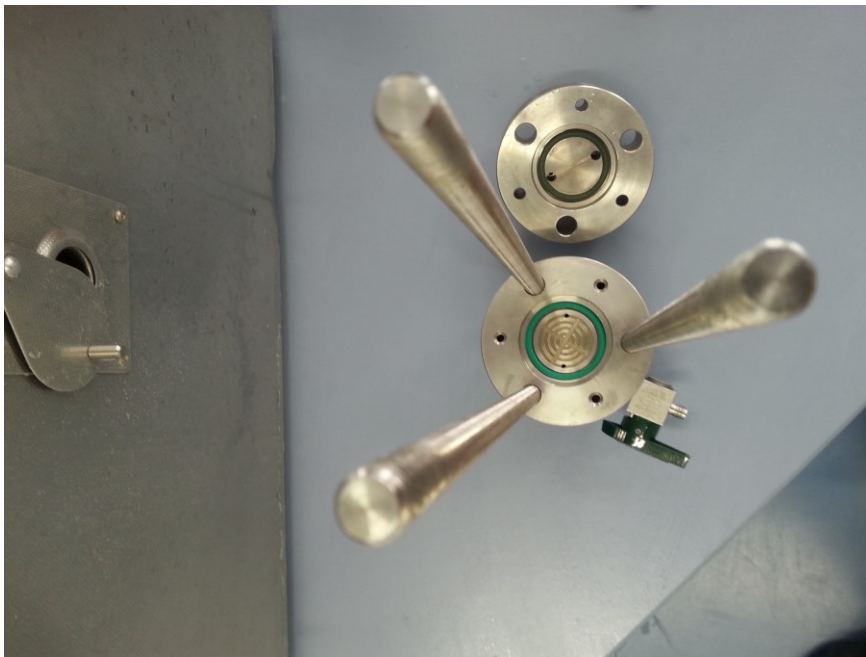


Figure 34: Mounting with O-Rings, threaded Rods and Valve

4.3 Pressure Sensors

To measure the pressure drop over the flow tube, one inductive differential pressure sensor with a 10 bar rating was installed (Figure 35). The pressure difference measurement over the gravel pack was taken by connecting the outlet of the bottom mounting on the one and the outlet at the middle of the flow tube on the other side. This measured the pressure drop over the lower half of the flow tube and allowed so to determine permeability reduction caused by the fine material invasion from the artificial formation into the gravel pack. This setup proved suitable and therefore was used for the whole testing program.

The inductive pressure sensor was connected to a pressure amplifier, which transferred the pressure data to the PC. The sample rate for this recording was 1/10s.

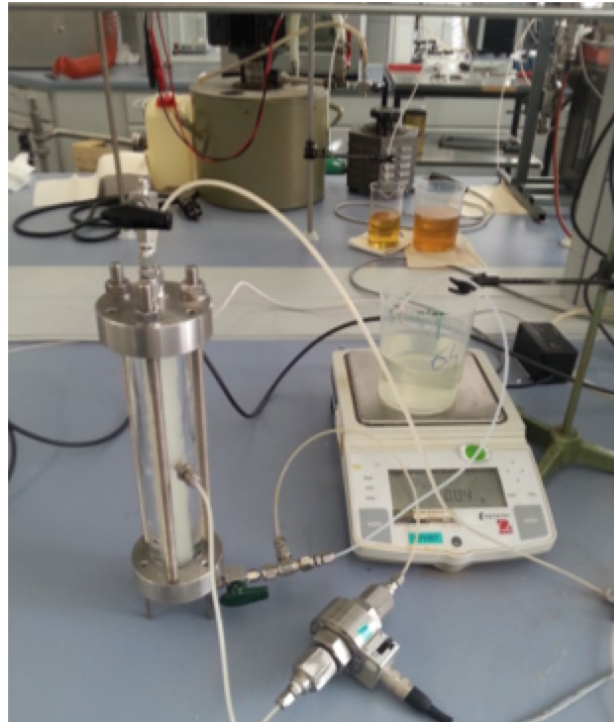


Figure 35: Delta-p Pressure Sensors mounted on the Flow Tube

4.4 Pumps

To produce sufficient flow rate and create the necessary pressure drop, six pumps were connected in serial: Three HPLC pumps able to deliver flow rates up to 50 ml/min each and three LP20-AD parallel double micro plunger pumps able to deliver flow rates of 10 ml/min each. All pumps were revised and maintained before the beginning of the tests including the renewal of the sapphire pistons for the LP-20AD and valves for the HPLC pumps (Figure 36).

To assure a constant test procedure and to minimize pressure shock wave effects, the flow rates were limited for the baseline permeability tests to 45 ml/min and for the fines invasion testing to 35 ml/min. These flow rates also guaranteed absolute pressures lower than the maximum allowable pressure for drilled plexi-glass even in the case of massive fines movement plugging the entire pore space of the gravel pack. Nevertheless for safety reasons, the pressure limit of the pumps was set to 7,5 bars. The maximum absolute pressure observed during the fines invasion tests without chemical treatment at 35 ml/min was 5 bars.

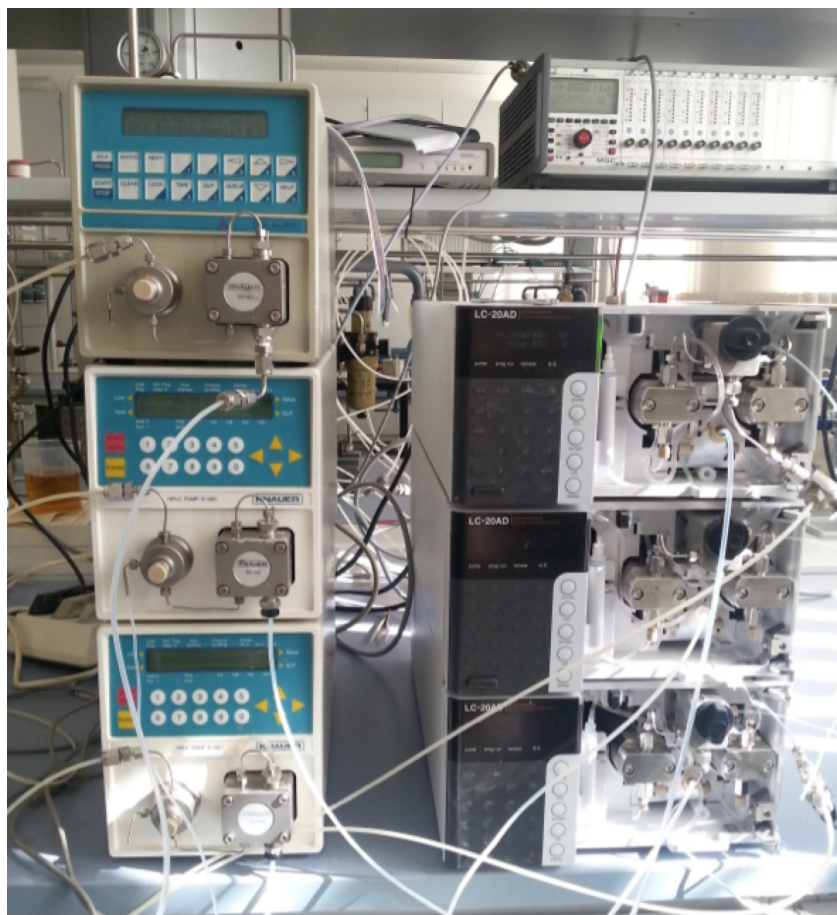


Figure 36: Pump Setup

4.5 Displacement Containers

Because of the high sensitivity of the HPLC pumps and especially their integrated ball valves, which were installed within the suction line to avoid backflow during the negative stroke, the media flowing through the pumps had to be chosen carefully. Water with 3% KCl could be used whereas other media like highly viscous polymers or resins were marked as incompatible.

Therefore a set of two connected displacement containers consisting of a flow-chamber, a mounting and threaded rods was interposed between the pumps and the flow tube (Figure 37). While the container connected to the flow tube was filled up with the chemical to be injected into the flow tube, the second container, which was connected to the pump and in serial to the first container, was filled with a buffer fluid. This way, the water sent through the pumps displaced the chemical into the flow tube without direct pump-chemical interaction.

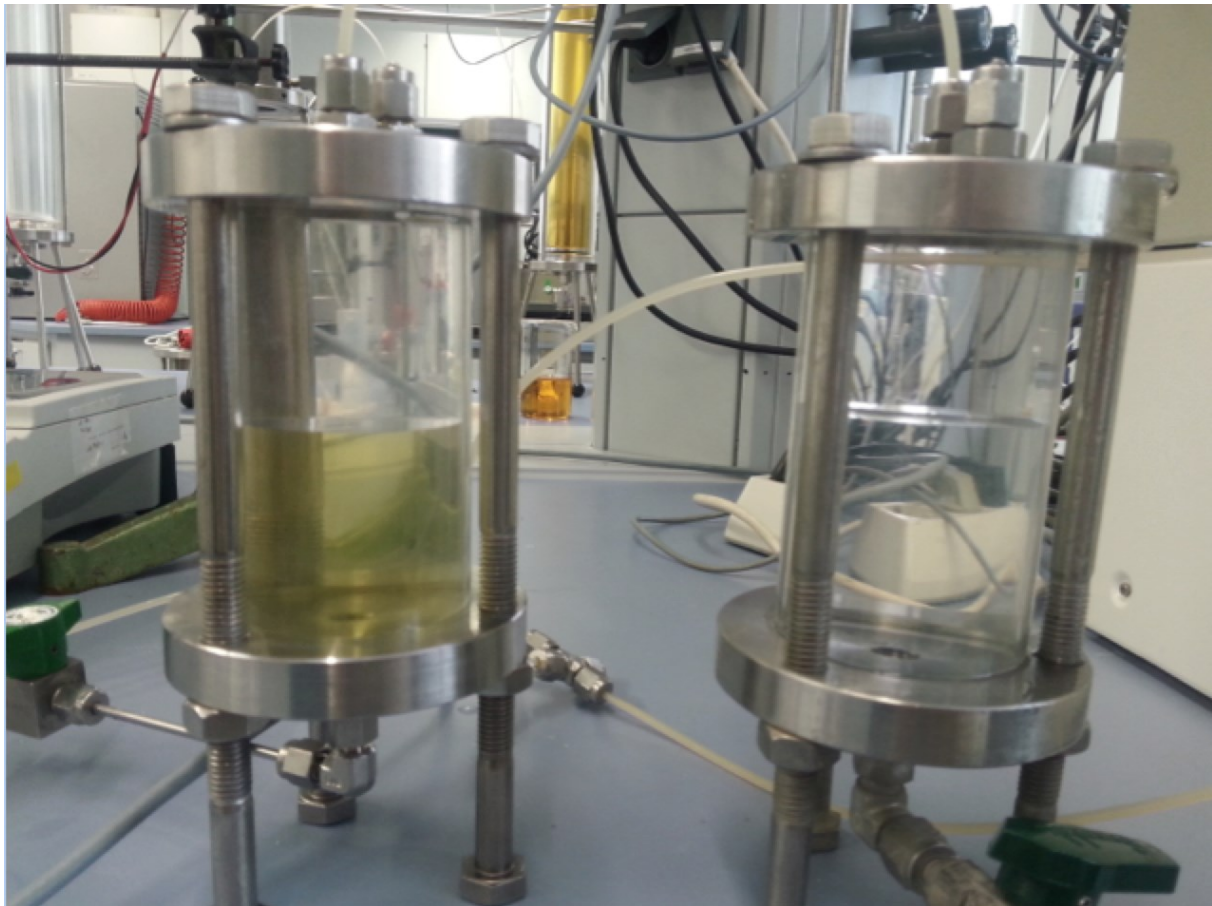


Figure 37: Displacement Containers

4.6 Filtration Unit

The efflux of the flow testing itself was analyzed in respect of fine particle content with a vacuum filtration

This efflux water, which contained dispersed sand or fines particles washed from the artificial formation through the filter medium was filled into a container installed on top of the vacuum filter unit (Figure 38). The efflux was flown through a 3 micron filter and then flushed with the same amount of distilled water to wash out potential un-dissolved salts. The filter was dried in a heating chamber at 80 degree Celsius for 24 hour before it was weighed and compared to the weight of the filter before use.



Figure 38: Filtration Unit

5 Test Methodology

5.1 Baseline Tests

First, the permeability of different filter materials without any kind of sand or fines contamination was determined for comparison purposes.

The flow tube mounted to the lower plate was filled with the test material to the top. To provide rhomboidal packing the materials were compacted by mechanical means using mechanical agitation. The flow tube was then placed vertically, connected to the series of pumps and saturated from the bottom to the top with 3% KCl at a flow rate of 5ml/min.

During the process the lower side of the pressure sensor was disconnected to remove possible air bubbles in the connection tubes eliminating the risk of the pressure measurement being compromised. This was repeated with the upper side of the pressure sensor as soon as the water column had reached the connection in the middle of the flow tube. Altogether two pore volumes of brine were pumped through the medium to make sure that all air had been removed from the filter medium and the flow and pressure sensor connections.

It was observed that flow rates higher than 5 ml/min showed lower efficiency in displacing trapped air during the saturation process: These air bubbles were recognizable because they were attached to the sidewall of the plexi-glass.

After the saturation process, the pumps were shut down and the flow tube was shut in by a valve at the bottom. The flow pass of the pumps was switched from below to the top of the flow tube. This was done to have a standardized procedure for all tests, considering that for testing chemical consolidation production was simulated from the artificial formation to the filter medium. The efflux line was routed from the bottom to the container situated on the scale for rate measurements. After the flow pass was switched, the valve at the bottom of the tube was reopened. Once the pressure being measured continuously stabilized, the differential pressure sensor was calibrated to zero and data recording started.

The tests were started at the flow rate of 45 ml/min and the pressure difference was measured for five minutes. The flow rate was then reduced to 35 ml/min for another five minutes. The recorded pressure differences were normalized and the final permeability vs. time curve was calculated.

5.2 Fines Invasion Tests in Proppant and Glass Beads

To get a reference value for permeability decrease in the filter medium, fines invasion tests were first conducted without any chemical treatment with different filter media.

