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MASTER THESIS

Title: Investigating the efficacy of proppant in maintaining open cracks following hydraulic fracturing

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Abstract

Hydraulic fracturing is used as one of the most effective well stimulation methods, with long-lasting effect, in order to enhance the effective permeability of the low permeability reservoir rocks, and to increase the production rate.

In this thesis, the key aspects of the hydraulic fracturing, such as their mechanics, geometry and design are reviewed. Predominantly, the key challenges and motivation behind the process are mentioned, and the principal objectives of the following experiments have been identified. The theoretical background on the hydraulic fracturing, proppant, it's influence on maintaining of hydraulic fractures, the mechanics of hydraulic fracturing, related industry challenges, several types of stimulations and innovations are talked over in one of the chapters. Experimental work, which illustrates the behavior of the shale formations during the proppant placement is performed in laboratory.

Two experiments are carried out: with cube-shaped sample and two cylindrical stack-on samples. The experiment consists of testing the propping agent under the load in uniaxial test machine in different conditions: filling the V-shaped crack of the cube in the cube experiment and testing a thin layer of proppant between two concrete cylindrical samples. The samples for these experiments are previously cast in the cement lab.

Test results are obtained and converted into the spreadsheet form at the end of the experiments, and then presented in the graph form afterwards. Typical stress/strain plot can be observed on following graphs, and for specific types of proppant, some trend can be distinguished. Later the difference between the various types of propping agents are given as well. After the samples collapsed, the grains are

thoroughly inspected under the microscope. The possible sources of errors are further listed, main problems associated with the experimentation are scrupulously discussed and additional recommendations for future work are provided. The foremost outcome can be acknowledged, as with the increase of density of the propping agent, the strength of the rock can be upgraded, and hydraulic fracturing done with the higher density proppant can better withstand the overburden confining pressure.

Xülasə

Hidravlik çatlatma, aşağı keçiriciliyi olan süxurların effektiv keçiriciliyini, və istehsal həcmini artırma üsullarının, ən effektiv və uzunmuddədtli nəticəyə malik biri kimi istifadə olunmaqdadır.

Bu tezisdə, hidravlik çatlatma üsulunun əsas aspektləri, məsələn onların mexanikası, həndəsəsi, və konstruksiyası nəzərdən keçirilir. Xüsusən, prosesin əsas problemləri və motivasiyası qeyd olunur, və gələcəkdə keçirilə biləcək təcrübələrin əsas məqsədləri müəyyənləşdirilir və tövsiyyələr sadalanır. Hidravlik çatlaq və çivləyici agent (proppant), hidravlik çatlaq mexanikası, bununla əlaqədar sənaye problemləri, stimulyasiya və yeniliklərin müxtəlif növləri barədə bir sıra ədəbiyyat nəzərdən keçirilmişdir. Daxilinə proppantın yerləşdirilməsi zamanı şist formasiyasının davranışını təsvir edə biləcək eksperimental iş təsvir olunur.

İki eksperimental iş aparılır: kub formalı nümunələr və iki üst-üstə bağlanmış silindrik nümunələrlə. Təcrübə çivləyici agentinin müxtəlif vəziyyətlərdə vahid test maşınında yük altında sınaqdan keçirilməsindən ibarətdir: kubun V-formalı çatının kub sınağında doldurulması, və iki beton silindrik nümunə arasındakı nazik təbəqənin sınanması. Bu təcrübələr üçün nümunələr daha əvvəl sement laboratoriyasında hazırlanmışdır.

Eksperimentlərin sonunda, nəticələr elektron tablo şəklində əldə edilir və daha sonra qrafik şəklində təqdim olunurlar. Tipik stress/dartınma sahəsi aşağıda göstərilən qrafiklərdə müşahidə oluna bilər, və bəzi proppant növləri üçün bir sıra tendensiya nəzərə çarpa bilər. Daha sonra müxtəlif çivləyici maddələr arasındakı fərqlər belə nümayiş olunur. Nümunələr qırıldıqdan sonra, onların kiçik hissəcikləri mikroskop altında hərtərəfli nəzərdən keçirilir. Daha sonra, mümkün olan səhv mənbələri

sıralanır, eksperimental təcrübə ilə əlaqəli əsas problemlər hərtərəfli müzakirə edilir, və gələcək işlərə dair əlavə tövsiyələr təqdim olunur. Əsas nəticə belə ifadə edilə bilər ki, çivləyici agentin sıxlığının artması ilə, süxur möhkəmləndirilə bilər və yüksək sıxlıqlı proppantla aparılmış hidravlik çatlama, üst layların təzyiqinə daha yaxşı tab gətirə bilər.

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Nomenclature

Symbol	Description	Units
Pbd	Breakdown pressure	psi
σmax	Maximum horizontal pressure	psi
σmin	Minimum horizontal pressure	psi
$T0$	Tensile strength	psi
ww	Fracture width at the wellbore	inches
μ	Viscosity of the fluid	cp (centipoise)
R	Fracture radius	ft
qi	Pumping rate	bpm (barrels per minute)
E	Elasticity modulus	psi
hf	Fracture height	ft
xf	Half-length	ft
G	Shear modulus	psia
k	Formation permeability	mD
kf	Fracture permeability	mD
Cfd	Dimensionless fracture conductivity	Dimensionless

List of abbreviations

Abbreviation	Meaning
CBM	Coal bed methane
EOR	Enhanced oil recovery
KGD	Khristianovic-Geertsma-de Klerk
PKN	The Perkins-Kern-Nordgren
NPV	Net present value
RCS	Resin coated sand
SG	Specific gravity
ULW	Ultra-lightweight
CFD	Computational fluid dynamics

Introduction

Background (key elements)

There are several reservoir stimulation techniques used in industry in order to increase the hydrocarbon production. One of the widely-known is the hydraulic fracturing. Hydraulic fractures are the fluid-filled cracks that occur as a result of a fluid pressure acting along the crack's surface. The wings of the fracture extend away from the wellbore in opposite directions depending on the primary stresses within the formation. Proppant, such as sands of a particular size, are mixed and pumped together with treatment fluid into the fracture to keep it open after the job is complete. Hydraulic fracturing creates high-conductivity channel within a large area of formation and eliminates any damage that may exist in the near-wellbore area (Schlumberger Oilfield Glossary). As the cost of hydraulic fracturing operation is very high, it is really important to control the promulgation of fracture. Fracture should be contained within the target layers, by preventing them from growing into neighboring formation. Therefore, it is necessary to simulate the fracture propagation to provide an estimate of fracture geometry before the real operation starts. [16]

Other industrial applications include waste remediation process, waste disposal and preconditioning in rock mining. Hydraulic fractures also occur in nature in the process of magma ascent through the lithosphere owing to a buoyancy force or as fluid-filled cracks in glacier beds.

First it was carried out in the Hugoton field Kansas, US in 1947 [1]. Initially, it was done for research purposes and no specific gain in gas production was obtained. However, later due the dramatic growth in oil demand and improvement of the directional, particularly horizontal drilling have kick-started the commercial development of the hydraulic fracturing in the late 1980s and caused the energy revolution, also known as the shale revolution in the US in 2000s [1].

The key challenge of the hydraulic fracturing process is to perfectly fracture the rock deep underground. The shape, dimensions and propagation are of the high importance in the fracturing operations design. Obtaining the information about the formation and fracturing fluid properties, along with the direction and magnitude of the principal stresses may help one to accurately predict the dimensions of the induced fracture within the reservoir rock [2].

Enhancement of the oil and gas production is the key motivation of using the hydraulic fracturing technique for the last forty years. The simplified process can be described as pumping the slick water into the wellbore under the high pressure what creates the zone of fractures. Further, the slick water is pumped out of the fractures and slurry (proppant and the chemicals) is pumped into the wellbore [3]. The proppant helps to hold the cracks open as they tend to close under the minimum horizontal pressure, as the cracks tend to propagate in maximum stress direction.

The mechanical properties of the propping agent, also called sand or proppant are to be examined throughout the study, the background on the topic is to be gathered.

Scope

The purpose of this study/experiment is to investigate the effectiveness of the proppant in maintaining open apertures during the hydraulic fracturing process. Particularly, the precise balance between the quality (type) and the quantity of proppant is to be obtained. This will help to prevent the use of the high amount of proppant what might lead to the fluid flow hindrance and unnecessary expenditures.

Problem statement and project objectives

Next objectives are to be met in the experimental part of this study:

- Developing a procedure for making artificial rock samples.

- Developing a procedure for forming stable cracks in such samples and injecting proppant (fine sand will be used, at least initially, but other forms may be considered if possible) into the crack.
- Developing a procedure for testing the proppant filled cracks.
- Forming conclusions and recommendations regarding possible future investigations

1. Literature Review

1.1. The mechanics of hydraulic fracturing

The hydraulic fracturing (also fracking, fraccing, frac'ing, hydrofracturing or hydrofracking) is used in conventional and unconventional oil and gas fields in order to enhance the hydrocarbon production. The tights sands, oil sands (tar sands) and shale oil can be considered as unconventional oil sources, whereas the CBM (coal bed methane), shale gas and tight gas as unconventional gas sources [4]. The technique involves pumping the fluid mixture consisting of plain water, chemicals and sand proppant at high pressure into the reservoir formation in order to create cracks in the deep-rock layers through which natural gas, oil, condensate and brine will flow with less restriction. When the hydraulic pressure is detached from the well, small grains of hydraulic fracturing proppants (e.g. sand or aluminum oxide) maintain the fractures open. There might also be some adjustments to plain water such as polymers and gelled fluids, as well as the surfactants [5].

The hydraulic fracturing process consists of two parts, which are the pad and slurry stages. At the first stage the fluid is injected into the well in order to fracture the formation and create a crack (pad), hence the name. The pressure at which the formation fails is a key parameter called *breakdown pressure*. Breakdown pressure is an essential parameter acquired during hydraulic fracturing stress measurements. It is supposed that the maximum horizontal stress can be calculated referring to the breakdown pressure, the minimum principal stress and the properties of the rocks. On the other hand, breakdown is known to be a complex process. The breakdown pressure is rate-dependent, size-dependent, and fracture fluid-dependent as well. As a result, many breakdown models exist. Formation properties define the magnitude of the breakdown pressure [15]. The first estimation is made from in situ stress analysis. Terzaghi presented the formula below in order to calculate the breakdown pressure:

$$p_{bd} = 3\sigma_{min} - \sigma_{max} + T_0 - p_p$$

The slurry stage is carried out after the pad stage is finished. The proppant is being mixed with the fracturing fluid and injected into the wellbore. The schematic of this process can be found on the figures 2 and 3. When the injection is finished the hydraulic fracturing stimulation is considered to be finished too [3].

1.2. Fracture geometry

Different fracture geometries might occur after the hydraulic fracturing procedure. Whether the single or multiple fractures occur after the hydraulic fracturing is still questionable. However, the both cases are observed based on the data obtained from tiltmeters [3]. Various mathematical models are developed in order to best predict the geometry of the created pad and listed below.

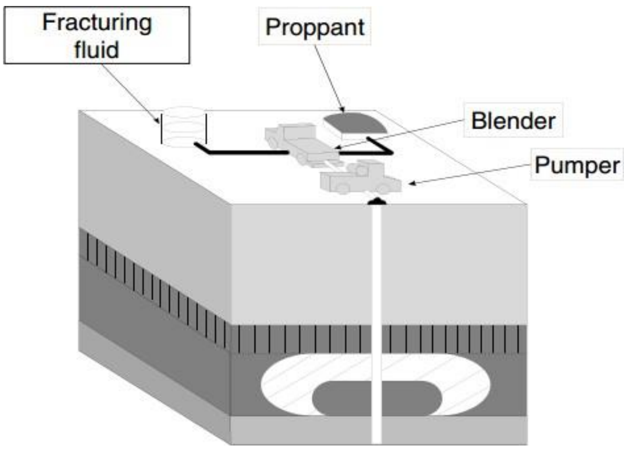

Fig 1. Simplified equipment layout **[3]**

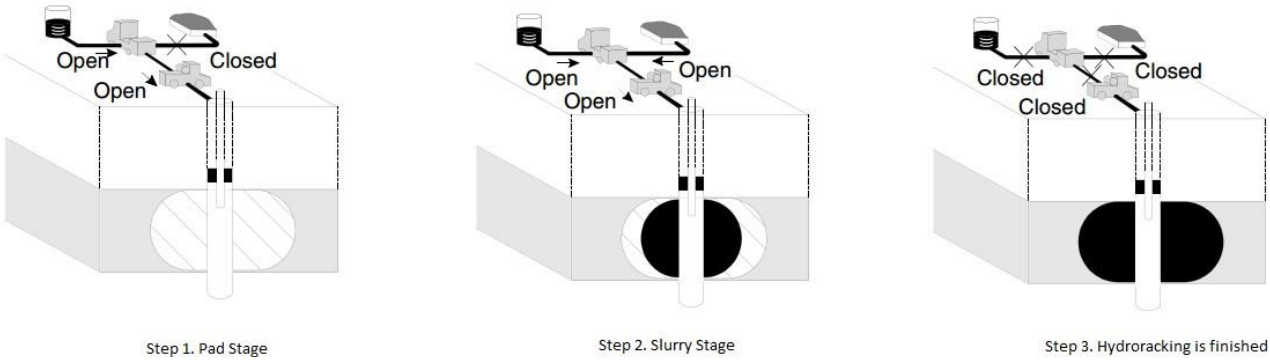

Fig 2. Hydraulic fracturing procedure **[3]**

1.2.1. Radial fracture model

Modeling of fracture propagation has improved significantly with computing technology and better understanding of subsurface data. With a 2D model, the engineer fixes one of the dimensions, usually it is fracture height, and then calculates the width and length of the fracture. With experience and accurate data sets, 2D models can be used in certain formations with confidence, considering that design engineer can estimate the originated fracture height precisely.