For the fines invasion tests, the procedure was kept similar. The only difference was that the flow tube was filled with filter medium on the bottom and the artificial formation on the top. The interface of the two materials was five millimeter above the connection of the pressure

sensors to ensure that the pressure difference was only measured over the filter medium. Mechanical agitation was only applied to the filter medium. This avoided fine particles of the artificial formation glass bead mixture prematurely invading the filter medium.

Furthermore the flow rate during the saturation phase was lowered to 3ml/min because the higher saturation flow rate used for the baseline tests showed imperfect air displacement and particle floating with the artificial formation. The tests flow rate applied from the top to the bottom was limited to a constant 35 ml/min over the whole testing period of 10 minutes.

5.3 Chemical Treatment Tests

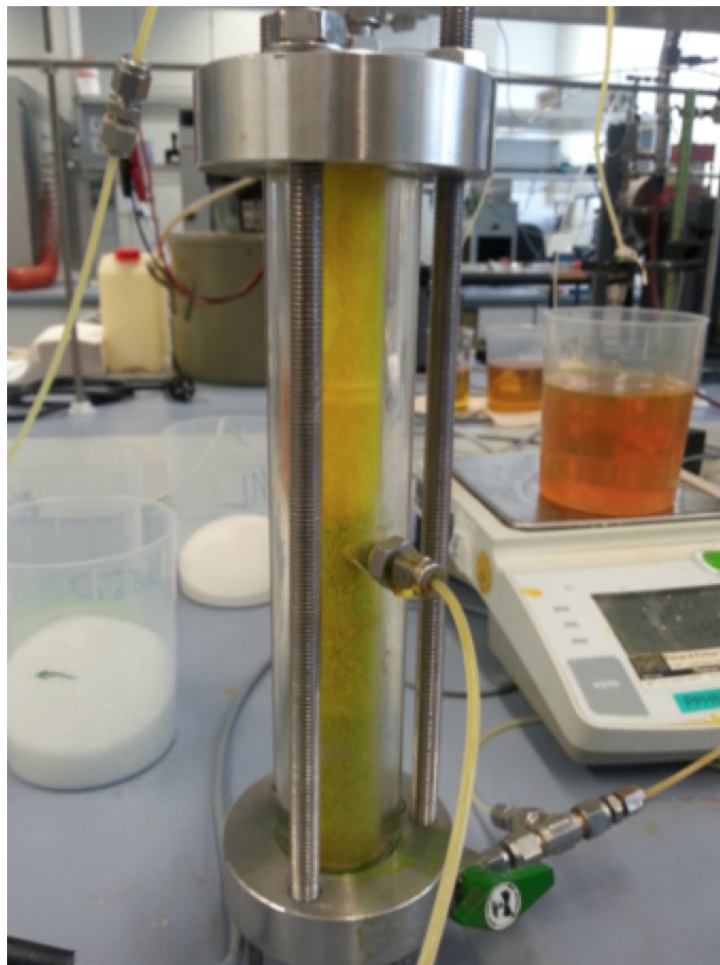


Figure 39: Chemical Injection with Fluorescein as Tracer

For the chemical tests, the procedure was kept the same, only adding the steps necessary to simulate the chemical treatment of either the filter material and the artificial formation or only the filter medium.

Chemicals directly injected into the formation (Figure 39) were filled into the displacement containers as described in the test setup. After the flow tube was prepared and saturated with brine as described above, the chemicals were injected at the same flow rate as the brine

from the bottom to the top. To ease fluid tracking and so ensure good saturation of the media in the flow tube, the chemicals were dyed with unreactive fluorescein. Generally three pore volumes of chemical flush were pumped through the filter and the artificial formation material for the tests, which was found sufficient for maximum chemical saturation.

Thereafter the flow line was connected to the bottom of the flow tube again and a post-flush of three pore volumes was applied at a flow rate of 3 ml/min from the bottom to the top. Connecting and disconnecting the flow lines to the differential pressure sensor to get them filled up with fluid was only applied in this last post-flush stage in order to avoid direct contact of the chemical with the pressure sensor.

Depending on the type of chemicals being used and the respective requirements, the sample was given time and exposure to temperature for consolidation either before or after the displacement and over-flush. Proppant covering consolidation chemicals on the other hand were pre-mixed by hand before being inserted into the flow tube. Since these chemicals enhanced the stickiness of the proppant, mechanical agitation was not sufficient to compact the filter medium inside the flow tube and was therefore stuffed. The test procedure for these chemicals was exactly the same as describe in section 5.2.

After the chemical treatment tests had been conducted, the flow tube as well as the whole test setup that had been contaminated with the chemicals was cleaned out carefully. While polymers were simply washed out with water, isopropanol was used to remove oil-based resins and HCl was used to remove carbonate scales. To avoid direct contact with the pumps, these fluids were injected into the flow tube via the displacement containers.

6 Description of Materials

6.1 Proppant and Glass Beads

As filter medium for gravel packs in Austria, low-density manmade ceramic proppant is commonly used. The technical specifications of the proppant are

Specific density	2.71 g/cm ³
Bulk Density	1.57 g/cm ³
Roundness	0.9
Solubility in Acid	1.2%

This material is available in mesh sizes ranging from 12/18 to 40/70 mesh and is generally used in the size of 20/40, 16/20 and 12/18 mesh in Austria. For the tests, mesh sizes 16/20 (=850-1180 μm) and 20/40 (=420-841 μm) were chosen. As alternative to the manmade ceramic proppant, the performance of glass beads as filter material was investigated. Various different types and sizes of glass beads were available of which three sorts were looked at to evaluate the materials' potential to replace the ceramic proppant. Test results of 400-800 μm standard glass beads, 600-850 μm and 800-1000 μm special quality glass beads were compared to the performance of the manmade ceramic proppant in the corresponding grain sizes of 20/40 and 16/20 mesh. The glass beads are made of recycled soda-lime glass that was formed to beads with over 80% roundness in gas-fired shaft furnaces. The chemical composition of these glass beads is SiO₂ (68-75%), CaO (7-12%), Na₂O (12-18%), Al₂O₃ (0-2,5%), MgO (0-5%) and others (max. 2%) while the bulk density is at 1.5-1.6. Crush resistance is claimed to be high, whereas acid solubility for acids generally used in sandstone formations was not specified and therefore was determined by exposing the beads for two hours to a 90 °C hot 15/3% HCL/HF mixture.

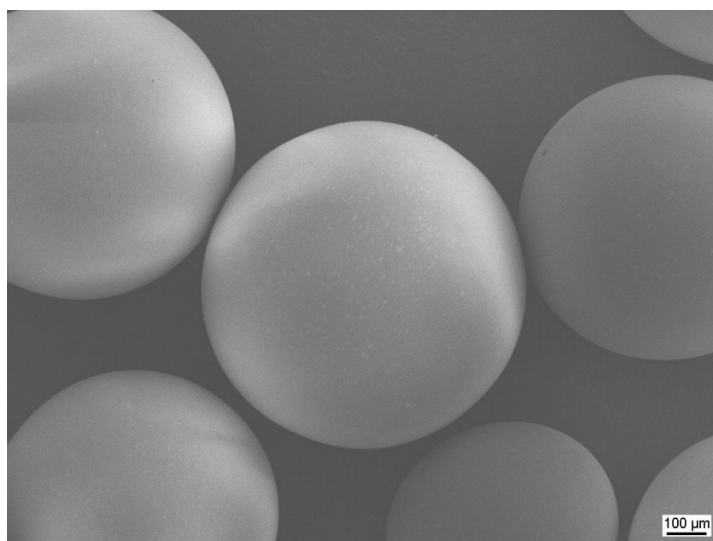


Figure 40: Glass Beads before Acid Treatment under Scanning Electron Microscope

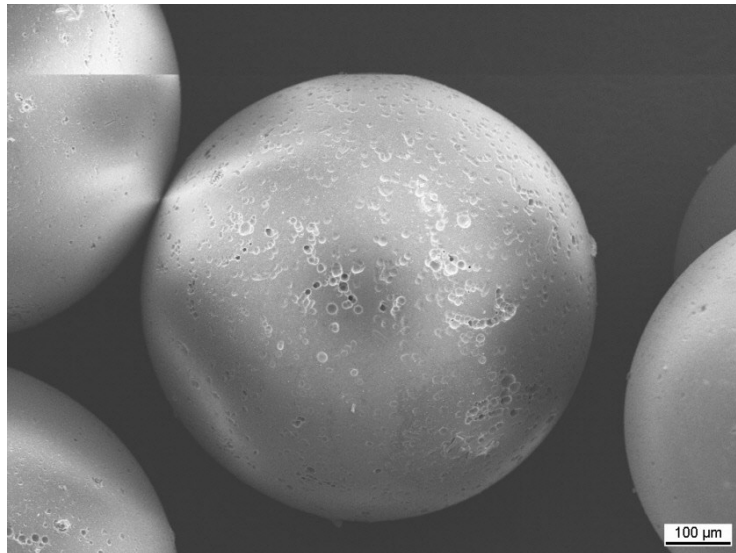


Figure 41: Glass Beads after Acid Treatment under Scanning Electron Microscope

As it can be seen in the figures above, the acid exposure did not show significant impacts on the glass beads (Figure 40 and Figure 41). Increased surface roughness could be recognized under the SEM but no significant damages or measurable weight losses were observed. Uncoated standard material as well as glass beads coated with hydrophobic material performed the same way. The 800-1000 μm special quality glass bead type, which was tested as a possible replacement for 16/20 mesh size ceramic proppant is formed by melting the recycled glass in troughs. This production technique where beads with a roundness of over 85% and perfect, crystal clear, seemingly polished surfaces are produced approximately triples the price per ton. The price can easily be justified by the outperformance of standard glass beads when used in road construction marking but because they show hardly any beneficial effects when used as a filtering material its price seems high. Since there are currently no other glass qualities available in this dimension resembling the 16/20 mesh ceramic proppant this glass beads type was seen as the only possible glass bead replacement.

Cum. % <	20/40	Cum. % <	400-800	600-850
	Proppant		Glass Beads	Glass Beads
600 μm	3%	400 μm	0-5%	
850 μm	93%	600 μm	35-60%	0-5%
1180 μm	100%	850 μm	90-100%	90-100%
		1000 μm	98-100%	98-100%

Table 2: Manufacturer Sieve Curve Data Proppant 20/40 vs Glass Beads 400-800 / 600-850

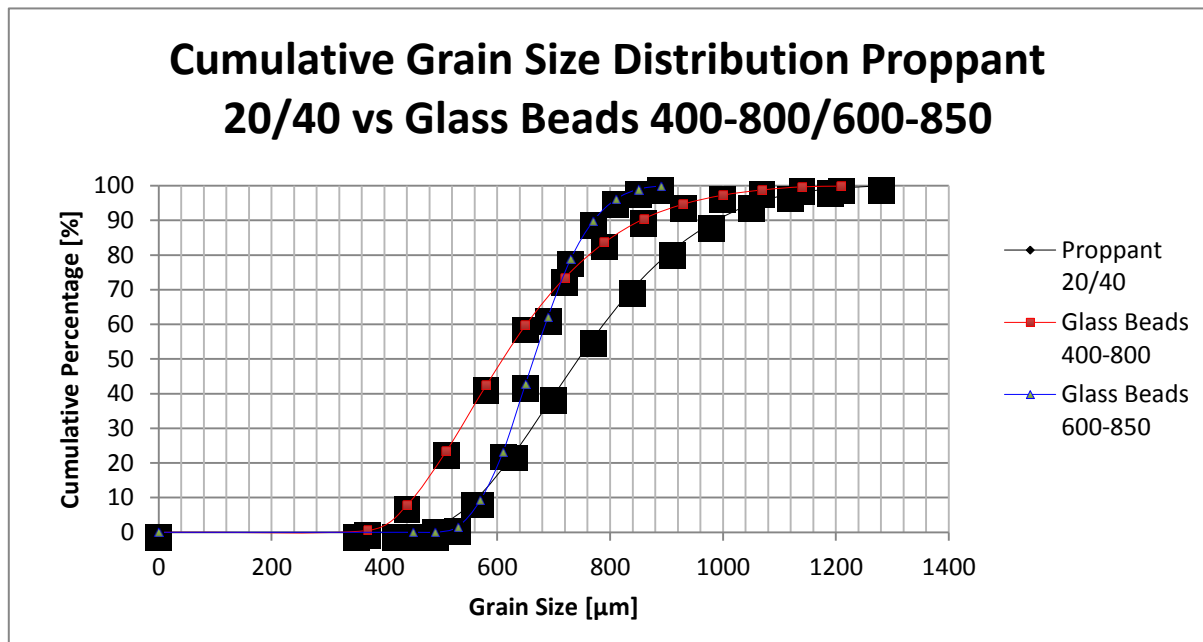


Figure 42: Cumulative Grain Size Distribution Proppant 20/40 vs Glass Beads 400-800 / 600-850

The motive in replacing manmade ceramic proppant with glass beads was the idea that the glass materials with their near-perfect sphericity and smooth surface would provide comparable permeabilities to the ceramic proppant at lower median grain size diameters (Table 2). Therefore they should provide better fines retention capabilities without a loss in filter medium conductivity.

Manufacturer data suggested 400-800 µm glass beads to have a smaller median grain size diameter than 20/40 mesh size proppant. 600-850 µm glass beads on the other hand should have a median grain size diameter in between the proppant and the 400-800 µm glass beads, but provide a narrower distribution curve and hence better sorting, leading to improved permeability.

In order to be independent from the manufacturer's grain size data that was provided, additional spectroscopic analysis were performed. While 400-800 µm glass beads came very close to the manufacturer's specifications with 97.3% of all particles having a diameter of less than 1000 µm, spectroscopical analysis of 600-850 µm glass beads showed significantly higher particle volumes of up to 20% above 850 and below 650 µm. Similar results were observed analyzing the 20/40 mesh size proppant. The laser diffraction particle size analysis showed that almost 30% of the particle volume lay outside the manufacturer's specifications (Figure 42).