Table 1. Comparison between traditional 2D hydraulic fracture models **[16]**

Model	Assumptions	Shape	Application
PKN	Fixed Height, Plain Strain in vertical direction	Elliptical Cross Section	Length »Height
KGD	Fixed Height, Plain Strain in horizontal direction	Rectangle Cross Section	Length «Height
Radial	Propagate in a given plane, Symmetrical to the wellbore	Circular Cross Section	Radial

The first ideal and simple fracture model is developed by Sneddon and Elliot in 1946. Also called a penny-shaped crack, this model is to be used when height growth is not constrained by any restrictions. In this model, the fracture is assumed to proceed within a particular trace and the geometry of the fracture is symmetrical with respect to the point at which fluids are injected [16]. The schematic of this model can be found in figure 3. Later on, Geertsma and de Klerk derived the formula in order to determine the width at the wellbore [3]:

$$w_w = 2.56\left[\frac{\mu q_i(1-\nu)R}{E}\right]^{1/4}$$

Where,

w_w – fracture width at the wellbore, in.

μ – viscosity of the fluid, cp

R – fracture radius, ft

q_i – pumping rate, bpm

E – elasticity modulus, psi

As the width decreases linearly from the wellbore to the tip, the average value for width can be found:

$$\bar{w} = 0.85\left[\frac{\mu q_i(1-\nu)R}{E}\right]^{1/4}$$

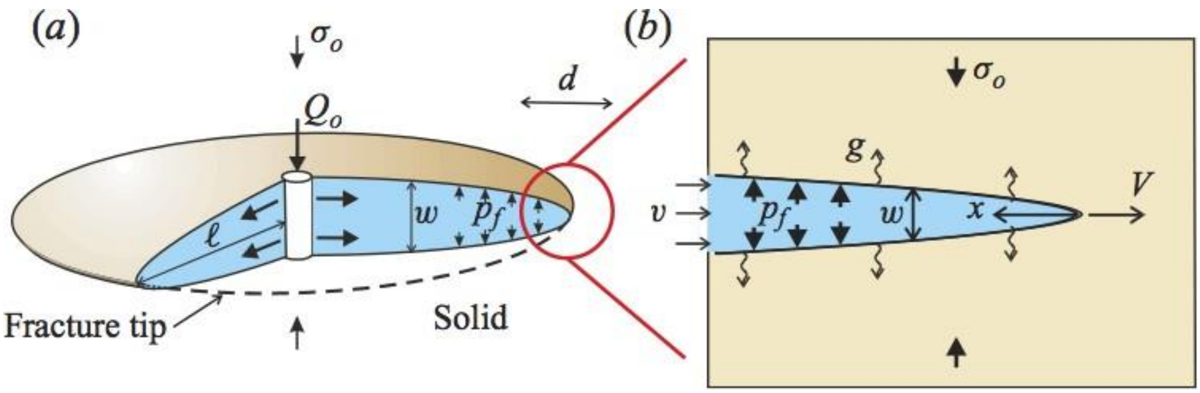

Fig 3. The radial fracture model **[6]**

1.2.2. The Khristianovic-Geertsma-de Klerk (KGD) model

Figs. 4 and 5 illustrate two of the most popular 2D models used in fracture treatment design. The Perkins-Kern-Nordgren (PKN) geometry (Fig. 5) is normally used if the fracture length is much more than the fracture height, while the Khristianovic-Geertsma-de Klerk (KGD) geometry (Fig. 4) is used if fracture height is more than the fracture length. In some sort of formations, any of these two models can be used successfully in order to design hydraulic fractures. Main point is to use models (any model) to make decisions, rather than trying to calculate precise values for fracture dimensions. The design must always compare actual results with the predictions from model calculations. By adjusting the 2D model with field results, the 2D models can be used to make design changes and improve the success of stimulation operations. If the correct fracture height value is used in a 2D model, the model will give reasonable predictions regarding value of created fracture length and width if other parameters, such as in-situ stress, Young's modulus, formation permeability, and total leak off coefficient, are also reasonably known and used. It is similar to penny-shaped fracture model; however, the height constraint is taken into account.

The drawing of the KGD model is represented in figure 4. This model presented by Khristianovich and Zheltov in 1955.

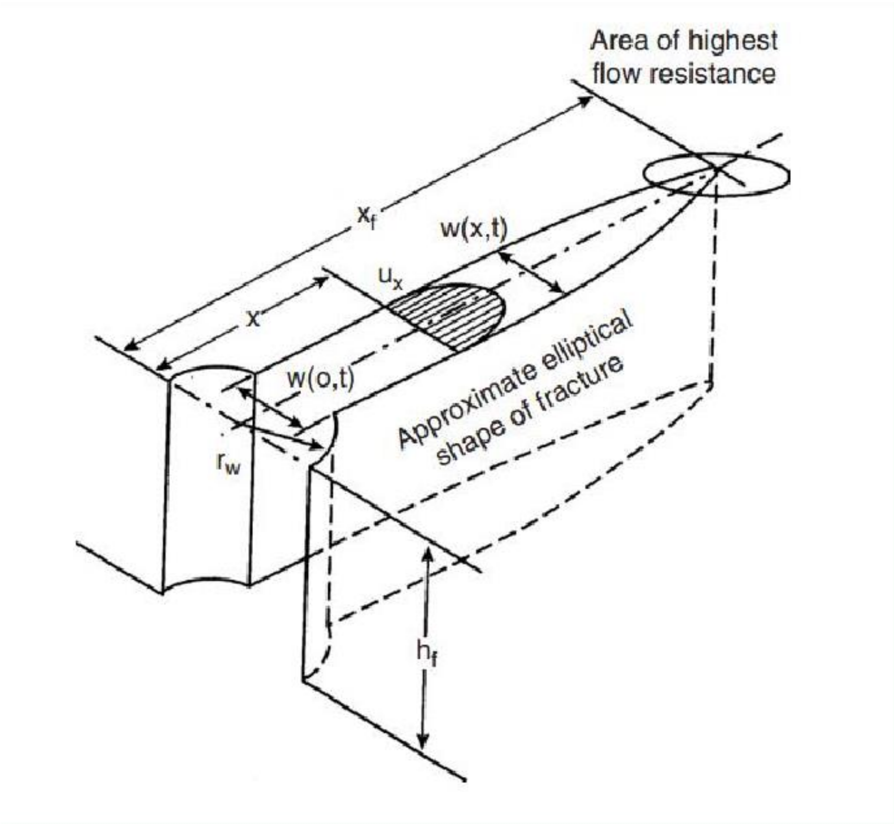

Fig 4. The KGD fracture model **[3]**

In this case, the width of the pad does not depend on the vertical position and depends only on the distance from the wellbore. The flow rate is also assumed constant in the fracture, hence the pressure, except the small area of the fracture tip, where the fluid does not penetrate, therefore no pressure is presented there. Geertsma and de Klerk simplified the solution to the given problem, which is referred now as KGD model. The average width of the model is expressed as:

$$\bar{w} = 0.29 \left[\frac{\mu q_i (1-\nu) x_f^2}{G h_f}\right]^{\frac{1}{4}} \left(\frac{\pi}{4}\right)$$

Where,

x_f – half-length, ft.

G – shear modulus, psia

h_f – fracture height, ft

The rest of the terms description can be found above

1.2.3. <u>The Perkins-Kern-Nordgren (PKN) model</u>

Initially, Perkins and Kern found a solution for a crack with the fixed height as shown below, in figure 5. Nordgren amended the solution by adding storage and leakoff in the fracture. The final model is presented as PKN model [3]. The PKN model assumes, that fracture toughness could be neglected, because the energy necessary for fracture to spread was significantly less than that required for fluid to flow along fracture, and the plane strain behavior in the vertical direction, and the fracture has a continual height, and spreads along the plane direction. From the characteristic of solid mechanics, when the fracture height, is fixed and is much smaller than its length, the problem is reduced to two-dimensions by using the plane strain assumption. For the PKN model, plane strain is considered in the vertical direction, and the rock response in each vertical section along the x-direction is assumed independent on its adjacent vertical planes. Plain strain infers that the elastic deformations (strains) to open or close, or shear the fracture are fully concentrated in the vertical planes sections perpendicular to the direction of fracture propagation. This is true if the fracture length is much larger than the height. In comparison with KGD model, two more assumptions are to be made. The first is the cross-sectional area of the fracture, which is elliptical and the other one is the absence of fracture toughness effect on fracture geometry [2]. The average width within the fracture can be found as

$$\bar{w} = 0.3\left[\frac{\mu q_i(1-\nu)x_f}{Gh_f}\right]^{\frac{1}{4}}\left(\frac{\pi}{4}\gamma\right)$$

Where $\gamma \approx 0.75$

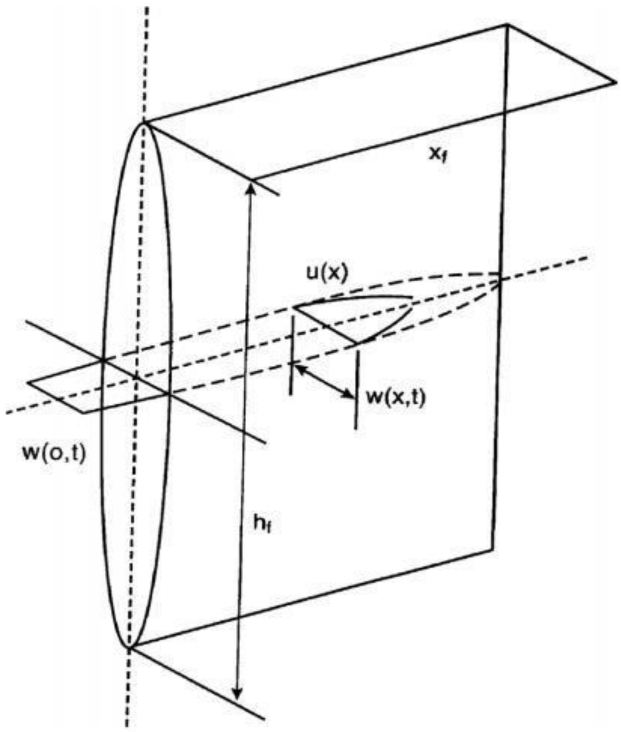

Fig 5. The PKN model **[3]**

The next assumption is always to be taken into account that the fracture length has to be at least three times the height. Otherwise, the solution of PKN model is not valid [3].

1.2.4. 3D models

As the 2D models shown above have their own limitations as the height constraints etc., the pseudo 3D models are developed in order to fulfill the task. One of the main assumptions made in 2D models that the flow development is radial and the height is fixed. Lumped and cell 3D pseudo models are the most common used ones. The lumped model has a defined shape consisting of two half-ellipses attached at the centerline. In comparison with lumped, the cell-based model is described as a matrix of cells which are linked to the fluid flow.