Still, comparing the data to each other, the grain size distributions were similar and resulted in what was expected. Both glass beads types showed lower median grain size diameters than the manmade ceramic material with the 400-800 µm beads being smaller than the 600-850 µm type and the later providing a smaller grain size distribution range.

Cum. % <	16/20 Proppant	Cum. % <	800-1000 Glass Beads
850 μm	2%	850 μm	0-5%
1180 μm	95%	1000 μm	90-100%
1700 μm	100%	1180 μm	98-100%
		1700 μm	100%

Table 3: Manufacturer Sieve Curve Data Proppant 16/20 vs Glass Beads 800-1000

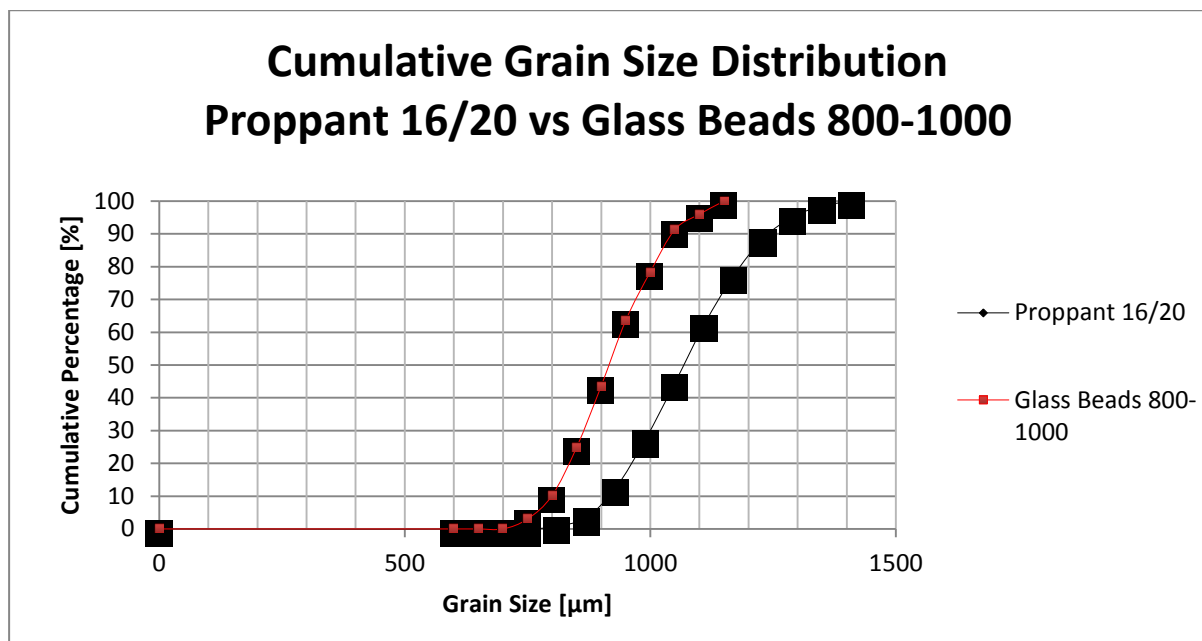


Figure 43: Cumulative Grain Size Distribution Proppant 16/20 vs Glass Beads 800-1000

For the glass material to be compared to the 16/20 mesh size manmade ceramic material, the spectroscopic analysis resulted in less outlying grain sizes. 800-1000 μm glass beads fulfilled the specifications at the upper grain size boundary but like the 600-850 μm glass beads showed higher volumes of smaller grain size diameters (Figure 43).

16/20 mesh proppant on the other hand (like 20/40 proppant) fulfilled the specification for the lower grain size diameter (Table 3) volume but showed significantly higher volumes of bigger grain sizes. Putting the results in relation, showed that the glass beads provide a smaller median grain size diameter and were therefore considered suitable to be used to investigate the theory that the materials with smaller median grain size but comparable permeability will perform better in sands and fines retention compared to manmade ceramic proppant.

6.2 Artificial Formation

After the characterization of possible filter materials, an artificial formation containing fines, similar to the ones causing plugging and permeability reduction in producing wells, had to be mixed. The totally unconsolidated artificial formation was simulated with a mixture of different glass bead types, which were easily available in a wide range of grain size distributions (Figure 44) and (Table 4).

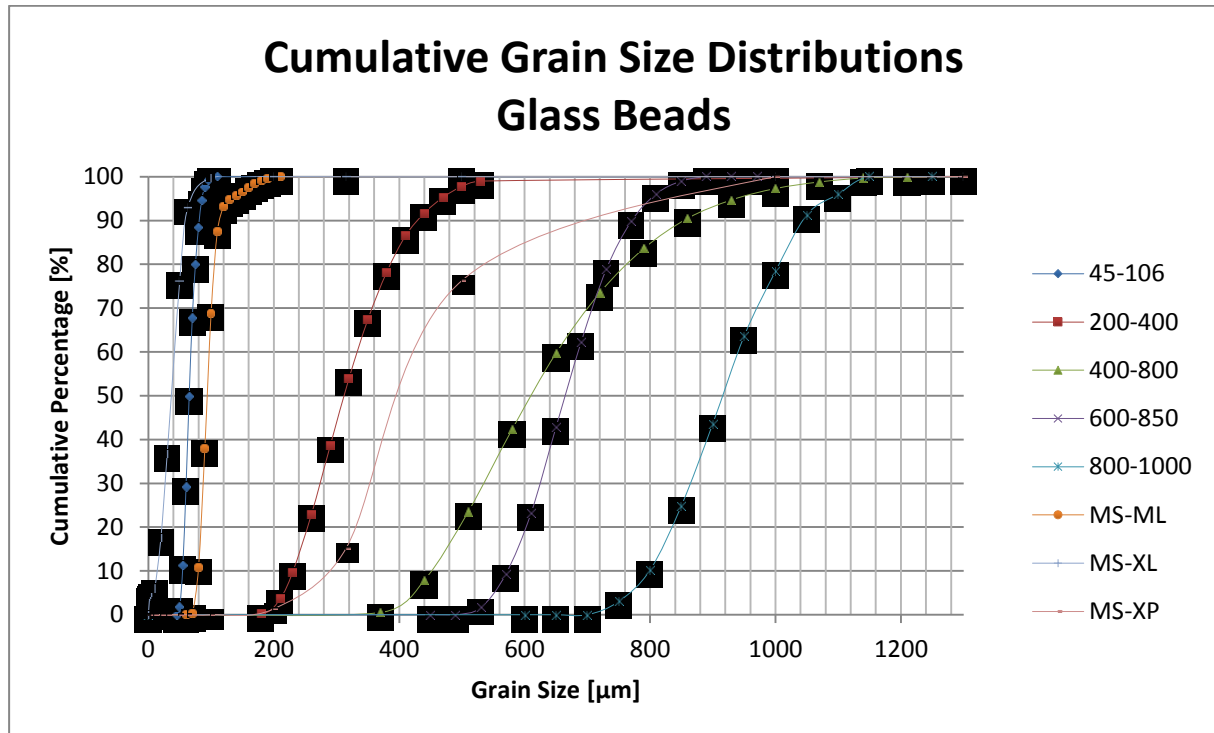


Figure 44: Cumulative Grain Size Distribution Glass Beads

Glass Bead Type	Median Grain Size Diameter [μm]
MS-ML	94
MS-XL	36
MS-XP	400
45-106	65
200-400	312
400-800	610
600-850	665
800-1000	916

Table 4: Median Grain Size Diameter of different Glass Bead Types

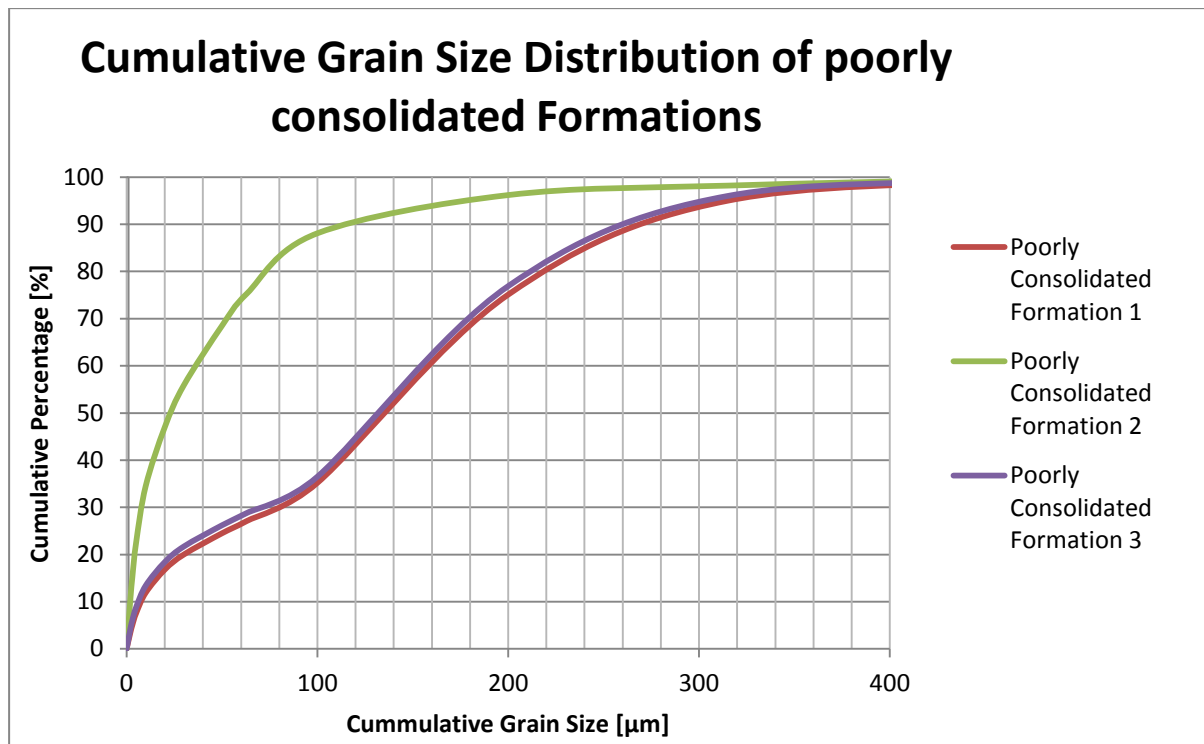


Figure 45: Cumulative Grains Size Distribution of poorly consolidated Formations

Three different grain size distributions were used as an example for the unconsolidated formation (Figure 45). Since general industry standard is that particle production of sizes below 45 μm can be tolerated and grains of higher diameters shall be retained well by adequate gravel pack proppant sizing, the main focus was put on the critical grain size range of 50-100 μm . This grain size is causing most problems in production and is also present in large volumes in the samples that have been investigated.

Furthermore, the mixture of glass beads representing the formation had to fulfill a number of criteria to be regarded suitable for invasion tests. The mixture had to contain fine 50-100 μm particles in an amount, sufficient to observe permeability decrease in the gravel pack when high flow rates were applied to mobilize formation particles. Coarse particles on the other hand should provide sufficient structural integrity of the artificial formation to avoid fines migrating into the gravel pack before applying high flow rates to simulate the dissolving of the formation. The selection of the coarse particles was of special importance since they had to be sized small enough for the fine particles not to show any gravity separation effects over time but coarse enough to allow the fine particles to migrate through the formation into the gravel pack when the migration tendencies were to be tested.

To do so, several tests were conducted, leading to the result that the most suitable mixture fulfilling all these criteria was a combination of 45-106 μm glass beads for the fine particles and 600-850 μm glass beads for the coarse particles mixed in the ratio 1:2. To ensure constant quality over all tests, this mixture was prepared separately in small amounts of 75g before every test.

Note that the composition of the 45-106 μm glass beads differs significantly from the composition of the standard soda lime glass beads like 600-850 μm that has already been described before. 45-106 μm glass beads consist of barium titanate glass with a high refractive index of >1.9 since they are commonly used for road markings or reflective textiles. They show the same bulk density as other glass bead types (app. 1.5) and a high degree of roundness of $>80\%$. The manufacturer's specifications for the grain size distribution could be met accurately in this case. Although consisting of a different material, this type of glass beads was not tested for acid solubility since it should only be used as a laboratory tests material and not as a potential filter medium.

7 Laboratory Test Results

7.1 Baseline Tests

For the baseline tests of potential new filter media, the procedure described in chapter 6 was applied. First, the 20/40 mesh size manmade ceramic material was tested and compared to the glass beads types' of similar size. The flow tube was filled with each material three times and each of these fillings was tested twice, giving a total of 6 tests per filter material. For the calculation of permeability, the Darcy equation was used.

$$k = \frac{q \cdot \mu \cdot L}{A \cdot \Delta p} \quad (11)$$

where k is permeability [m^2], q is the flow rate [m^3/s], Δp is the pressure drop [Pa], μ is the fluid's dynamic viscosity [$Pa \cdot s$], A is the sample's cross section [m^2] and L is the length of the sample [m].

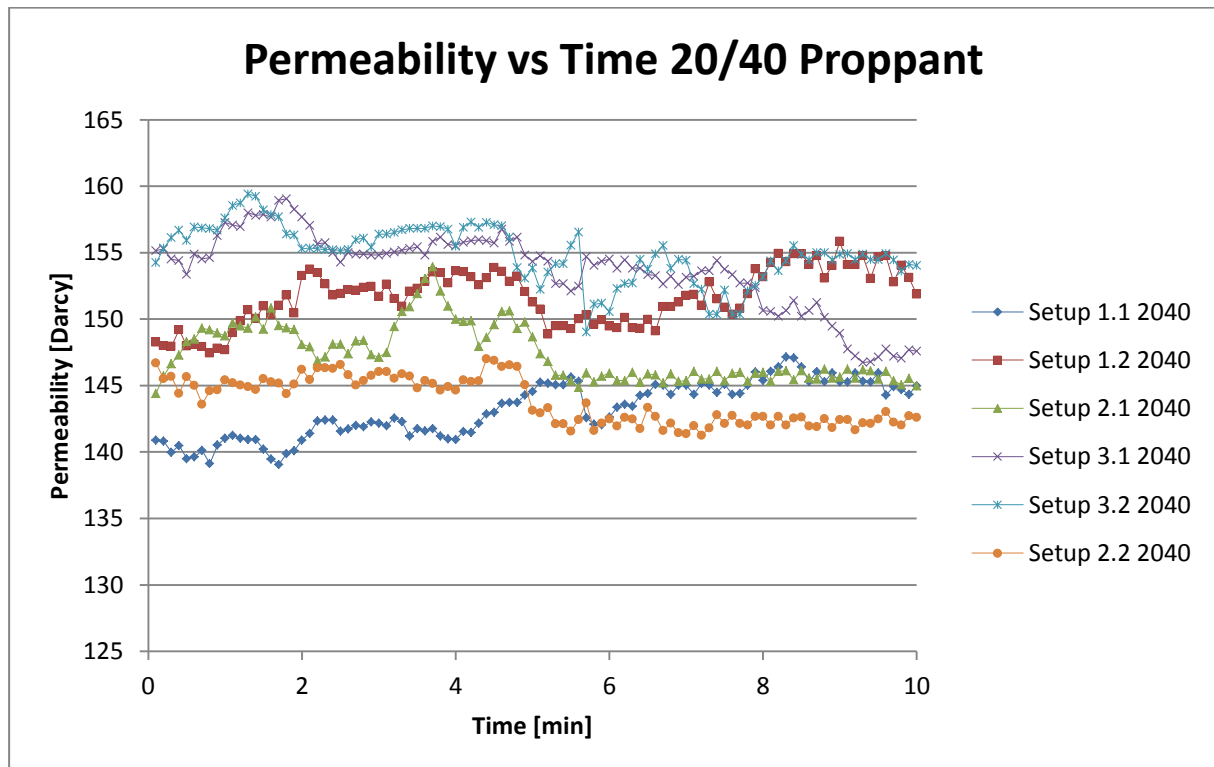


Figure 46: Permeability vs Time 20/40 Proppant

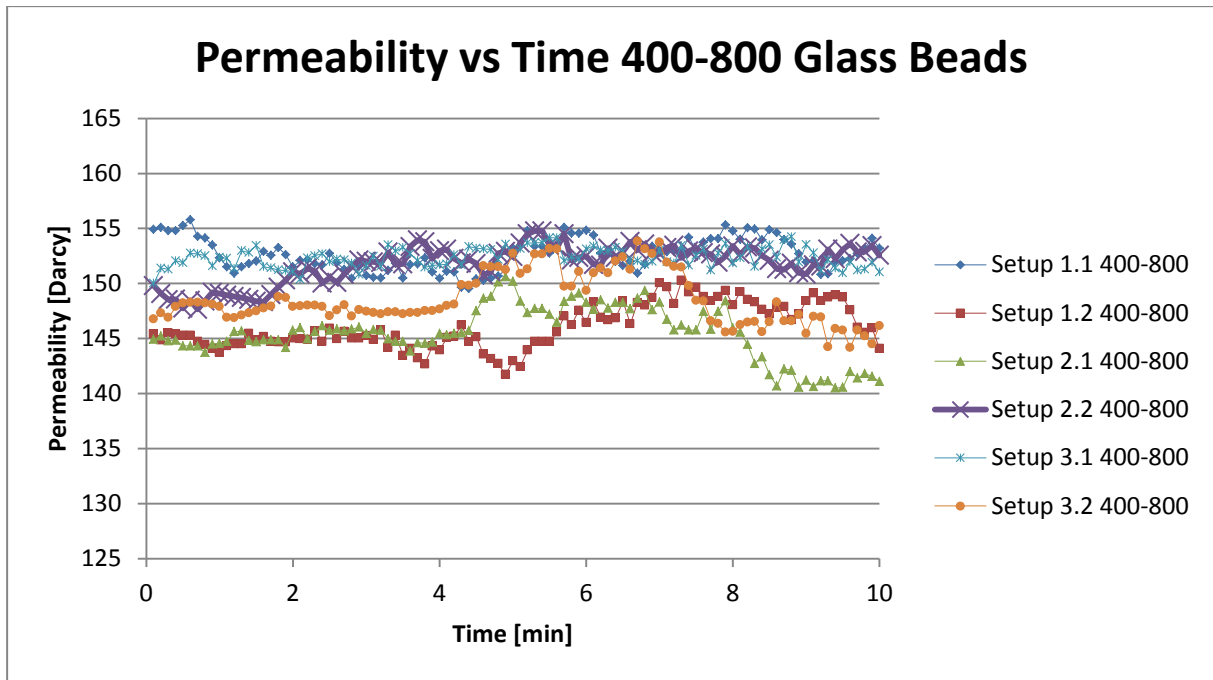


Figure 47: Permeability vs Time 400-800 Glass Beads

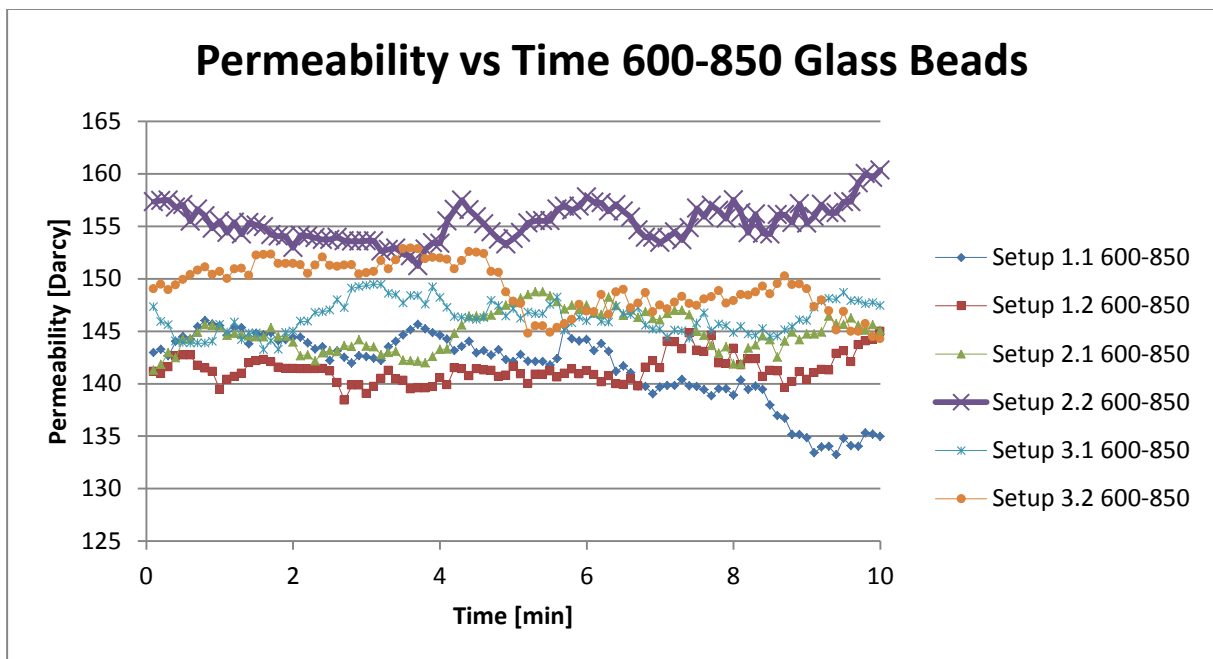


Figure 48: Permeability vs Time 600-850 Glass Beads

Material	Average Permeability [Darcy]	Standard Deviation [Darcy]
20/40 Proppant	150,02	4,46
400-800 Glass Beads	149,47	3,51
600-850 Glass Beads	146,44	5,28

Table 5: Tested Baseline Permeabilities 1

The tests conducted on the materials proved to provide constant and comparable results not only over time but also over different tests, showing very small standard deviations (Table 5). As expected, the permeability results for the chosen glass beads types were indeed comparable to the proppant's (Figure 46) although having smaller median grain size diameters. Note that 600-850 μm glass beads (Figure 48) did not give better results in terms of permeability than 400-800 μm glass beads (Figure 47). Despite better sorting and a higher median grain size diameter, the material was resulting in less fines retention capability. Considering that these 600-850 μm glass beads are also slightly more expensive than the 400-800 μm standard glass beads, it was decided to continue all further tests with the 400-800 μm glass beads.

For the 16/20 mesh size proppant and the equivalent glass beads, tests according to the same standardized procedure were conducted next.

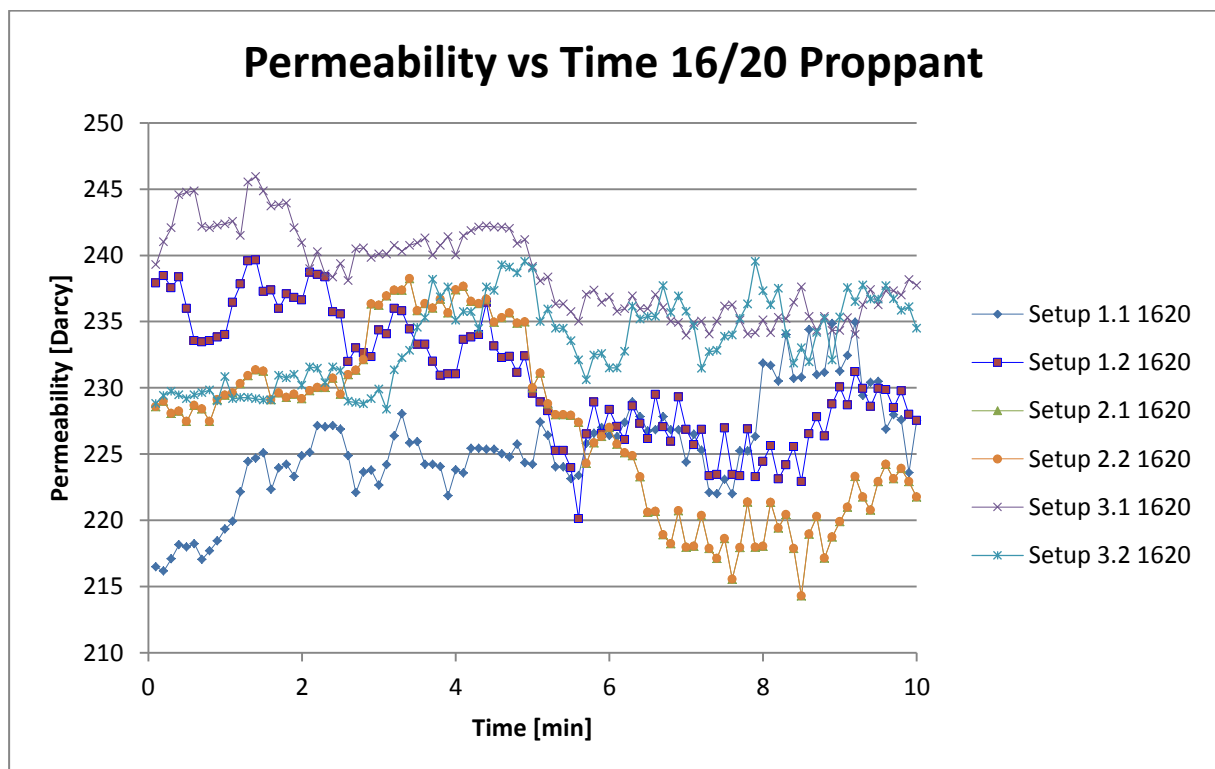


Figure 49: Permeability vs Time 16/20 Proppant

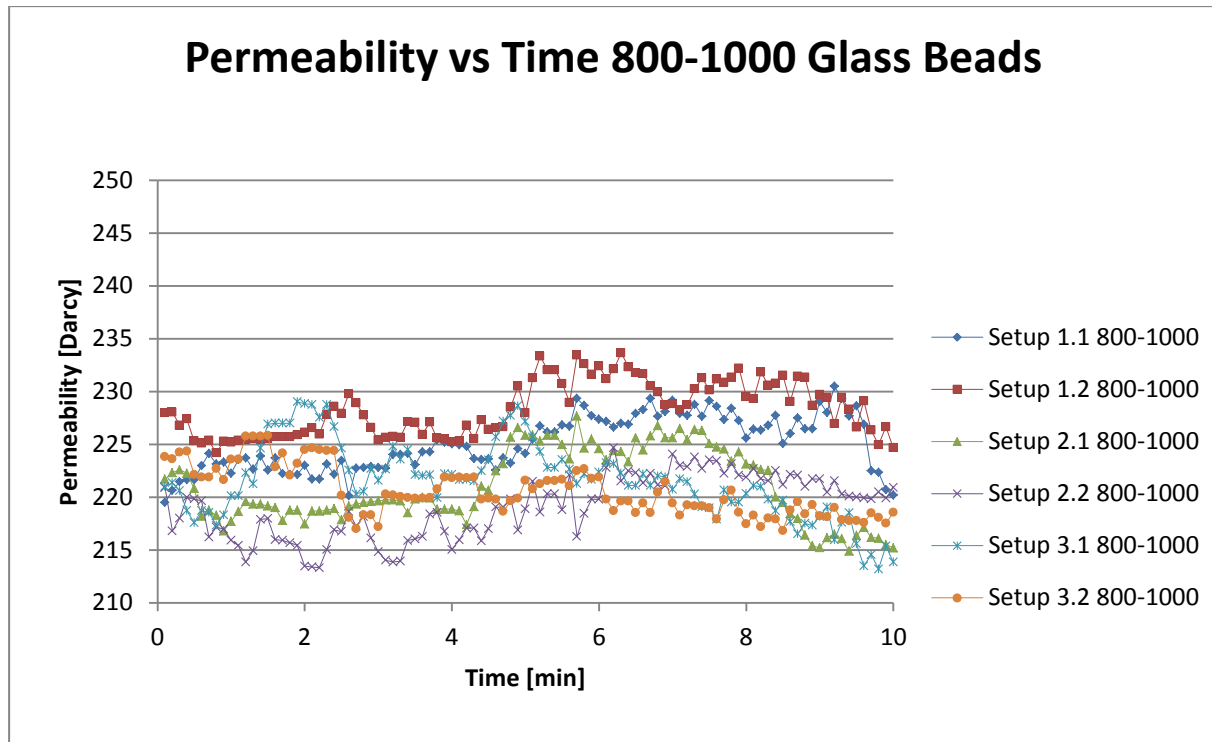


Figure 50: Permeability vs. Time 800-1000 Glass Beads

Material	Average Permeability [Darcy]	Standard Deviation [Darcy]
16/20 Proppant	230,45	6,69
800-1000 Glass Beads	222,59	4,31

Table 6: Tested Baseline Permeabilities 2

Like before, the tests conducted showed that the type of glass beads selected as an alternative filter medium had a similar permeability compared to the proppant used (Table 6). The higher difference in median grain size diameter than before between the glass beads and the proppant of approximately 130 μm did not result in a significant permeability difference (Figure 49 and Figure 50). This can also be explained by the even better roundness of the 800-1000 μm glass beads that were produced in improved Megalux quality.