1.3. Fractured wells productivity

The fractures act as a corridor between the reservoir formation and the wellbore. They receive the hydrocarbons from the formation and transport them into the wellbore. Thus, how well the fracture will implement these two tasks defines the productivity of the fractured well. The shape and size of the crack determine how well the fluids will flow into the fracture from the formation while the fracture conductivity shows how permeable the crack is. For this purpose, the dimensionless fracture conductivity concept is introduced [3].

$$C_{fd} = \frac{k_f * w}{k * x_f}$$

Where C_{fd} is dimensionless fracture conductivity,

k_f – fracture permeability, mD

w – fracture width, in

k – formation permeability, mD

x_f – fracture half-length, ft.

1.4. Design of hydraulic fracturing

Hydraulic fracturing design can be described as the process which first takes into account the net present value (NPV) of the well. The maximizing the NPV is of the high importance in the process design. The procedure below highlights the main steps to be fulfilled when considering the hydraulic fracturing design:

1. Selection of a fracturing fluid
2. Selection of a sand/proppant
3. Calculation of the maximum possible pressure applied
4. Selection of a fracture geometry
5. Evaluation of the fracture length and sand concentration
6. Production forecast
7. Net present value analysis

The fracturing fluid is one of the essential components of hydraulic fracturing system, as it is the main agent that will transport the sand underground. Several losses occur during the process. Fluid-loss coefficient C_L and spurt-loss coefficient S_L describe the main losses. Spurt losses occur until the mud cake is formed. After the development of the filter cake, the fluid loss starts to occur. Too high rates of the losses decelerate the fracturing process, hence, the selection of the fluid with lowest loss rate is preferred. The viscosity also plays the main role in fluid selection. Maintaining it within the range is highly important. The proppant is selected based on the confining stresses and fracture geometry. This will later be thoroughly discussed. The calculations for maximum allowable pressure can be found in the technical literature in [3]. While selecting a crack geometry in-situ stress is to be taken into account. Creating 3D model might take too much time and 2D model does not simulate the real-life conditions. Usually, pseudo-models are used as the best solution to this problem [3]. The next step to be undertaken is a determination of the treatment size. The fracture length is the key parameter which controls the volumes of the propping agent and fluid. The final things while considering the hydraulic fracturing design are the future productivity and NPV analysis.

After the hydraulic fracturing is done there are several methods that are being used to evaluate the job. Different methods such as pressure-matching and well test analysis can be used to carry out the post - frac operations. The other procedures are the injection of radioactive material, which will be touched on later and use of the logging tools [3].

The next chapters will focus on the propping agent, also known as a proppant, its various types and shapes used in industry, as well as the techniques for successful delivery into the created fractures.

1.5. Proppant purpose and types

The main purpose of the proppant is to keep the propagated cracks open. After the first hydraulic fracturing process in 1947 with silica sand, many more types of propping agents are introduced. Natural sands, fused zircon, sintered bauxite and many other are used as proppant in hydraulic fracturing during the next fifty years. The stronger bauxite proppant is preferred for a long time in industry as they could withstand the high confining stresses of several thousand psi [7]. Later on, the ultra-lightweight proppant had been discovered. It is the breakthrough in hydraulic fracturing industry, as its transportation did not require high viscosity fluids anymore.

The proppants currently used in the industry can be classified into the three groups:

- Uncoated sand (referred to sand)
- Resin coated sand (RCS)
- Ceramics

The schematics of different tier sands is shown below

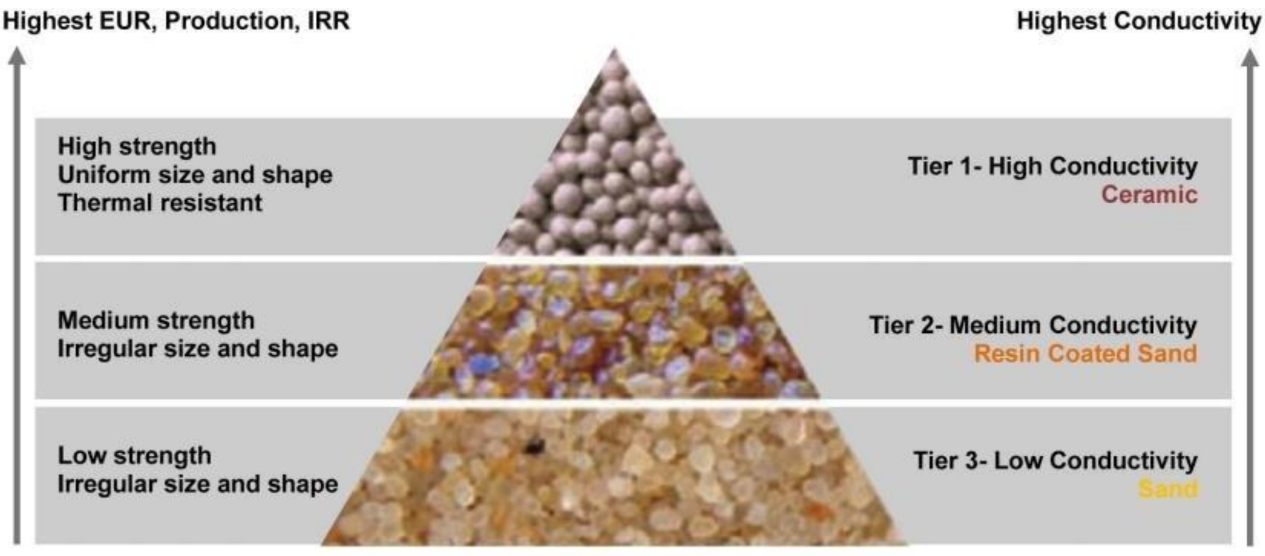

Fig 6. Proppant conductivity hierarchy **[7]**

The higher the tier of the proppant the higher its conductivity, what leads to the higher production rates. But due to the higher cost of ceramics, the sand is the most widely used propping agent.

Quartz sand with the high-silica proportion is the main component of the silica sand, also known as ‘frac sand’. It first should be processed before exploitation. First, it is should be extracted from the sand deposits, crushed, cleaned and sieved. The cleaning process usually consists of polishing and drying the sand grains. Due to the high availability, it is one of the most commonly used proppant types. Usually, two main types: brown and white sand are used for rock fracturing. Due to impurities, the brown sand is less strong and less expensive than the white sand.

However, the silica sand is not used in deep formations as it is quite fragile. For this case, the resin coated sand is more preferred. The advantages of the RCS are their ability to distribute the applied pressure more uniformly rather than the silica sand. Also, it prevents the flowback into the wellbore as the broken grains being entrapped in the coating material. The modern coating technology allows coating the proppant grains during the placement into the reservoir or it can be done at the facility too. The coating can either be curable or pre-cured. It is done in order to increase the mechanical strength of the proppant [7]. In the first case, the well is to be shut-in and let the sand cure while for the pre-cured sand the coating is applied onto the proppant surface and no further procedures are required. Phenolic and epoxy resins are the most common used coating materials.

There are some formations where silica sand and RCS are not applicable. Due to the demand of the higher-grade sand the ceramics (ceramic sand) have eventually been created. As bauxite and kaolin are the primary materials used in the manufacturing of the ceramic proppant, it has higher strength. The higher roundness of the grains helps to increase the fracture conductivity, as the hydrocarbons move through the smoother surfaces. The higher cost of this type of proppant causes its rare usage in the industry.

One of the main parameters taken into account during the selection of the proppant is its specific gravity. As the brine and water are the main fluids used for the transportation of the propping agent the density of the latter should not exceed the density of the former. There are some challenges associated with high density proppant. For a given amount of proppant, the volume it occupies will be smaller than for the less dense proppant. Also, the quick settling time and higher cost demand careful consideration of the fluid and proppant combination. One of the ways in order to tackle this problem is the usage of the slick water with high viscosity, however, for the shale formations it is not convenient, as too dense fluid damages the rock more than its less dense counterpart by higher percolation ability. Higher pumping rates are used to push the proppant into the formation, nevertheless, the lightweight proppant can also be used in order to solve this problem. There are several ways to obtain the proppant with low specific gravity. Choosing the lower specific gravity material is one of the main methods. Less strong proppant particles will be crushed under the high confining load what will reduce the crack aperture and crushed particles fill the flowing space. Later on, the different proppant such as resin coated walnut hull and deformable proppant are introduced as ultra-lightweight proppant, which can withstand harsh conditions such as high pressure and temperature [7]. The value of specific gravity is around 1.25 what is much less than usual values for ceramics. The other way to lower the specific gravity is to integrate the void spaces into particles. New developments of coating the strong proppant with low density coating can help to increase the buoyancy of sand. Nut and seed shells, as well as the fruit pits can be used as a natural base material for ULW proppant. The strength of the deformable proppant can be upgraded with nanofillers. The specific gravity values for different materials can be found below in table 1.

Table 2. Specific gravity for different proppants **[7]**

	Proppant	Specific Gravity (S.G)	Reference
Sand	Nature Sand	2.65	Carbo[3]
RCS	Resin Coated Sand	2.55 to 2.60	Carbo[3]
Ceramics	Lightweight ceramics	2.55 to 2.71	Carbo[3]
	Intermediate-Density Ceramic	~3.27	Carbo[3]
	High-Density Ceramic	~3.5	Carbo[3]
	USHP	~3.9	Palisch et al. 2014
	Advanced Ceramic Proppant	2.0 to 2.9	Mack and Coker 2013a
Lightweight Proppant	Walnut Shells	~1.25	Parker et al. 2012
	Hollow Glass Spheres	0.8 to 1.4	Parker et al. 2012
	Porous Ceramics	1.8 to 2.4	Parker et al. 2012
	Plastics	1.1 to 1.4	Parker et al. 2012
	Thermoplastic Alloy	1.08	Parker et al. 2012
	Resin-impregnated and coated, chemically modified walnut hull	1.25	Rickards et al. 2003
	Resin-coated porous ceramic proppant	1.75	Rickards et al. 2003

The fracture geometry is one of the most arguable questions in the hydraulic fracturing. Mathematical models (described in the previous section) and modern technologies are developed in order to give a better picture of the underground processes. Radioactive and acoustic logs help to predict the shape of the crack. Special coating that emits gamma rays can be used and after nuclear detectors record the signals. The other advanced technique which is proposed in [7] is to replace the common coating with special non-activated material which can be activated by neutron impulse from the source. A special device is moved down the wellbore to create the neutron surge. Limitation of this method is the possible activation of formation radioactive substances which can distort the data and give a lot of false information.

1.6. Proppant size and shape

The size of the proppant particles varies from 105 μm to 2.38 mm (8-140 mesh) [8]. The size of the particles is usually shown within the range, for instance, 20/40 mesh is proppant particles between 420 μm and 841 μm. The larger the mesh the finer the sand, the worse the fracture conductivity, as less inter-particle space is available for flow. In order to determine the size of the proppant, the method of the dry sieve is used. The table below shows the most common used proppant mesh sizes and what metric range the mesh size sit within

Table 3. Proppant mesh size **[8]**

Tyler Mesh Size	Particle Size Range
10/14	1400 – 2000 μm
12/18	1000 – 1700 μm
16/20	850 – 1180 μm
16/30	600 – 1180 μm
20/40	420 – 850 μm
30/50	300 – 600 μm
40/70	212 – 420 μm

The desirable shape for the proppant is an ideal sphere. It provides more space between the pores and has a smoother surface. The chart below shows the reference values for sphericity and roundness of the proppant.

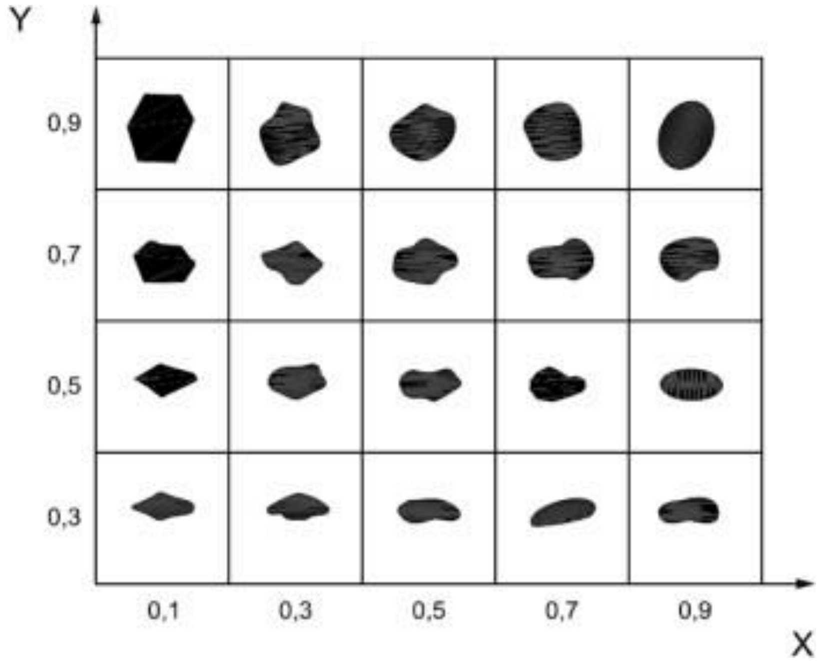

Fig 7. Sphericity and roundness scale for proppant particles **[7]**

The average value for roundness and sphericity for ceramics is around 0.7.

The next sections will review the techniques used by industry in order to efficiently deliver the propping agent into the created fracture and keep the aperture open.

1.7. Graded proppant injection

As the cracks propagate in a tree-like structure and get narrower moving from the wellbore to the edges the different sizes of proppants are to be used during the hydraulic fracturing. One of the proposed solutions to this problem is the injection of the graded proppant. Graded proppant technique is the injection of the proppant particles, which concentration decreases, and dimensions increase during the injection process. It results in better percolation as the smaller particles can better pass through the narrow fractures. Thus, the small size proppant is to be injected first followed by the large one. The schematic of this technique is shown below in figure 8.

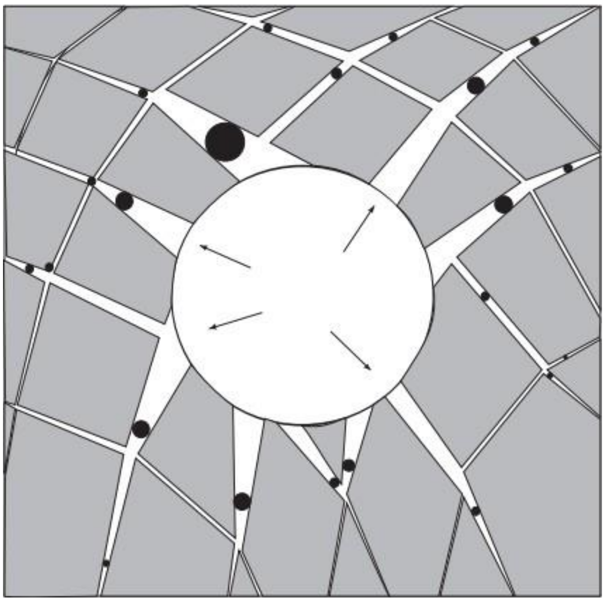

Fig 8. Graded proppant injection result **[9]**

The concentration of the proppant is to be increased as more fractures to be formed moving towards the edges. Thus, the larger concentration is required to fill the cracks in order to keep them open.

Two competing concepts further described are to be considered during the proppant selection, which can influence the permeability of the rock. The confining pressure of the rock will tend to close the aperture of the crack and proppant particles might create extra plugging of the open fracture what leads to the reduction in permeability of the formation. However, on the other hand when the proppant particles are located too sparsely to each other it maximizes the effect of the confining stresses on the aperture and when they are too close, the additional tortuosity for the flowing hydrocarbons is observed. Thus, the optimal amount of the proppant concentration is to be determined and selected during the process. Usually, the intermediate range is chosen, as it helps to minimize the both effects described below and can provide the maximum flow conductivity for this fracture system. The selection of the optimum concentration of the injected sand is usually based on consideration of the reservoir pressure, formation properties and the strength of the injected material, i.e. proppant. In order to prevent the complicacy of the flow paths the method of the partial monolayer is proposed and described below [9].

1.8. Partial proppant monolayer

Creation of the conductive routes in the direction of the wellbore is all-important. The usage optimum amount of the proppant is very significant and has its own application in the hydraulic fracturing practice. The fractures are usually filled with the proppant packs in order to maximize the flow capacity, as they are helpful to maintain the maximum width within the crack [10]. However, the width is not the only parameter which determines the flow capacity. The permeability of the fracture along with the width affects the hydrocarbon flow performance through the network of crack [11]. For narrow fractures, the partial monolayer of proppant would be preferred instead of the proppant pack, as the excessive use of the latter can plug the aperture and hinder the hydrocarbon flow. The proppant monolayer is a scattered layer of the low-density proppant particles, as the relatively low density helps to effectively transport the proppant into the narrow fractures. This technique has its own merits and limitations, which will further be discussed.

As it can be seen from the figure 9 below the space between the particles might provide better fracture conductivity than the full monolayer and even more than the proppant packs.

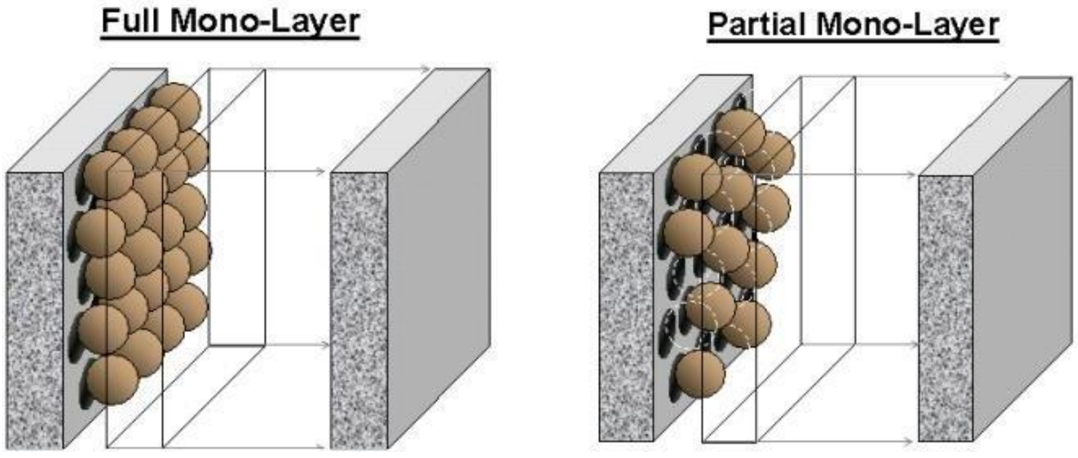

Fig 9. Schematic of full and partial monolayers **[12]**

Nevertheless, the single layer of the proppant can also lead to the loss of the main parameter, i.e. the fracture conductivity. In soft formations, it tends to embed into the formation while in the harder ones it crushes under the high overburden pressure. According to Khanna et al. [10] the experimental studies showed that there are certain levels of the proppant concentration at which the fracture conductivity reaches maximums for various confining stresses, hence the flow capacity. Harold [12] states that despite the theoretical proof the experimental application of partial monolayers have not succeeded, as the optimal allocation of the particles is mostly impossible. However, one of the methods to achieve that is by placing the full monolayer of proppant mix, consisting of common proppant and oil-soluble sand particles with the further dissolving of the latter [13]. Later on, the invention of the ultra-lightweight proppant stimulated the wider industry application of this technique [12].

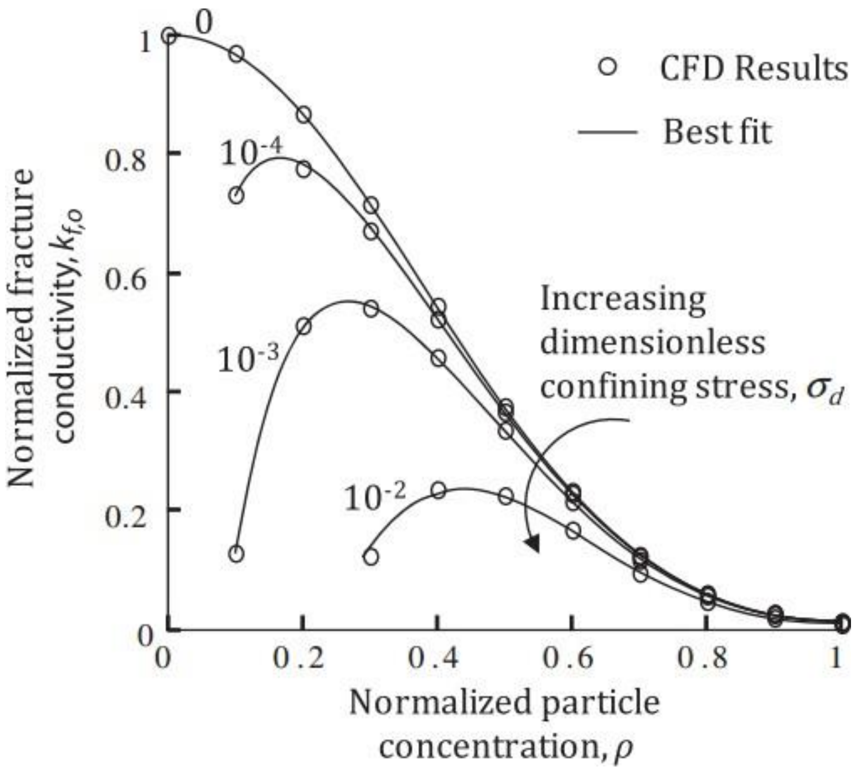

Fig 10. Fracture conductivity vs Particle concentration for various confining stresses **[10]**

It can be observed from the graph in figure 10 that for advanced confining stresses the particles concentration is higher than the lower confining stresses and a monolayer becomes full rather than the partial.

The physical properties of the proppants and the formation, such as the strength and the hardness affect the magnitude of the fracture conductivity [10].

The limitation of the system is the relationship between the experimental/computational model and real-life data. The mathematical and analytical models are designed with numerous assumptions and simplifications.

The consequences of proppant embedment into the formation, crushing under the high load and failure of the rock in localized zones have not been taken into account [10].

2. Experimental work

2.1. Research methodology

The experiment consists of testing the proppant under the load. Two separate set of experiments with concrete cubes and cylinders are done in order to determine the properties of the propping agent. The uniaxial test machine Instron 8500 is used as the loading force in order to simulate the field conditions of cracks which tend to close under the overburden pressure.

Note: Due to absence of necessary equipment on my location, the experiments have been conducted in workshop/laboratory of Bahrain Polytechnic University, by my colleague. Entire process was under my guidance and monitoring. At the end of each experiment, stress/strain values acquired from Instron testing machine, were sent to me in initial, unprocessed form. Risk assessment regarding these experiments is attached to this thesis as appendix.

2.2. Proppant properties

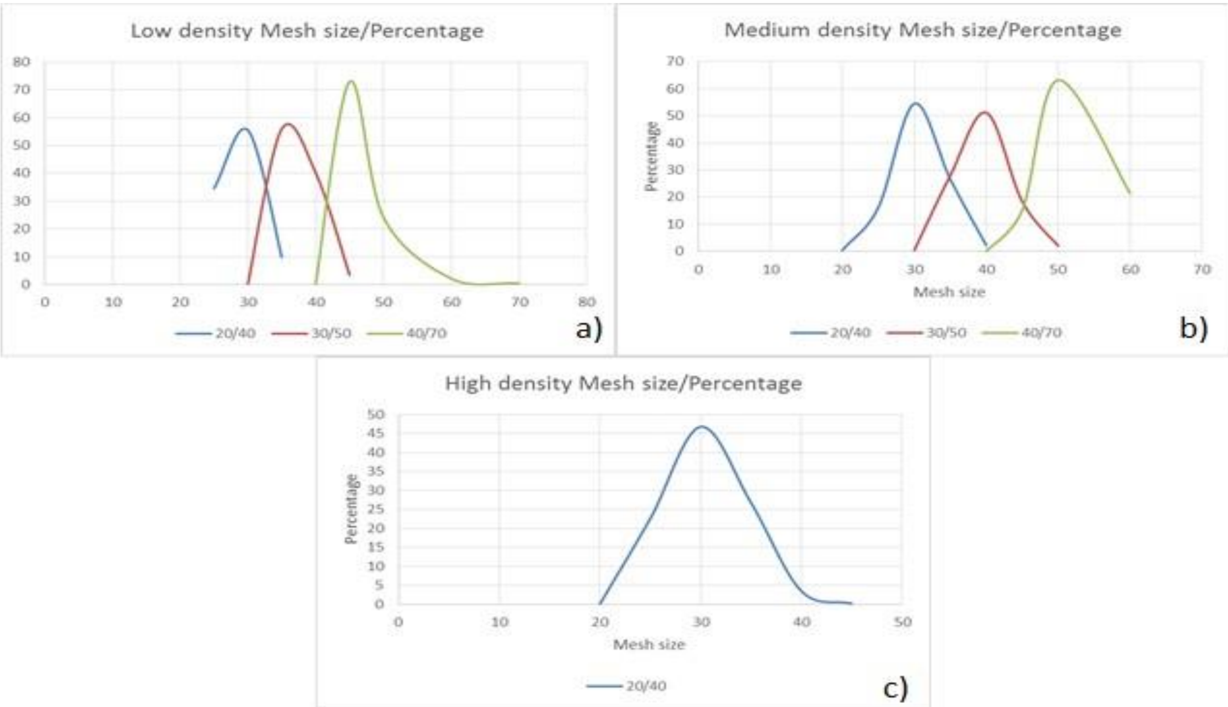

Fig 11. Low (a), medium (b) and high density (c) proppant mesh size/percentage

Four different propping agents are used during the experiments: three types of ceramic proppants with different density values which used in industry for hydraulic fracturing operations and common silica sand. The properties of the proppants for different grades and mesh sizes are given below in figure 11 [14].