7.2 Fines Invasion Tests

To get a reference value for permeability decrease in the filter medium, fines invasion tests were first conducted without any chemical treatment with different filter media according to the test procedure described before. Five tests with each filter medium were done with every filling being tested once.

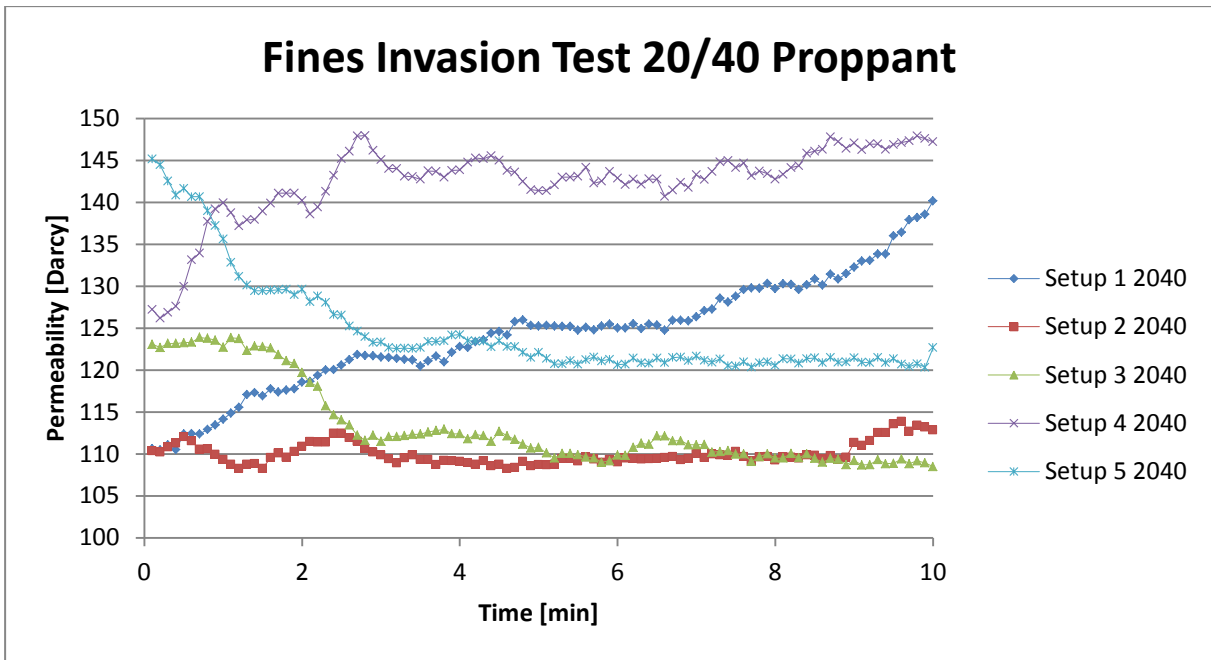


Figure 51: Fines Invasion Test 20/40 Proppant

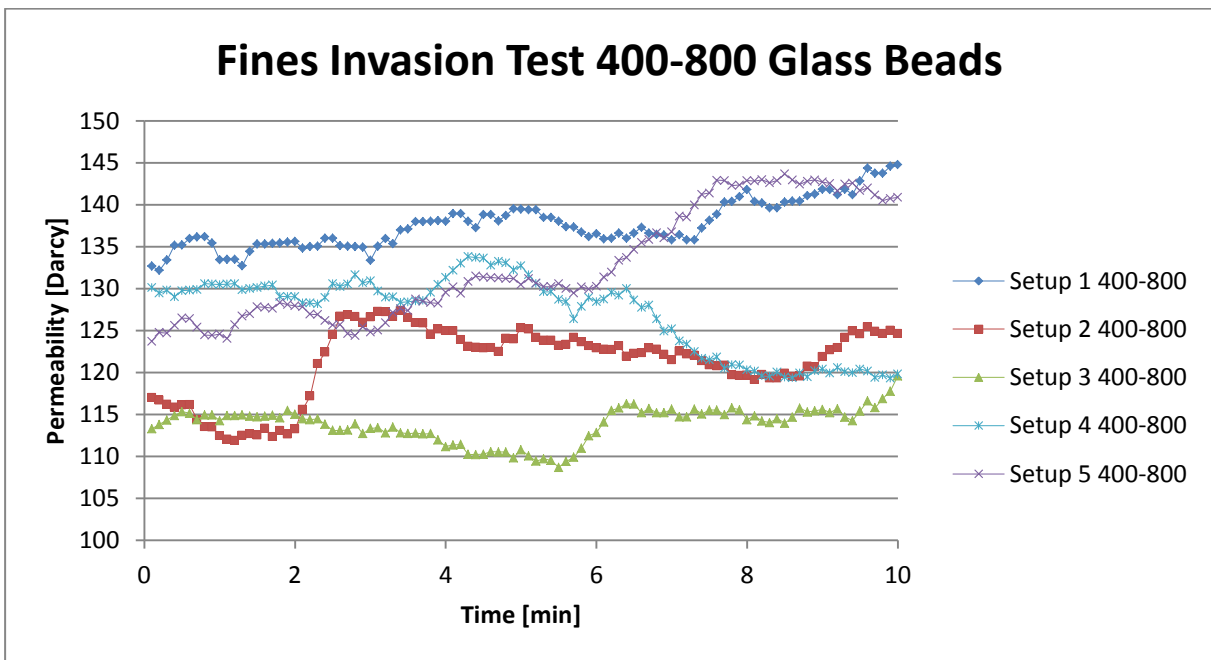


Figure 52: Fines Invasion Test 400-800 Glass Beads

Material	Average Permeability [Darcy]	Standard Deviation [Darcy]	Permeability Loss [%]
20/40 Proppant	122,96	12,46	18,04
400-800 Glass Beads	126,49	9,47	15,37

Table 7: Permeability Data Fines Invasion Tests 1

First, tests with the smaller filter medium grain size were conducted. The fines content in the efflux was constantly below 0.1g but as shown in the figures above (Figure 51 and Figure 52), permeability reductions as compared to the baseline tests could be measured. As expected, the glass beads showed slightly better fines retention capabilities than the proppant material.

Still, this setup with a resulting permeability reduction of less than 20% (Table 7) due to only small amounts of fines invading into the medium was found to be not suitable in the next step of chemical testing.

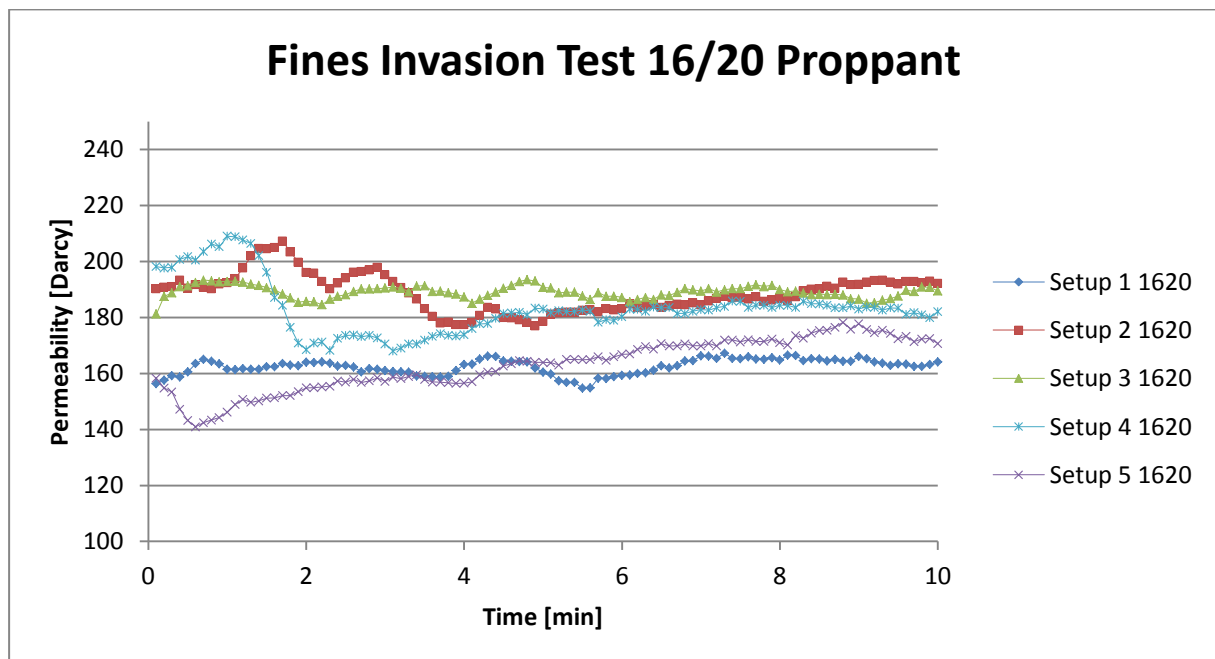


Figure 53: Fines Invasion Test 16/20 Proppant

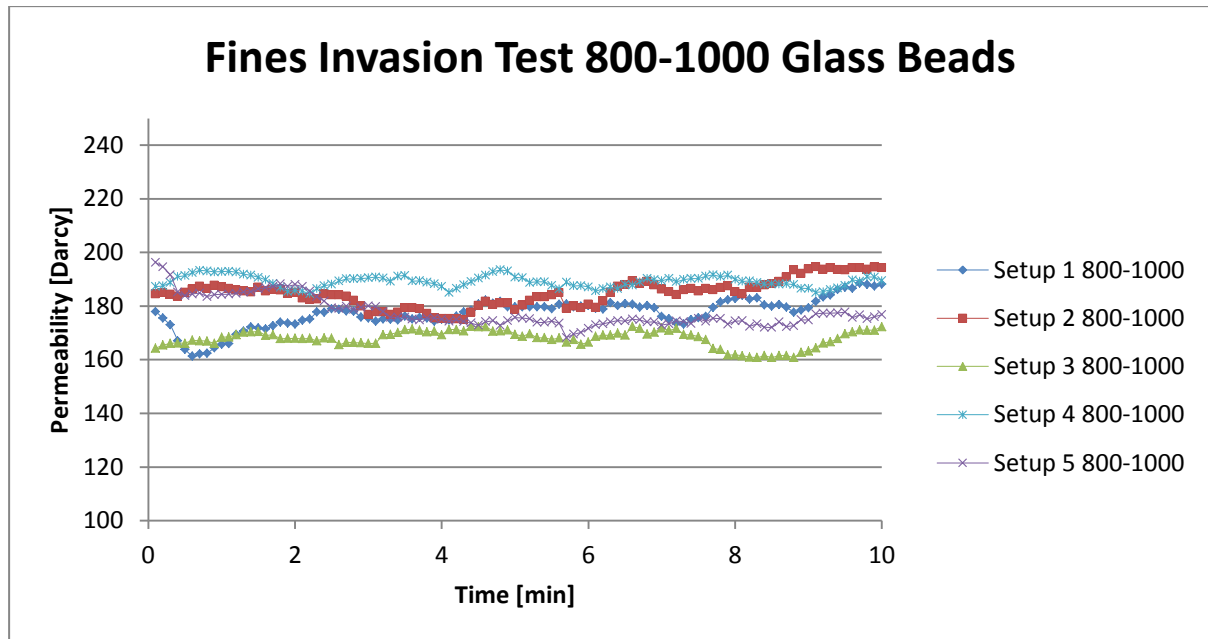


Figure 54: Fines Invasion Test 800-1000 Glass Beads

Material	Average Permeability [Darcy]	Standard Deviation [Darcy]	Permeability Loss [%]
16/20 Proppant	176,07	13,75	23,06
800-1000 Glass Beads	179,38	8,55	19,41

Table 8: Permeability Data Fines Invasion Tests 2

The fines invasion tests for bigger grain size diameters showed similar results as before on the first view (Figure 53 and Figure 54). Permeability loss during fines invasion was at around 20% with the glass beads showing slightly lower losses (Table 8). Other than with the smaller grain sizes diameters, massive amounts of fines were observed and measured in the efflux, which was considered as an explanation for the observed low permeability losses. Due to bigger pore size diameters, fines tended to migrate through the filter medium into the efflux without plugging up the pore space significantly and therefore reduce the permeability measurements only slightly. This made these setups unsuitable for further permeability tests with chemical consolidation methods as well.

So, it was decided to further investigate chemical methods with another fines invasion test as a setup. The lower half of the flow tube containing the filter medium was split up into halves again. While the upper part consisted of 16/20 mesh size proppant allowing fines to invade the simulated gravel pack, the lower half consisted of 20/40 mesh size filter medium and was expected to stop a great percentage of migrating particle volume and cause plugging of the 16/20 pore space this way. It was aimed to maximize permeability loss in order to get reference curves for later chemical treatment tests.