Other properties such as roundness, sphericity and density are presented in table 3

Table 4. General properties of the ceramic proppants **[14]**

	Low density	Medium density	High density
Roundness	0.9	0.9	0.9
Sphericity	0.9	0.9	0.9
Bulk density/gcm^{-3}	1.60	1.85	2.00
Apparent density/gcm^{-3}	2.80	3.25	3.50

2.3. Cube experiment

The first set of experiments consists of testing the sand in the created V-shaped notch in the concrete cube. The concrete is used as a base material in order to cast the concrete samples for further experiments. The following drawings had been submitted to the workshop.

Based on the drawings provided the workshop has modified the details and amended the available cubic molds in order to create the necessary experimental kit. The dimensions of the cubic mold are 100mm*100mm*100mm.

Twenty-two cubic samples are cast in the concrete lab and cured for seven days (except two samples which are cured for fourteen and twenty-one days and will accordingly be labeled later) to fulfill the following experiments (Fig 12). The image of the rock sample can be found below:

Fig 12. Cube sample

Later this specimen is filled with the propping agent. The propping agent has accurately been blown into the crack in the concrete sample and the sticky tape is used in order to keep the proppant in situ.

The next step is to test the piece of rock under the load in uniaxial test machine (Fig 13).

Fig 13. Cube sample under the load in the uniaxial test machine. No sand used

Finally, the sample becomes crushed under the continuous high load. Multiple cube samples are tested without any propping agent. It includes three experiments with the concrete cubes cured for seven days and three cubes with a curing time of seven, fourteen and twenty-one days. Experimental data are presented in the Analysis section where it is thoroughly discussed, and further recommendations are given.

2.4. Two cylinders experiment

The idea behind the next set of the experiments is to test the propping agent between two cylindrical samples in confined surroundings. A cylindrical sample will be placed on the bottom of metal sleeve, the layer of the sand will be poured on top (Fig 14, a, b) and the other concrete sample will be placed onto the sand layer, thus making a “sandwich” structure (two concrete cylinders with a layer of proppant in-between)

(Fig 14, c). For the purpose of developing the confined test, the metal sleeve is meant to be used.

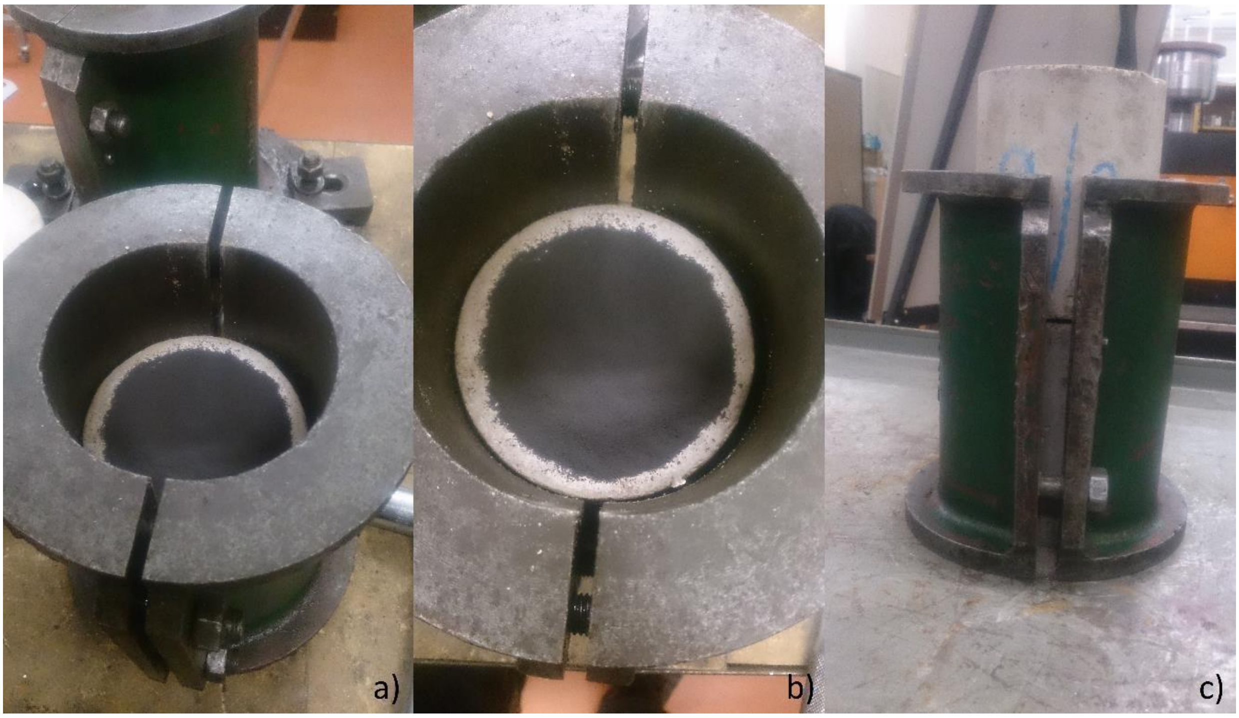

Fig 14. (a), (b) proppant on top of the concrete cylinder and (c) two cylinders "sandwich" structure with proppant in-between

The cylindrical moulds available in the workshop are agreed to be used as the steel sleeve.

The height of the cylindrical mould is 200mm and the diameter is 100mm. The moulds are filled with concrete for sample casting from the bottom to the 60% of the overall height (120 mm), as the mould will later be used as a sleeve to keep the proppant in place. So, the height of the overall "sandwich" structure is around 240mm.

The assembling is tested in the uniaxial test machine Instron the same way as the cube samples (Fig 15).

Fig 15. Two concrete cylinders ("sandwich" structure) under the load in uniaxial test machine

Eighteen cylindrical samples are cast in the concrete lab for this set of the experiments. Three experiments are done for each type of the proppant, what results in nine experiments (eighteen rock samples, as every time two samples are required).

2.5. Microscopic observation

The particles are examined under the microscope after they are compressed between two cylinders (**Fig 16**).

Fig 16. Microscope

However, some particles are embedded into the concrete and cannot be retrieved from a specimen after the experiments are done.

3. Results and Analysis

3.1. Cube results

Force versus displacement data is obtained from the uniaxial test machine. In order to calculate the stress/strain relationship the former is divided by the area of cube sample which 0.01 m^2 and the latter by the length of the cube 100 mm. Multiple plots describing the obtained results are presented below. Each plot represents a set of three experiments which are done under the same conditions (the same type and amount of proppant are used). Each of the graphs is accordingly noted and the nomenclature can be found in Table 4. Each label shows the date when the cube is put into the water bath for curing (due to a number of samples they are accordingly labeled in order not to be confused), type of sand which is used (or "nosand" if no sand is used) and the position of the experiment. For example, *4_3workshopsand2* means the cube is left for curing on 4^{th} of March (4_3), silica sand taken from the workshop (workshopsand) is used as the propping agent and is a second experiment

(2) in succession to previous.

Table 5. Cube samples nomenclature

Label	Type of sand	Label	Type of sand
3_3workshopsand1	Silica sand	4_3lowdensity1	Low density proppant
4_3workshopsand2	Silica sand	4_3lowdensity2	Low density proppant
9_3workshopsand3	Silica sand	4_3lowdensity3	Low density proppant
10_3nosand1	No sand	8_3mediumdensity1	Medium density proppant
10_3nosand2	No sand	8_3mediumdensity2	Medium density proppant
10_3nosand3	No sand	8_3mediumdensity3	Medium density proppant
3_3nosand7daycure	No sand	8_3highdensity1	High density proppant
3_3nosand14daycure	No sand	9_3highdensity2	High density proppant
3_3nosand21daycure	No sand	9_3highdensity3	High density proppant

On the figures 17 and 18, the results of the experiments of no sand used can be found. Figure 17 shows a set of experiments which are done in order to be compared later with the results of other experiments which involved the cubes cured for seven days only.

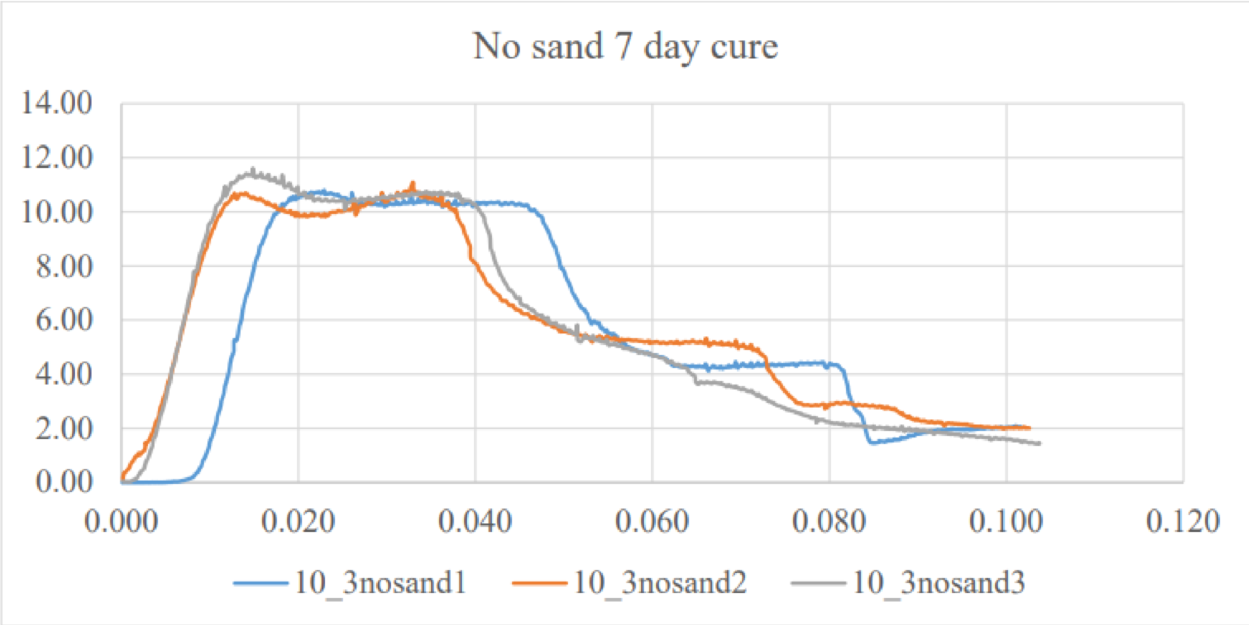

Fig 17. Cube experiment without propping agent. All samples are cured for seven consecutive days

However, the experiments, which results can be found in figure 18 are conducted in order to define the difference between the samples which are cured for seven, fourteen and twenty-one days.

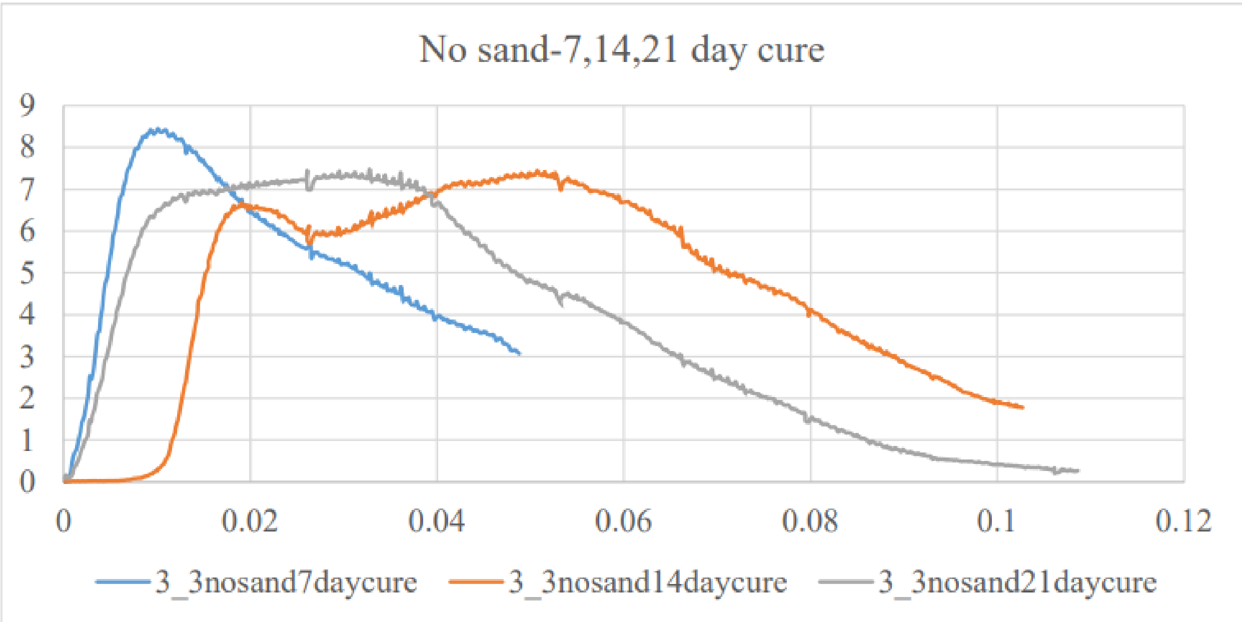

Fig 18. Cube experiment without propping agent. The samples are cured for seven, fourteen and twenty-one days.

The results of experiments with propping agents can be found below in figures 19, 20, 21 and 22. The first three plots represent results of ceramic proppant and the last shows how the common silica sand supported the crack aperture.

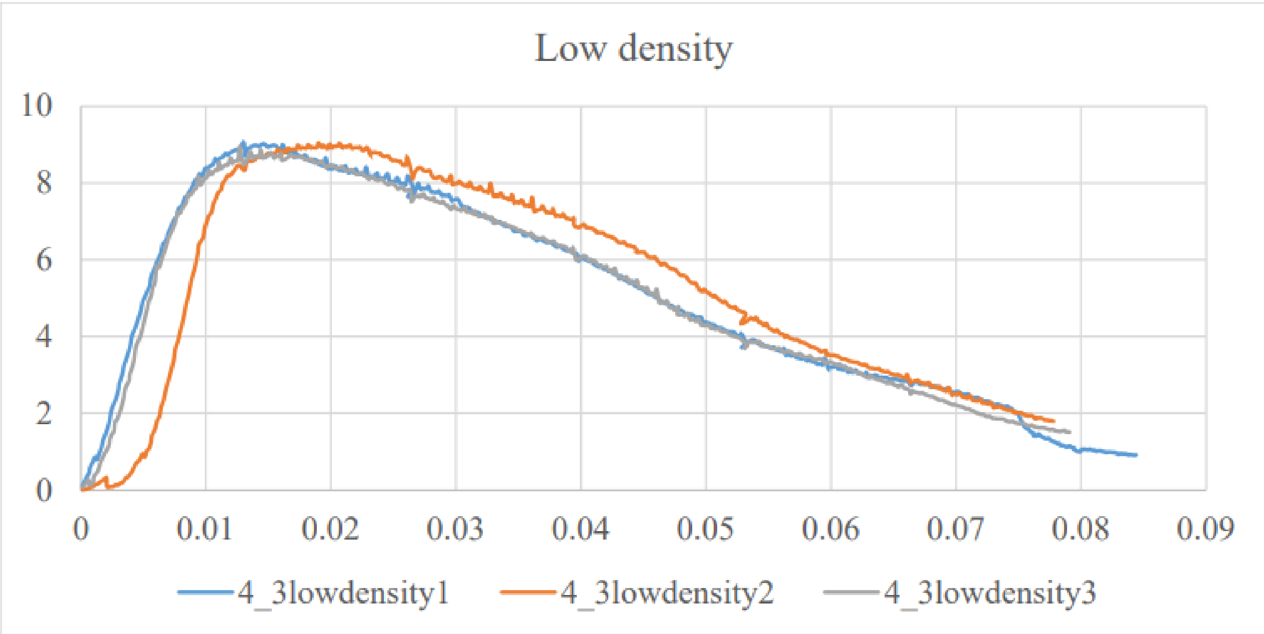

Fig 19. Cube experiment with low density ceramic proppant

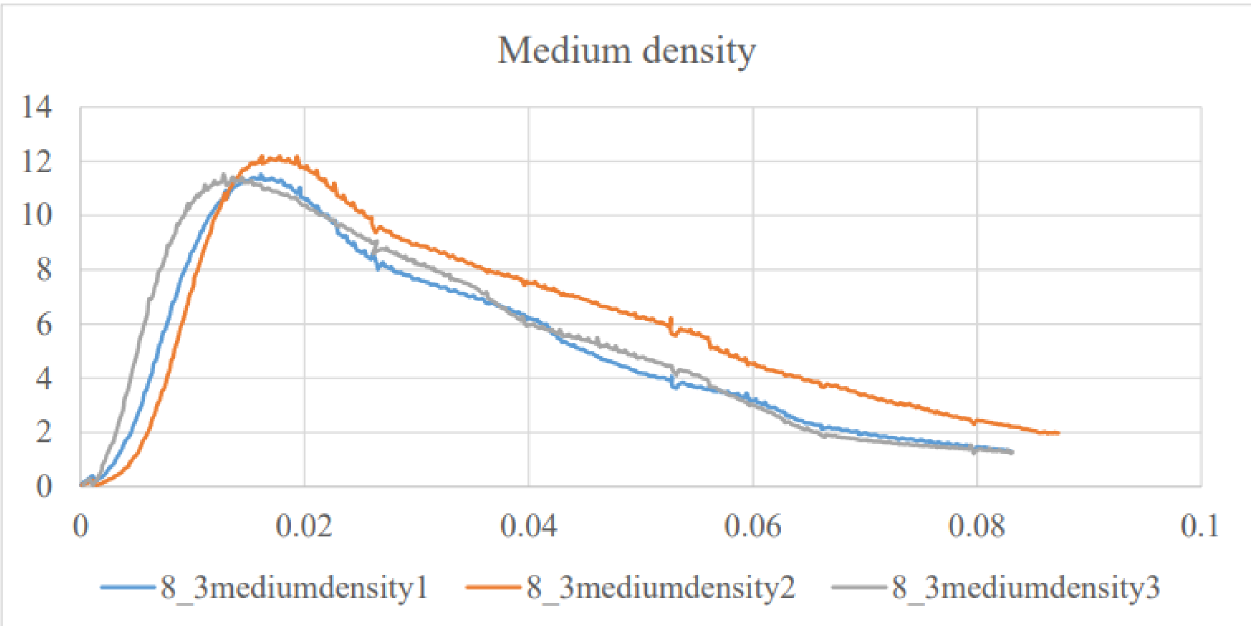

Fig 20. Cube experiment with medium density ceramic proppant

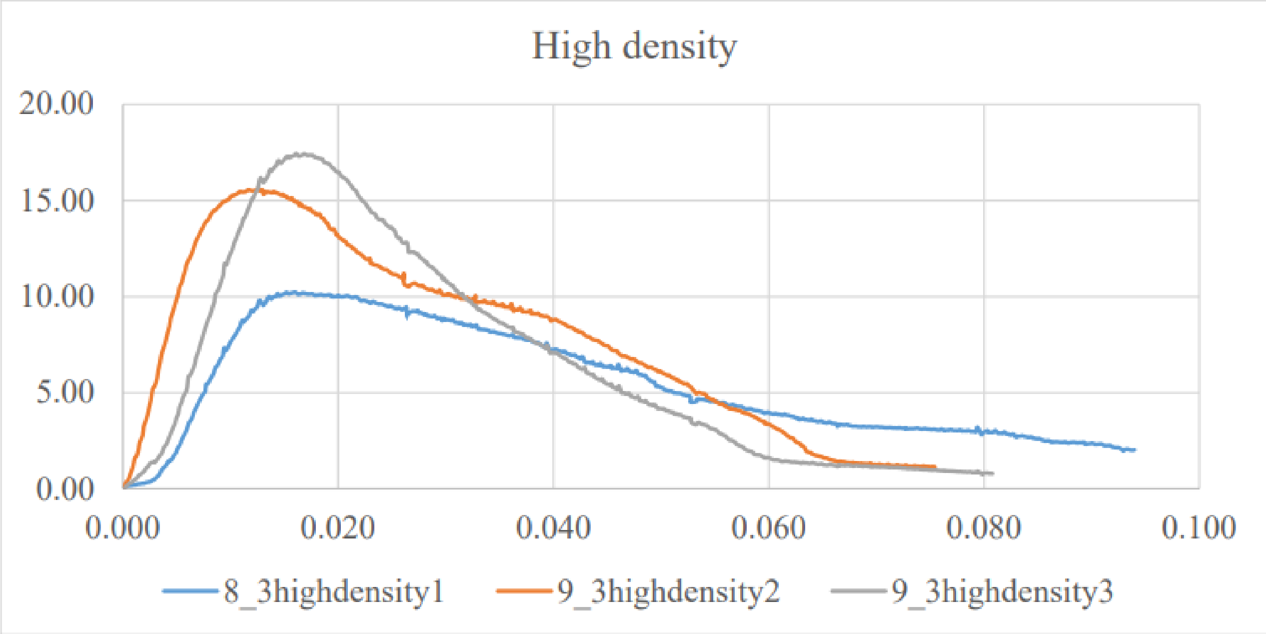

Fig 21. Cube experiment with high density ceramic proppant

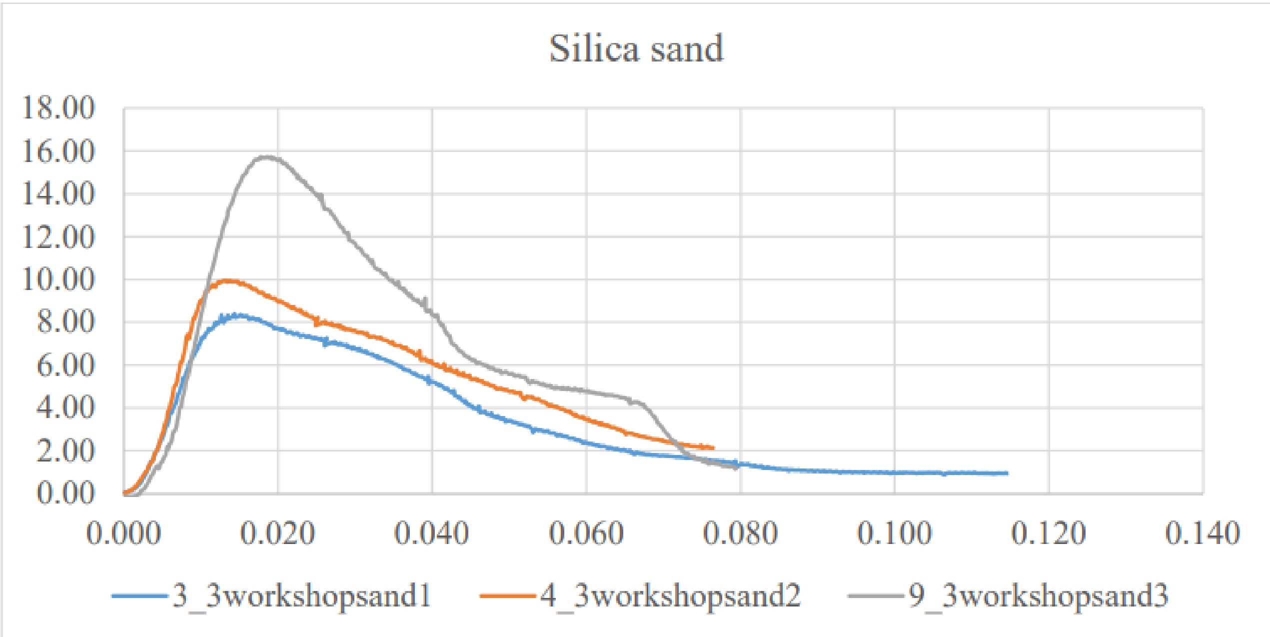

Fig 22. Cube experiment with silica sand used as the propping agent

It can be clearly observed from the plots that the denser the propping agent the more force is required to compress the sample until failure. For low density proppant, the peak stress it can withstand is around 9 MPa, whereas for medium and high-density proppant these values are 11 and 15 MPa correspondingly. More information about the physical properties of cube samples filled with different sand types is given below in the analysis part. For more information about the errors and data discrepancies see the errors and inaccuracies section.