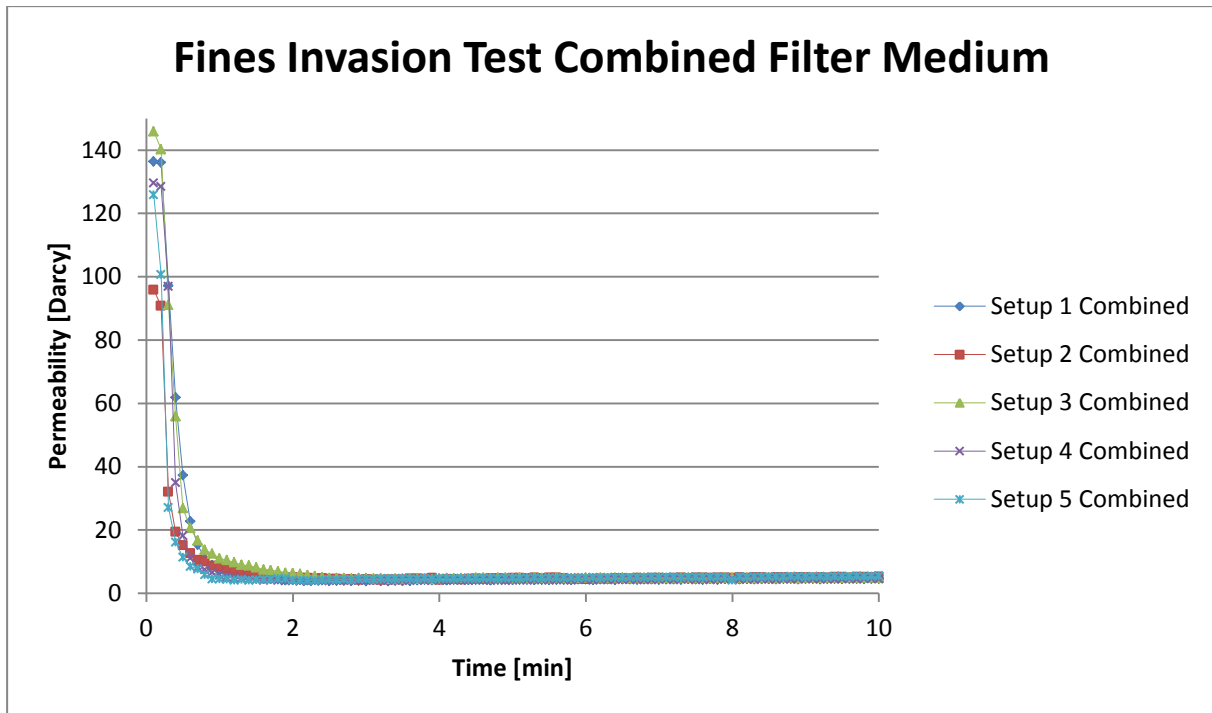


Figure 55: Fines Invasion Test Combined Proppant Filter Medium

As expected, fines migration indeed led to plugging of the pore space for this setup in all 5 tests conducted (Figure 55). The increase in pressure difference occurred very fast over the first 30 seconds leaving only a small rest permeability of approximately 5 Darcy that remained constant after about 1 minute after the start of the test. Fines were stopped at the borderline to the 20/40 mesh size proppant resulting in constantly less than 0.1g of fines measured in the efflux.

Since the loss of permeability was at over 90% and the effects of fines migration without chemical treatment could be observed visually as well (Figure 56), it was decided to use this setup as a reference for the following efficiency tests of chemical treatment methods.

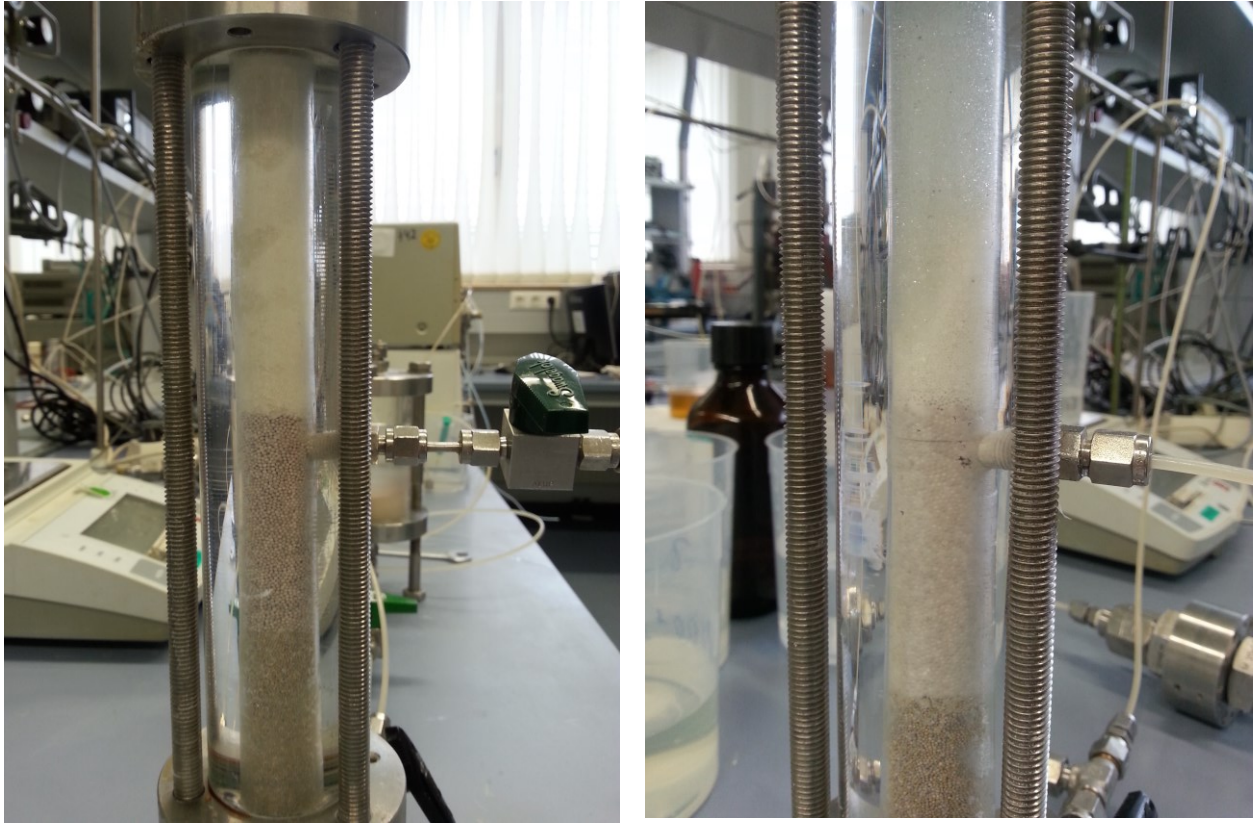


Figure 56: Combined Proppant Medium Gravel Pack before and after Fines Invasion Test

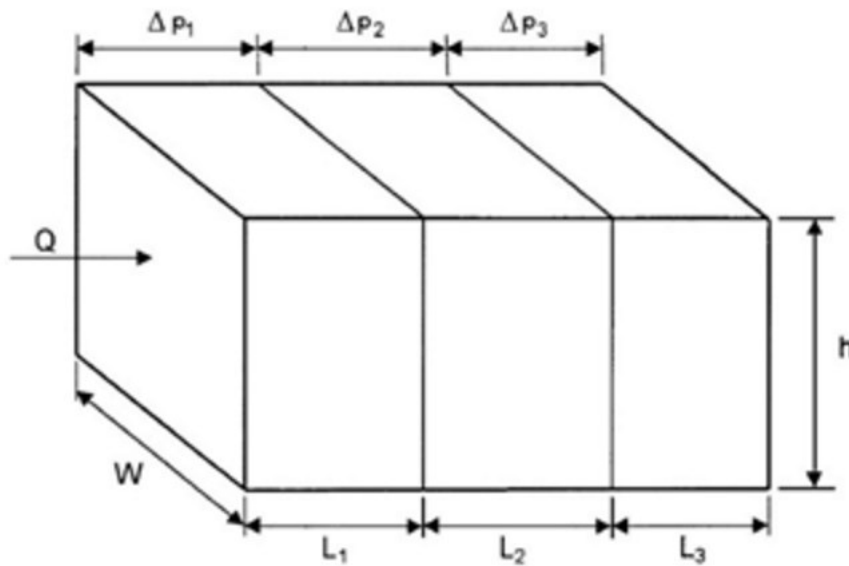


Figure 57: Harmonic Average Permeability [35]

In this case, the total pressure drop is the sum of all the pressure drops of all materials (Figure 57). Substitution for Δp in the Darcy equation results in a simplified formula for the harmonic average permeability [35]

$$\Delta P_t = \Delta P_1 + \Delta P_2 + \dots + \Delta P_n \quad (11)$$

$$\frac{q*\mu*L}{A*k_{avg}} = \frac{q*\mu*L_1}{A*k_1} + \frac{q*\mu*L_2}{A*k_2} + \dots + \frac{q*\mu*L_n}{A*k_n} \quad (12)$$

$$k_{avg} = \frac{L_1+L_2+\dots+L_n}{(L_1/k_1)+(L_2/k_2)+\dots+(L_n/k_n)} = \frac{\sum_1^n L_i}{\sum_1^n L_i/k_i} \quad (13)$$

where ΔP_t is the total pressure drop [Pa], ΔP_n is the pressure drop along material n [Pa], L is the total length [m], L_n is the length of Material n [m], k_{avg} is the harmonic average permeability [Darcy] and k_n is the permeability of material n [Darcy].

By this formula, the baseline permeability for the ceramic proppant mix was calculated (Table 9), which was thereafter used as a reference value to calculate the percentage of permeability lost when fines invasion occurs after the application of chemical treatment methods. In case of successful application with the ceramic proppant as a filter medium, the chemical treatment should be tested with the glass beads as a filter medium as well.

Material	Baseline Permeability [Darcy]
16/20 Proppant	150,02
20/40 Proppant	230,45
Combined Proppant	181,73
400-800 Glass Beads	149,47
800-1000 Glass Beads	222,59
Combined Glass Beads	178,84

Table 9: Baseline Permeabilities of Filter Media and Combined Filter Media

7.3 Chemical Treatment Tests

7.3.1 Proppant Coating Resin

The first chemical treatment test was conducted with a proppant-coating multi-purpose resin commonly used in fracturing operations. This chemical is commonly used for improvement of fracturing results, the elimination of incompatibility effects as well as several others like

- Reduction of fines migration
- Protection against proppant diagenesis
- Enhancement of fracture conductivity
- Enhancement of frac-fluid clean-up
- Improvement of permeability of the proppant pack

For the intended application, especially the reduction of fines migration by repelling them at the border to the filter medium and the improvement of permeability due to the increased porosity of the proppant pack was of interest. Like for the fines invasion tests, the flow tube was filled up five times with every filling being tested only once.

Resins of this type often require direct physical contact with the proppant for efficient covering, which can be a problem in field operations since they are usually mixed into the blender mixing tub concomitantly with frac gel or fluid additives. The combination of several chemicals mixed at once can lead to poor proppant covering efficiency and reduce the beneficial effect of the treatment. The product tested is therefore optimized for pre-mixing with the proppant in a dry blender where the problems described before like imperfect proppant covering can be avoided since there is only one chemical present. This procedure has already proven to be effective in field operations where the resin is used in a quantity of 0.15-0.41 gal/100 lbs, depending on the proppant mesh size as well as the fines content. For the given test conditions, it was decided to go with a dosage of 0.3 gal/100 lbs (Table 10).

Sand Size / Mesh	Dosage (gal/100 lbm)
20/40	0.15 – 0.27
16/30	0.18 – 0.30
12/20	0.21 – 0.33
In presence of fines	Increase 0.03 – 0.08 gal/100 lb

Table 10: Proppant Coating Resin Dosage

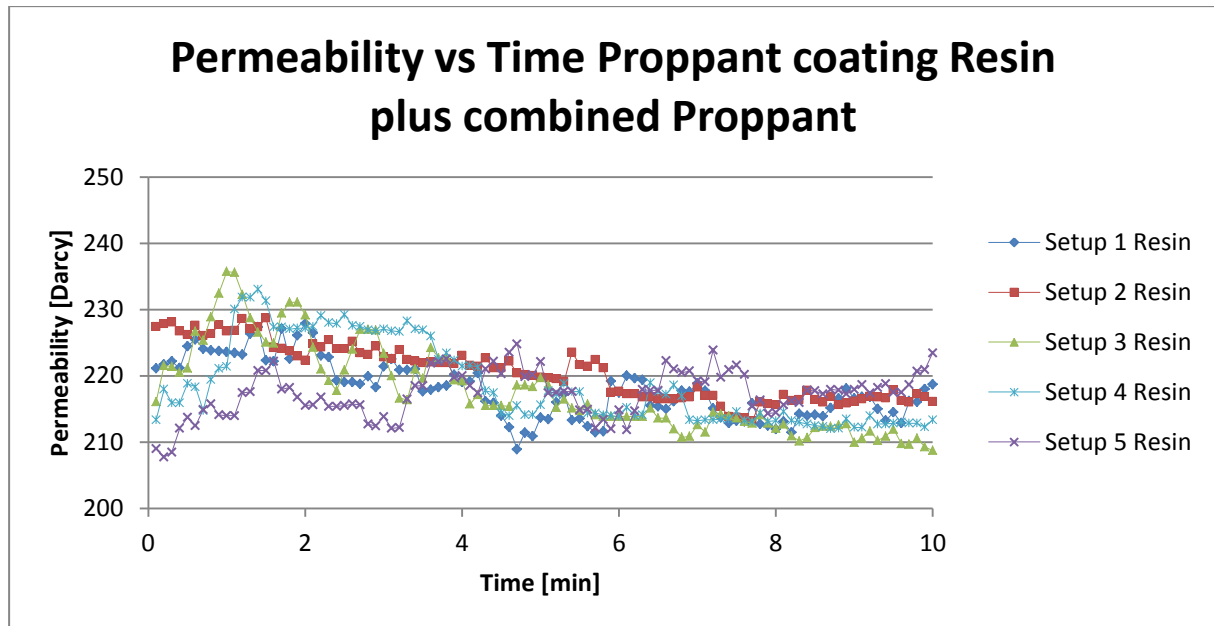


Figure 58: Permeability vs Time Proppant coating Resin plus combined Proppant

As you can see in Figure 58 permeability was enhanced in all five tests with the combined proppant as a filter medium at the bottom. Fines invasion into the filter medium could neither be observed visually nor in the efflux water being filtrated. Fines movement within the artificial formation on the other hand could be observed very well: As expected, the fines showed a tendency to migrate through the coarse part of the formation, being stopped and accumulating at the boarder to the filter medium material but not invading it.