3.2. Two cylinders results

In the case of two cylinders to convert force vs displacement plot into stress vs strain graph, the force and displacement should be divided by area and total original length (height of "sandwich" structure) correspondingly. The area of the cylinder is 7.85e-3 m^2 and the total length is measured for each assembly as the lengths of cylinders slightly vary from each other. Nine of two cylinders experiment are conducted, three for each type of the proppant. Only ceramic proppant is used as the propping agent layer between two cylinders. Each has also been labeled and the nomenclature can be found in Table 5. The label means a type of experiment (in order to be distinguished with cube experiments), type of proppant used and position of the experiment. For instance, *2cls_med1* means this is the two cylinders experiment, medium density proppant is used as the propping agent and it is the first experiment among all three experiments for this type of proppant.

Table 6. Two cylinders experiment nomenclature

Label	Type of proppant
2cls_low1	Low density proppant
2cls_low2	Low density proppant
2cls_low3	Low density proppant
2cls_med1	Medium density proppant
2cls_med2	Medium density proppant
2cls_med3	Medium density proppant
2cls_high1	High density proppant
2cls_high2	High density proppant
2cls_high3	High density proppant

The same trend of increasing of the stress with the increase of density of proppant is not clear on the following graphs and more detailed explanation will be given in the errors section.

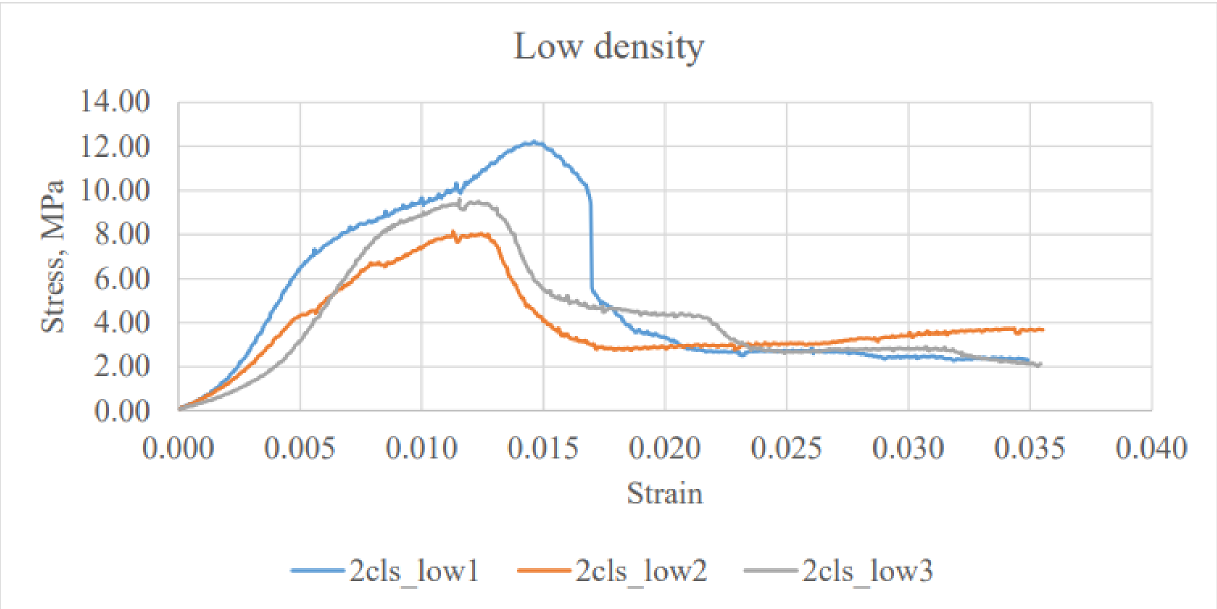

Fig 23. Two cylinders experiment with low density proppant

The sudden drop in of the stress can be observed in figure 24 which is due to the partial failure of the specimen.

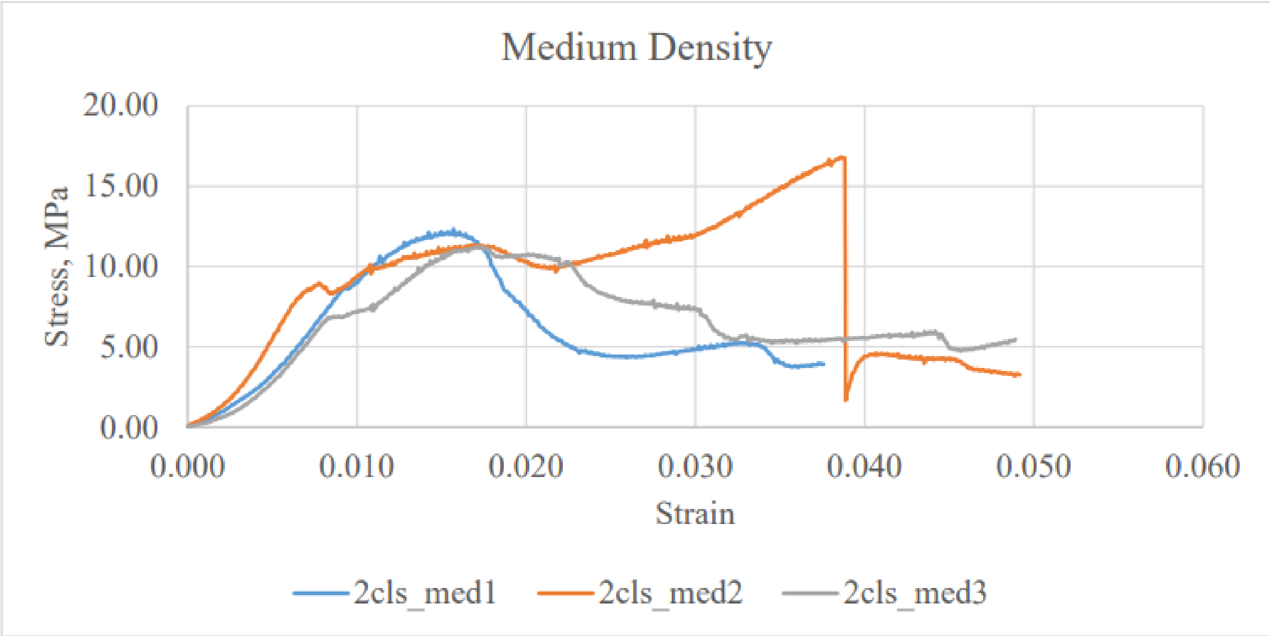

Fig 24. Two cylinders experiment with medium density proppant

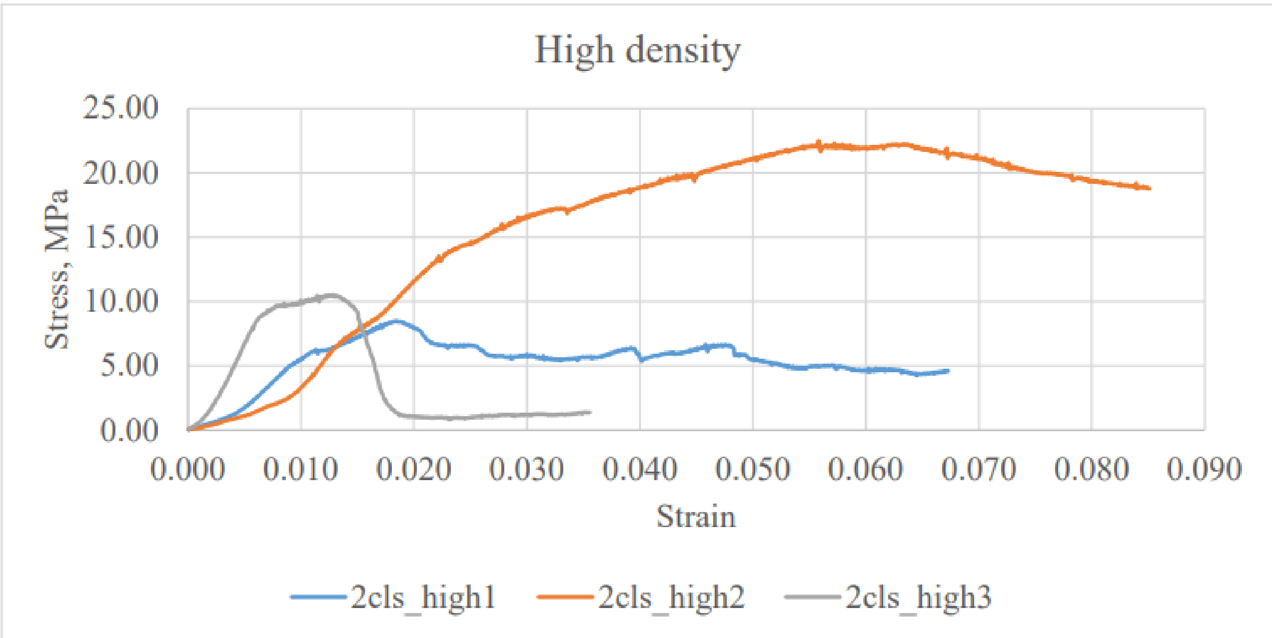

Fig 25. Two cylinders experiment with high density proppant

3.3. Microscope results

After the inspection of the proppant compressed between two cylinders, some sand grains changed their shapes. Approximately every tenth grain is found to reshape after compression what can be extrapolated that less than 10% of all grains changed their shapes. The photos shown below are taken with the digital static camera on top of the microscope. As the proppant is a coarse type of sand the minimum fiftyfold magnification is enough to measure the dimensions of the grains before and after the experiments. The high rate of sphericity and roundness can also be noticed on following images.

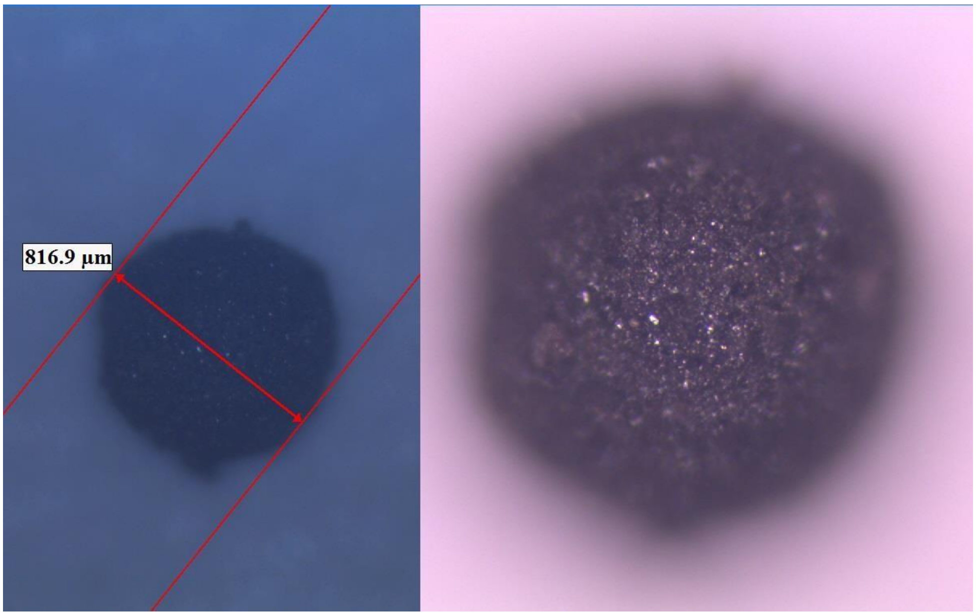

Fig 26. Sand grain before experiment a) 50x magnification with dimensions and b) 100x magnification