Permeability of the filter medium was indeed increased due to stickiness of the proppant, which resulted in non-perfect packing, increasing permeability as well as pore throat size.

Material	Expected Permeability [Darcy]	Measured Permeability [Darcy]	Fines Efflux [g]
Combined Proppant	181,73	218,49	<0,1

Table 11: Permeability after Fines Invasion Test with Resin plus combined Proppant

Since the results of the first tests with the manmade ceramic proppant as a filter medium seemed to be very promising (Table 11 and Figure 58), it was decided to conduct the same tests with mixture of smaller 400-800 μm glass beads at the bottom and larger 800-1000 μm glass beads at the top as well.

First visual tests showed, that the resin could also be dry mixed with glass beads covering the surfaces. Using the same dosage of resin, the glass beads turned out to be stickier too and had to be stuffed into the flow tube five times with every filling being tested once. Note that for the tests, only uncoated glass beads were used. Hydrophobically coated glass beads

were available but since they showed no difference to uncovered glass beads after being dry mixed with the resin it was decided to use the non-coated material.

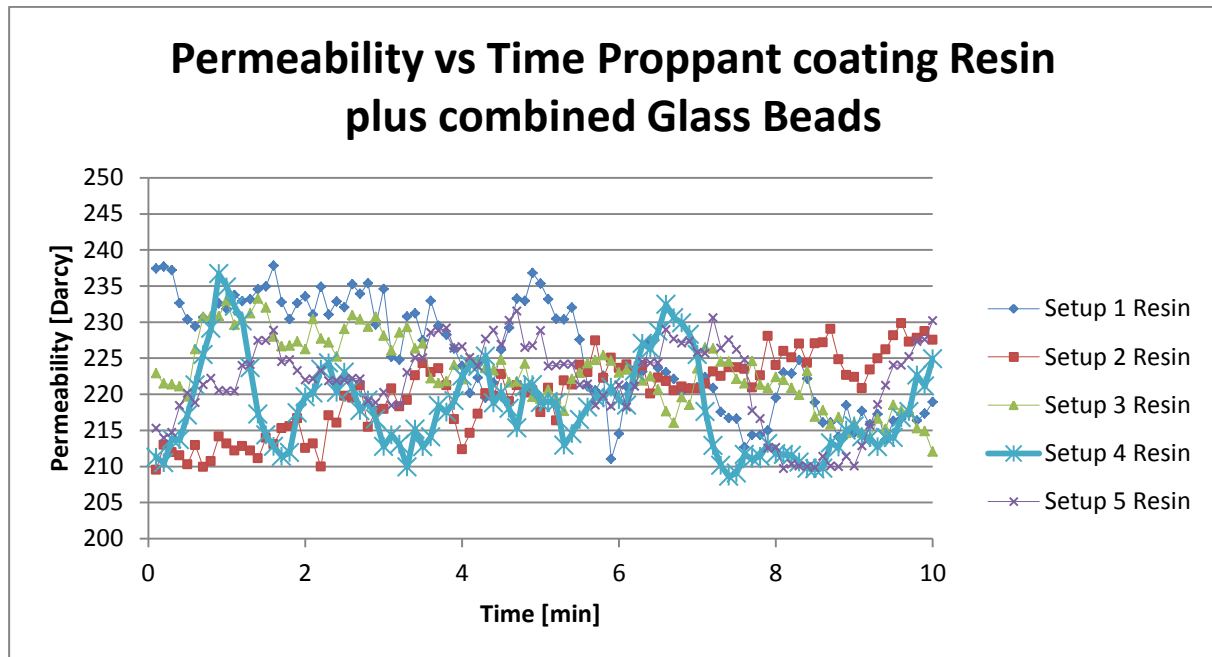


Figure 59: Permeability vs Time Proppant coating Resin plus combined Glass Beads

The effects observed at the glass beads tests were very similar to the ones with manmade ceramic proppant (Figure 59). Permeability was increased due to stickiness and increased porosity, while fines were kept from invading into the filter medium section. Again, no fines invasion could be observed either in the filter medium part of the flow tube nor in the filtered efflux.

Material	Original Permeability [Darcy]	Measured Permeability [Darcy]	Fines Efflux [g]
Combined Glass Beads	178,84	221,80	<0,1

Table 12: Permeability after Fines Invasion Test with Resin plus combined Glass Beads

Positive effects on consolidation could also be observed with the resin being brought in contact with the artificial formation that started to stabilize. Still, it can be assumed that much of the original permeability and porosity was lost in the process since the chemical was not designed to serve this specific purpose. A similar chemical from the same manufacturer can be used instead but is currently not available within the European Union due to new labeling requirements. Moreover the chemical seems to be unsuitable to be pumped into the formation because high viscosities of 555 cp could be measured with a fan-viscosimeter at a shear rate of $7s^{-1}$.

In terms of practical application, it shall be noted that this chemical is very easy to be mixed in a dry blender since it is delivered as a ready to use solution that has to be mixed in a dry blender in small doses. The proppant covering was very efficient and post-application cleaning could be achieved residual-free by the use of isopropanol.

7.3.2 Water-based Proppant Coating

Another proppant coating to reduce fines migration with different working mechanisms was tested as well. Other than before, the product was water-based including nano particles supposed to keep fines from entering into the filter medium by electrostatic repulsion and the use of weak non-covalent molecule interaction forces, the so-called Van-der-Waals forces. This product is commonly used in fracturing operations covering proppants and keeping fines from migrating to the near-wellbore region but also to cover gravel pack sand to stabilize formation fines. The product can either be pre-mixed in a dry blender separately or combined with other additives and chemicals. For the tests it was decided to carefully pre-mix the proppants with the chemical at a ratio of 1gal chemical/ 1000 lb proppant. The mixed product was then filled into the flow tube and stuffed into it since stickiness was increased which again led to imperfect proppant packing with increased porosity. During the pre-flush saturation, it could be observed that the chemical was partially washed off the proppant by the 3% KCl water but a sticky film remained on the proppant covering it. Like before, five tests were conducted with five different proppant fillings.

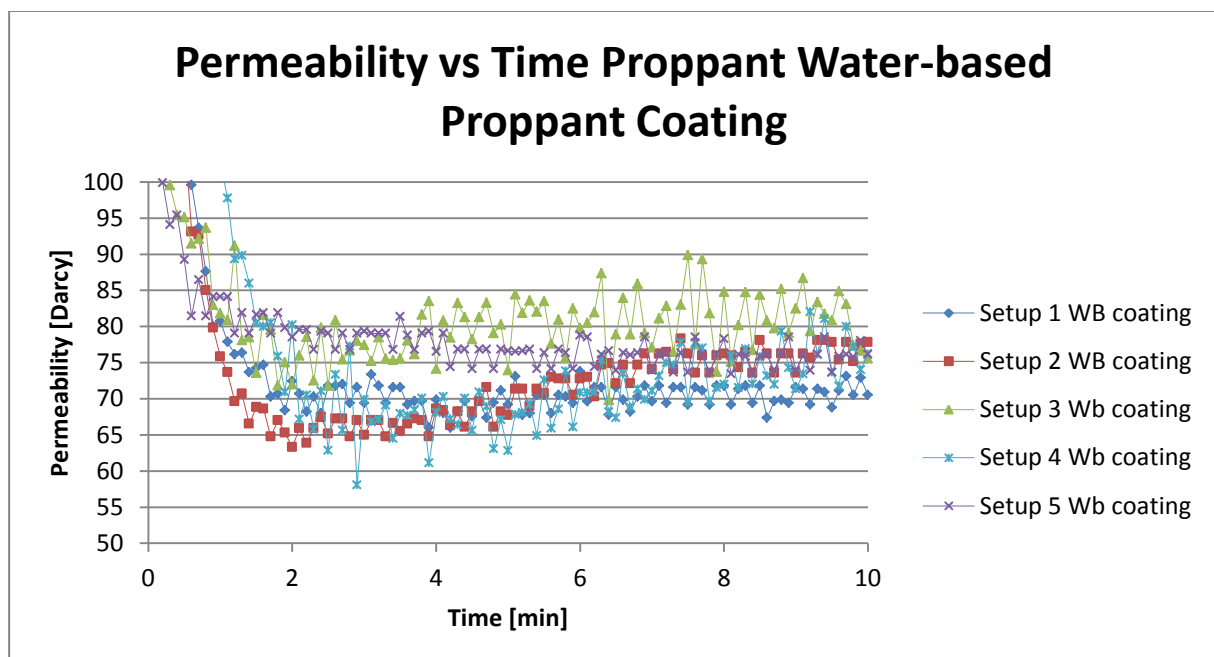


Figure 60: Permeability vs Time Proppant Coating Water based plus combined Proppant

The results obtained showed, that fines invasion could not be stopped by the application of the water based proppant cover (Figure 60). Imperfect packing and the associated increase in porosity resulted in fines invading the proppant pack that not only reduced the permeability of the filter medium but also led to massive amounts of fines observable in the efflux.

Although the chemical was delivered as a pre-mixed solution, easily applicable and water-soluble without residues it was found to be not suitable for the practical field application since the main goal of stopping the fines invasion could not be reached. It can be assumed that the electrostatic and Van-der-Waals forces are not strong enough to keep greater amounts of fines away from the filter medium in case the region is subjected to strong forces by fluid flow. Due to the negative test results with ceramic proppant, no further tests with glass beads were conducted with this type of proppant covering chemical.

7.3.3 Formation Resin

Another approach on the mitigation of fines migration into the gravel pack was taken by another resin to be tested. While all chemicals up to this point had focused on simply keeping the fines out of the gravel pack but not stopping them from migrating inside of the formation, this (acrylic) resin should consolidate the fines in-situ.

To do so, the combined proppant was filled into the flow tube with the artificial formation on top and as usual saturated with 3% KCl water. To then prepare the formation for the resin treatment, a mixture of 2-phenoxyethanol and isopropanol was injected in the extent of two pore volumes. The main flush was then conducted with a liquid mixture consisting of several types of acrylates and alcohols in order to glue the grains together and to stabilize the artificial formation. To ensure full saturation of the entire artificial formation, fluorescein tracer was first used as well as the already mentioned displaced containers, which was of critical importance. An activator was mixed into the main flush liquid to ensure consolidation. After the main-flush, a post-flush of 3 pore volumes of isopropanol was conducted to leave only small amounts of the chemical inside of the formation, claimed to be sufficient for consolidation purposes. All other parts of the setup were cleaned out with isopropanol as well to avoid possible plugging of critical parts.

Thereafter the flow tube was shut in completely and placed into a heat chamber (Figure 61) at a temperature for 85 °C for 20 hours. Consolidation was supposed to start after one hour of retardation.



Figure 61: Heat Chamber

After consolidation the flow tube was supposed to be flushed with 3% KCl water from the bottom to the top again before the beginning of the fines invasion tests. Initially, 5 tests were planned to be conducted with this chemical.

This was not possible due to problematic consolidation behavior that could be observed in the first test. The chemical indeed consolidated very well but completely destroyed all permeability within the artificial formation whereas in the filter medium a small rest of permeability could be seen. Water saturation was only possible up to the proppant/artificial formation boundary where the increasing pressure build-up due to the destroyed permeability quickly triggered the overpressure valves of the pumps.

Therefore fines invasion tests could not be conducted. Moreover the acrylate based chemical could not be removed from the flow tube non-destructively neither by chemical nor by mechanical means (Figure 62).



Figure 62: Flow Tube with insoluble Content after Consolidation

Different results obtained by the manufacturer's laboratory claiming to prove residual permeabilities of 50% on the same materials can be explained by slight differences in the test setup. Shrinking films used on the sidewalls of the flow tube to remove the consolidated column and put it back again probably lead to the creation of small interstices, allowing fluid to flow between the impermeable consolidated column and the flow tube sidewall.

Due to the complete destruction of the flow tube as well as the artificial formation's permeability and the significant workovers required, it was decided not to go for any further tests with this specific chemical.

Moreover the practical application of the resin with its insoluble nature would be very risky since parts of the equipment used could easily be destroyed if not cleaned very properly.

7.3.4 Artificial Scaling Treatment

A similar approach of consolidating the fines in-situ was taken by a mixture of several chemicals. In this case the fines should be stabilized by the induction of artificial scaling in the formation. Other than all chemicals tested before, this chemical treatment was not provided as a ready-to-use mixture but had to be prepared carefully directly before the application into a glass beaker with a magnetic stir rotating in it. The steps required had to be kept in the same order and all chemicals had to be mixed in quickly as soon as the chemical from the step before had dissolved completely.

The prepared 100 ml solution was then ready for use and had to be applied as soon as possible since the chemistry of the mixture only allowed air contact for 2 hours before it lost its effectiveness for consolidation. A saturation pre-flush with 3% KCl was applied as usual

before the main flush of 3 pore volumes of chemical had to be injected. Thereafter the flow tube was shut in and exposed to a temperature of 65 °C for 48 hours.

After 48 hours a post-flush of 3 pore volumes was applied with 3% KCl water from bottom to top before fines invasion testing from top to bottom started. The planned test series only consisted of 3 tests since the preparation of the mixture as well as the consolidation were very time-intensive.

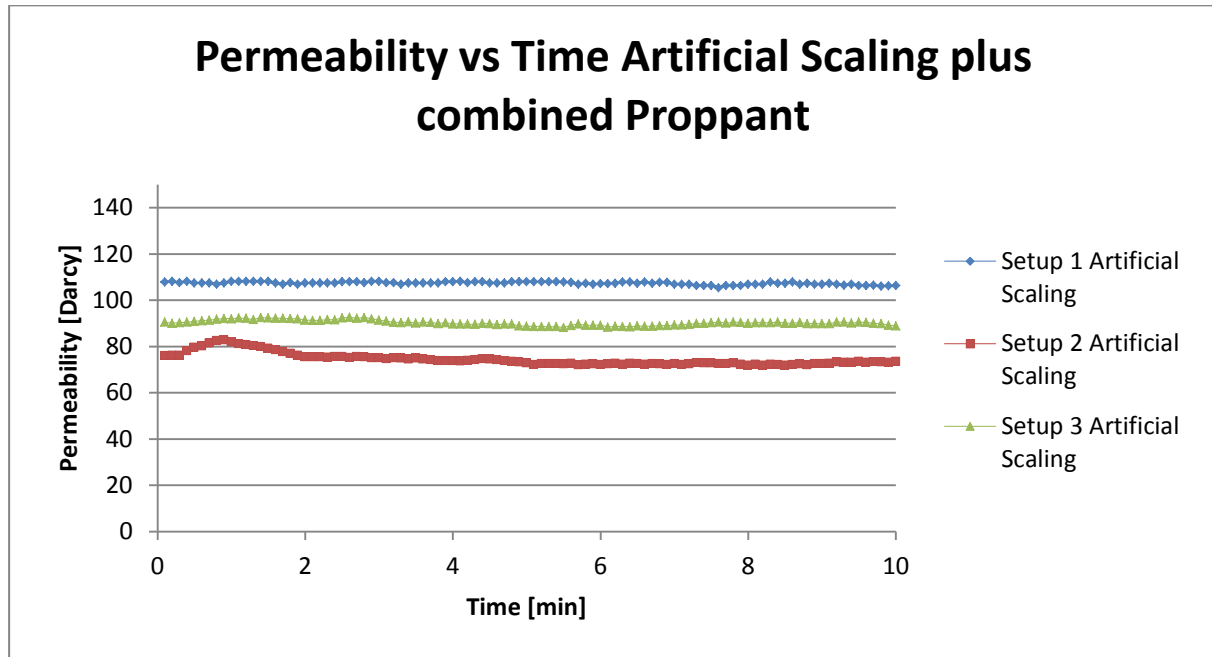


Figure 63: Permeability vs Time Artificial Scaling Treatment plus combined Proppant

The results obtained all showed the same picture: Permeability was reduced initially by artificial scaling (Figure 63) but fines movement even within the artificial formation could be stopped entirely. Accumulations of fines at the filter medium/artificial formation boundary could not be observed like in the case of proppant coatings, which lead to the conclusion that the formation had actually stabilized. Neither could fines be measured in the efflux. The reduction of permeability was in the range of 50% (Table 13) proving the chemical to be suitable for field application

Material	Original Permeability [Darcy]	Measured Permeability [Darcy]	Fines Efflux [g]
Combined Proppant	181,73	90,71	<0,1

Table 13: Permeability after Fines Invasion Test with Artificial Scaling plus combined Proppant

In terms of practical application the chemical has to be seen more critical: The mixture had to be dosed very exactly and could only be subjected to air for a short period of time. Moreover

the consolidation effect based on artificial carbonate scaling might lead to problems over the lifetime of a well since HCl acid jobs cannot be conducted without removing the consolidation effect.

7.3.5 Polymer Treatment

An environmentally-friendly non-hazardous alternative to other consolidation types could be found in the application of polymers to invade unconsolidated formations. The polymers used for this purpose were supposed to stabilize the pore walls by forming a film around them to prevent erosion even in regions with strong flow forces acting like the near-wellbore region (Figure 64). Although no consolidated rock matrix was available in the artificial formation, the manufacturer claimed that consolidation effects should still be observable.

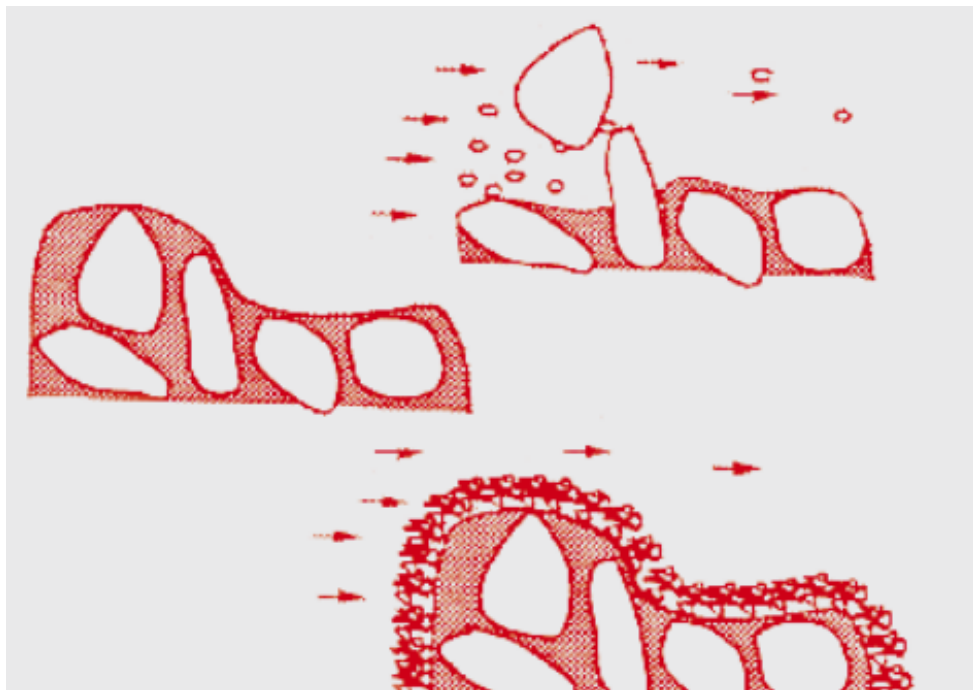


Figure 64: Polymer Stabilization Working Mechanism

Different types of polymer grains were available for application, all with the same working principles but with different maximum allowable application temperatures. Since they were all claimed to be working at room temperature as well, it was decided to test the polymer with a high maximum temperature rating, since it would be applicable in most types of reservoirs in Austria.

To do so, the polymers flakes were first carefully mixed into a beaker in which a mixer was rotating at a rate of 400 rpm to creating a 0.5% solution after a hydration time of 2 hours. This solution was then diluted further to the highest applicable concentration of 0.03 % before being injected into the flow tube in an amount of 3 pore volumes. Consolidation time after the main flush was not required and so a post flush of 3 pore volumes was conducted thereafter. Five tests on different samples were conducted.

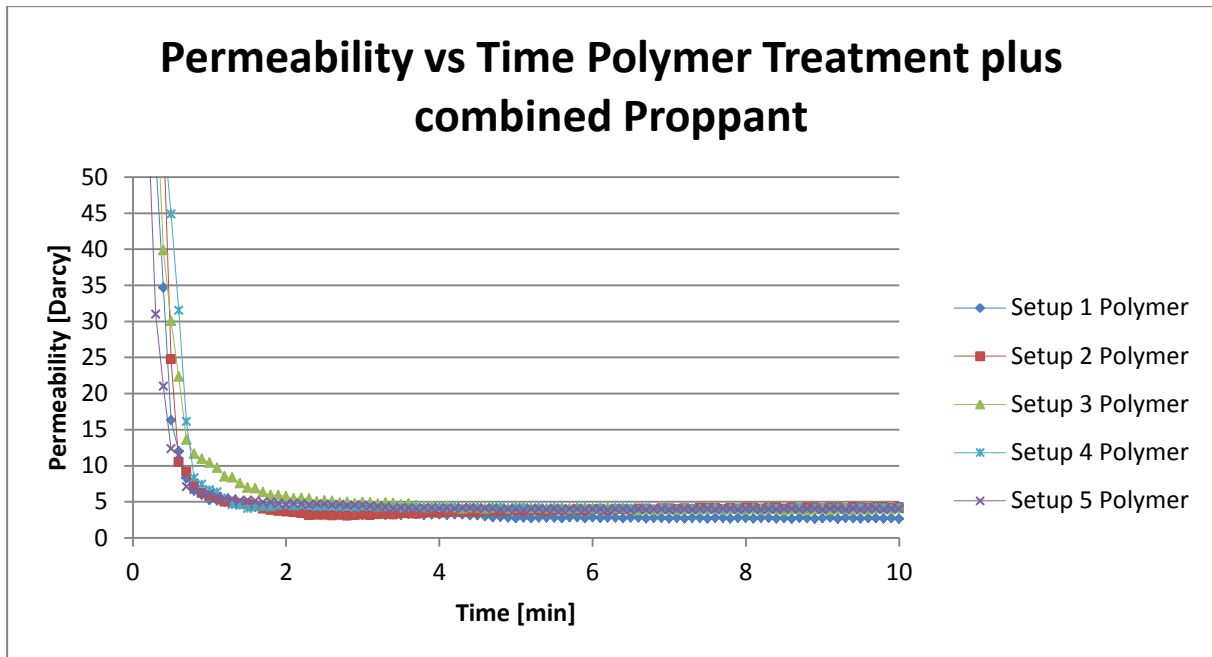


Figure 65: Permeability vs Time Polymer Treatment plus combined Proppant

All five tests conducted showed the same picture of the treatment being completely ineffective (Figure 65). Like in the original untreated fines invasion tests, there were no fines observed in the efflux but permeability was reduced quickly and significantly to a very small residual level. Significant fines movement was also be observed visually within the formation.

The results are indicating that this treatment method is very likely unsuitable for application in poorly consolidated formation since a base rock matrix that can be stabilized is required.

In terms of practical application it shall be noted that the product is easily disposable and leaves no residues if cleaned with water but has to be mixed carefully. Polymer grains falling out of the mixer vortex can settle on the ground and will not be dissolved in the water.

8 Discussion

In order to provide adequate sand and fines retention for poorly consolidated sandstone formations, different mechanical and chemical retention methods were tested for their actual retention capabilities. An adequate flow tube setup including actual gravel pack media delivered constant, reproducible baseline values for permeability. The recreated artificial formation, based on real formation data, constantly showed massive fines migration tendencies when left untreated. This fines migration significantly reduced the filter medium's permeability by more than 95%, revealing the impact of these tendencies on impairment of sand control installations, thereby providing comparables that could later on be used to evaluate mechanical and chemical methods' efficiency. The principles of the evaluation comprised of the most important aims for sand control (lowering sand and fines production and avoiding sand control unit damage), therefore providing meaningful results for the actual method efficiency.

The results obtained while testing improved mechanical sand control methods were (like the baseline and fines invasion tests) constant and could be explained by the underlying mechanical concepts as well as verified by visual inspection. The glass beads were tested intensively and continuously delivered credible results that were similar or slightly improved compared to the ones of commonly used manmade ceramic proppant. 20/40 mesh size ceramic proppant and the corresponding 400-800 μm glass beads both showed average permeabilities of approximately 150 Darcy when not subjected to fines invasion in the baseline tests. During fines invasion tests, glass beads' permeability was reduced slightly less (15.37% avg. compared to 18.04% avg.) compared to ceramic proppant's permeability. The results for fines invasion into coarser 16/20 mesh size proppant material and the corresponding 800-1000 μm glass beads were similar, with the glass bead's permeability being reduced less (19.41% avg. compared to 23.06% for ceramic proppant).

As for the chemical methods, only a few samples of the vast variety of chemical consolidation methods could be tested. Still, since the chemical methods tested were based on several different consolidation mechanisms they may be regarded as representative for many chemical treatment options that are currently being applied in poorly consolidated formations worldwide. The results obtained by chemical testing were (like the results of the mechanical methods) constant and credible and could moreover be confirmed by visual inspection. Furthermore, frequent conferences, discussions and meetings with the project partners providing the chemicals ensured appropriate application and correct test setup for all chemicals giving the results further credibility. The proppant coating resin showed the best effects during fines invasion tests, not only stopping particles but also increasing the permeability of the gravel pack material an average of 20.22% when used in combination with proppant and by an average of 24.02% when used in combination with glass beads as filter material. The resin applicable for in-situ consolidation of the formation on the other hand resulted in the complete loss of filter medium permeability. Polymer consolidation treatment did not result in significant improvements in terms of fines invasion behavior compared to an

untreated system. Water based proppant coating showed only slight permeability reduction within the filter material during fines invasion, yet allowed the fines to migrate through the simulated gravel pack. Artificial scaling was capable of stabilizing the formation, resulting in a loss of filter medium permeability of 50.09%.

Altogether it can be stated that the setup of the tests, the measurement and evaluation methods and the application of the methods was done in a scientifically correct manner giving meaningful results for the further practical evaluation of these methods in actual reservoirs.

9 Conclusion and Recommendations

The testing of new glass beads filter materials for baseline permeabilities without fines migrating into the material, clearly showed that these are capable of delivering equal or even slightly higher permeabilities at lower median grain size diameters compared to manmade ceramic proppant. Fines invasion behavior was slightly improved compared to the conventional manmade ceramic proppant, making it a very suitable alternative, also considering that they come at significantly lower costs. The improved scaling behavior of the glass beads represents a further major advantage. Furthermore, compatibility of these glass beads with resin coating in gravel pack could be proven.

The chemical methods tested were partially successful as well. Especially the proppant coating resin that was dry mixed with the manmade ceramic proppant or glass bead material proved to be capable of retaining fines very well, while at the same time even further increasing permeability. The water-based proppant coating material tested on the other hand cannot be regarded as an efficient sand and fines retention tool since the resulting improper packing will lead to migration of sand and fines particles into the wellbore. Polymers proved to be inefficient for near wellbore zones with high pressure drops as well, especially in extremely unconsolidated formations with no cementation to adhere to. Artificial scaling on the other hand proved to be very effective although reducing the formation's and the gravel pack's permeability. Another disadvantage of this method is the limitation occurring after this consolidation method has been applied. Commonly applied HCl acid treatment will no longer be possible after the use of this treatment without resolving the precipitated calcium carbonate.

Concluding from these test results, it is recommendable to take the next step in the chemical treatment evaluation and test the application of the proppant coating resin system or the in-situ carbonate cement precipitation under real-field conditions. The other chemicals are at the current development status not recommended for field testing or larger scale use since they have either proven to be ineffective or showed severe operational restraints when being applied.

As for the innovative new filter material, the glass beads, testing in actual, poorly consolidated reservoirs is highly recommended. The positive results in terms of baseline permeability and sand and fines retention capability as well as the better economics compared to the manmade ceramic proppant make them a viable alternative. Considering their compatibility with the proppant coating resin, a combined retention system with glass beads and proppant coating is recommendable.

10 Registers

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