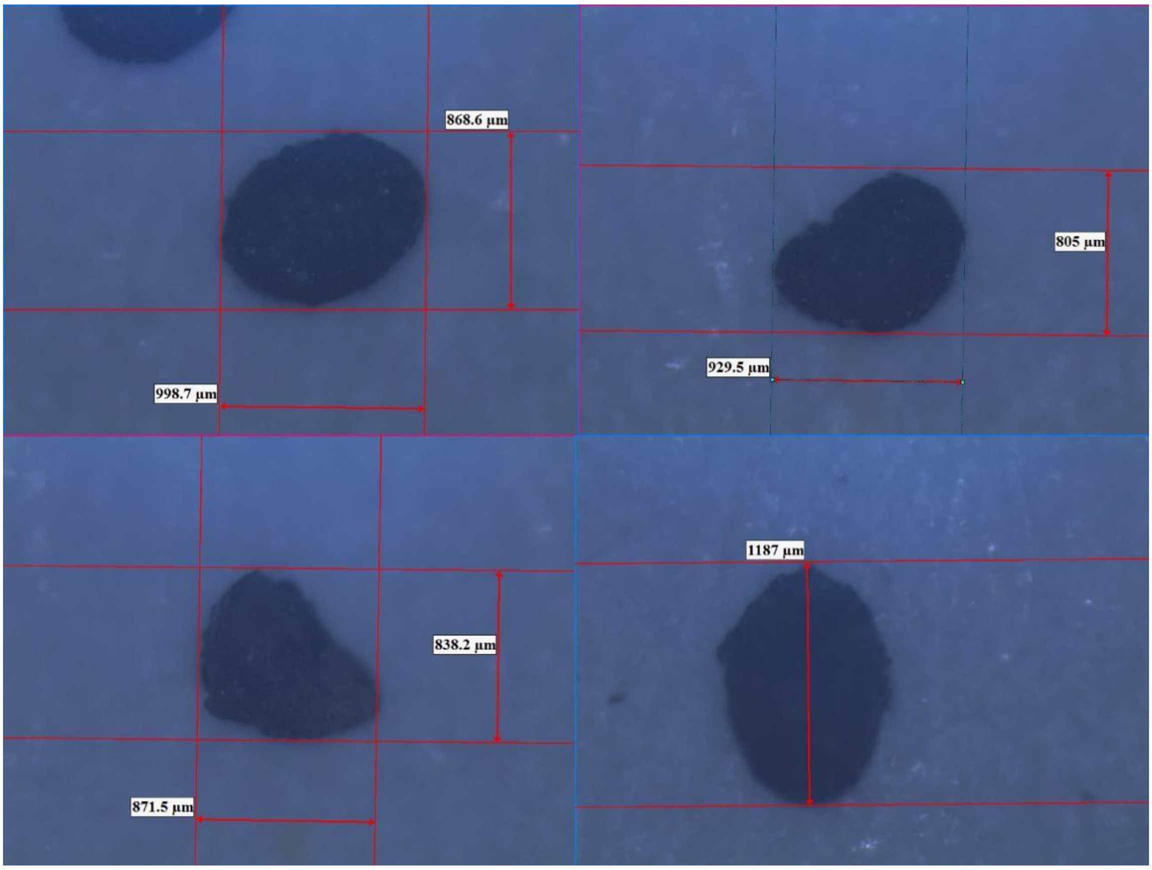

Fig 27. Sand grain examples after experiment and dimensions

3.4. Analysis

The comparison between the results of the experiments is given in Table 6. The method of how the values of fracture and Young's moduli, as well as the UCS, are found is explained in figure 6. The value of the fracture modulus is evaluated as the slope of the initial increment of the graph where the stress is applied in order to close the crack (the interval between the circle and triangle). The Young's Modulus is estimated from the graphs as the slope of the elastic region, which ends at the value of yield stress point (the interval between triangle and square). The ultimate confined stress (UCS) is labeled with a star on the plot, the maximum stress the sample can withstand without failure.

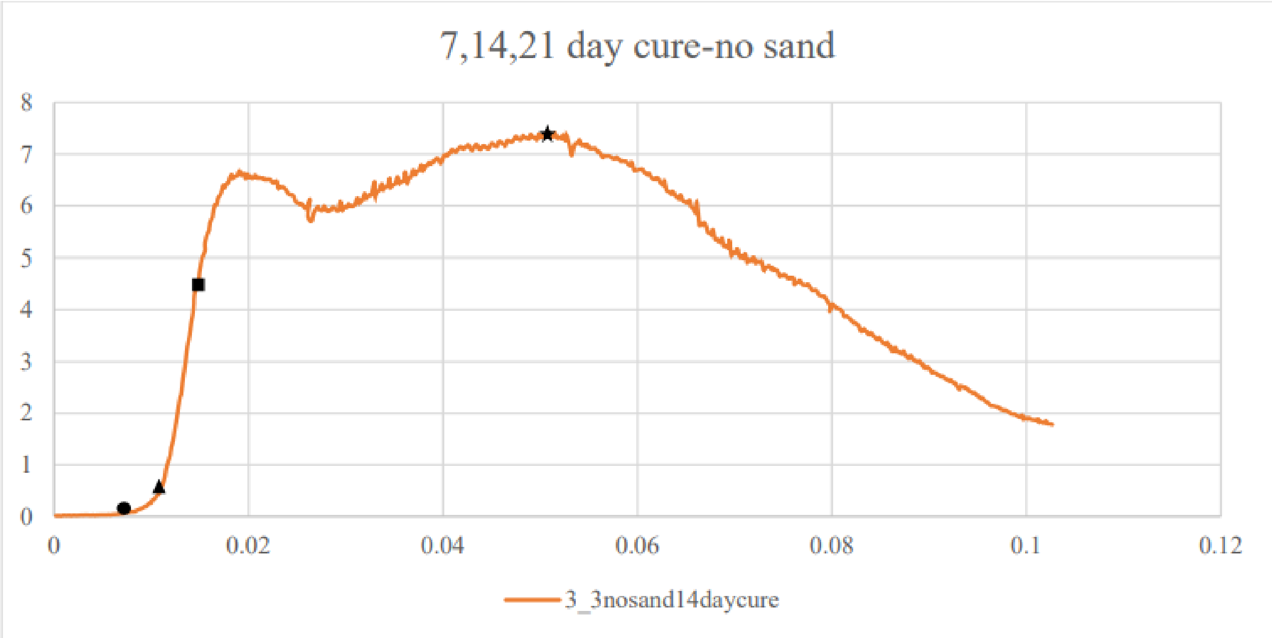

Fig 28. Mechanical properties of the cube sample explained on the graph

The certain trend can be observed for ceramic proppants. With increasing density, the mechanical properties such as fracture and elasticity moduli and UCS also increase.

Table 7. Mechanical properties of the cube sample filled with different propping agents

	Density	Fracture modulus of elasticity	Young's Modulus	UCS
No sand	-	145	1266	10.8
Silica sand	2.60	179	1206	9.2
Low density	1.60	130	1099	9.03
Medium density	1.85	199	1277	11.7
High density	2.00	108	1668	16.5

3.5. Errors and inaccuracies

There are various sources of errors that could lead to the inaccurate data obtained at the end of the results. The main error is due to the inconsistent mixture proportion. As the mechanical scales balance is not precise the electronic scale use is more considerable for accurate data acquisition. The other errors occurred due to the unfinished surface. When the top ram of the uniaxial test machine has not been properly set on top of the sample (it could be partly on top of the sample as the surface could be slightly inclined) this could lead to discrepancies in displacement data, thus, the strain values in the beginning of tests might slightly be inaccurate. Negligibly different shapes of the cubes and different heights of the cylinders could also cause some errors, but these values are marginal in comparison with ones previously mentioned. Manual mixing of cement could lead to some inconsistency of samples. All the errors discussed above can be applied both the cube and two cylinders experiment.

The other error source in two cylinders experiment (not applicable to the cube experiment) is the high confined conditions. Once the concrete cylinder is removed from the mold after being cast it is hard to fit it back into it for compression experiment (as the same mold is used as a sleeve for experiment with Instron). First experiments are done with screwed molds and this could prevent the cylinders from moving freely within the sleeve. However, it is later decided not to screw the mold parts together in order to allow the samples to move freely, hence it could have distorted the data of some experiments in the beginning.

The summary of the errors and the required actions which need to be undertaken in order to avoid these problems in the future are presented below:

- Unfinished surface - to rasp or file tool should be used to polish the surface

- Different mixture proportions - to be consistent with the mixture and use electronic scale
- Slightly different shapes - to be attentive during the cement pouring (marginal)
- High confinement - follow consistency in experiments, unscrew the mold parts
- Manual mixing - use of mixer is preferable

Conclusion

Experiments have been carried out with the intention of obtaining the optimal balance between the quality and quantity of the propping agent. Specifications of various types of proppants such as their strength and quantity are determined during two different experimental procedures. The first set of experiments was testing the propping agent in a V-shaped notch in the cube-shaped concrete samples. For these purposes, corresponding cube specimens have been cast in the molds and later are tested in the uniaxial test machine until their breakdown. The results that have been obtained at the end of the experiment, are presented in the Results and Analysis section in the graph form and communicate a clear picture of proppant density and strength correlation. With increasing the density, greater stress is applied on the cubic-shaped samples.

For two stack-on cylindrical sample experiment, the similar procedure has been performed. A thin layer of proppant is tested between two cylindrical samples. The cylindrical mould in which concrete cylinders are initially cast is used in order to keep the structure of two cylinders and proppant stable, preventing it from sliding and proppant from falling. Results from this experiment can also be found in the Results and Analysis section.

After the proppant grains are examined under the microscope, it was observed that some of the particles have changed their shapes. The particles became more ellipsoid and elongated.

Finally, the table with the comparative results of different moduli and strengths has been presented in Analysis section. The certain trend can be noticed on this table, thus approving the above - mentioned statement about the increase of the applied force with increasing density. In the real-life situation, it can be insinuated as the higher density proppant is more effective for the high-pressure conditions, where the usage of low density proppant is not sufficient enough. The error sources are listed in errors and inaccuracies section and further recommendation is given as well, afterwards.

The experiment can be improved in the future with adjustment of concrete strength to strength of shale formations, in order to simulate the real-life conditions.

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Appendix: Lab risk assessment

What are the hazards?	Who might be harmed and how?	What are you already doing?	Do you need to do anything else to manage this risk?	Action by whom?	Action by when?	Done
Handling cement, plaster of Paris and fine sand	*Staff & students working in the lab* Cement and plaster of Paris can harm lungs, eyes and skin, fine sand can irritate.	Students wear protecting dust mask, safety googles and gloves. Reactions are exothermic – ensure reacting material does not make contact with skin, if reacting material lands on gloves remove gloves and clean/replace before proceeding further.	Keep work area tidy, clean and dry.	Students	Before and after the lab session	
Use of cement mixer	*Staff & students working in the lab* Hair, jewellery and clothing might get entrapped within the concrete mixer moving parts The students might injure themselves by electric shock due to poorly isolated or damaged wires and conductors.	Operators to remove all the jewellery, tie back long hair and tuck in loose clothing before operating equipment. Check power cables are in a good condition and protected from rotating parts before use. Keep hands clean and dry when operating equipment. Ensure floor is clean and dry before switching on. Wear rubber soled shoes/boots.	All the students are to be trained by one of the technicians before the lab session on how to use the concrete mixer. The saw will not be used – all samples will be cast. Ensure all the cables are kept away from abrasion	Students	Before the lab session	
Carrying samples and equipment	*Staff & students working in the lab* Students can be injured by strike of moving parts and fall of heavy objects	Safety shoes and hard hat are worn to protect against the heavy objects in the workshop. Check the route is clear and free from slip or trip hazards before commencing transportation.	Keep the work area clean and tidy and dry.	Students	Before the lab session	

What are the hazards?	Who might be harmed and how?	What are you already doing?	Do you need to do anything else to manage this risk?	Action by whom?	Action by when?	Done
Electrical Shock	Students, by using damaged wires	Check for frayed and damaged cables before use	-	Students	Before the lab procedure	
Moving Parts	Students, by leaving long hair and clothes exposed	Tie back the long hair and tuck in loose clothing	-	Students	Before the lab procedure	
Crush Risk	Students, by not using protective equipment	Use safety boots	-	Students	Before the lab procedure	
Flying Debris	Students, by not wearing safety goggles	Use safety glasses	-	Students	Before the lab procedure	
Slips, trips and falls	Students, might fall on slippery floor	Check for spills in working area. Wipe up the floor in the case of hazard	-	Students	Before and during the lab procedure	
Inhalation and cement dust	Students, dust inhalation	Wear protective mask	-	Students	Before the lab procedure	
Noise	Students, by not plugging the ears	Use the ear plugs	-	Students	Before and during the the lab procedure	