

# **Numerical Investigation of Nanoparticle-based Breakers Suitable for Removing Synthetic Filter Cakes**

By

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## **Originality Statement**

I, Timur Tasmukhanov, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgment is made in the thesis.

Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation, and linguistic expression is acknowledged.

Signed on 15.04.2023

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## Abstract

Filter cake formation is an integral part of the drilling process and provides wellbore stability and eliminates mud circulation loss. As drilling fluid containing solids is pumped under high pressure solid particles tend to deposit on wellbore surface forming an impermeable layer between the well and the reservoir. However, it causes a detrimental effect on production. In order to restore the initial permeability, engineers apply chemical treatment to dissolve the filter cake. Acids, oxidizers and chelating agents are usually used for such purpose. The use of conventional techniques may not be feasible in certain instances due to factors such as expensive chemicals, compatibility problems, and environmental considerations. Nano-breakers have drawn much attention in research community as an alternative to conventional methods. Due to unique properties such as small size (nanoscale) and high surface area nanoparticles show high penetration rate and filter cake removal efficiency. This study aims to estimate the efficiency of two nanoparticle-based breakers, namely silica and titanium dioxide, using numerical simulation by studying the size distribution and return permeability. The 500 datasets for the numerical simulation were synthesized from a laboratory data. This synthetic data was governed by Darcy equation to investigate the flow of nanoparticle-based filter cake breakers through ceramic disc. Moreover, the statistical analysis was conducted to predict the return permeability after nano-breaker treatment using MATLAB Machine Learning toolbox. The prediction accuracy of two statistical methods, namely Multiple Linear Regression and Artificial Neural Network, were compared in terms of coefficient of determination ( $R^2$ ). Artificial Neural Network modeling showed a better fitting with synthetic dataset with  $R^2 = 0.99$  compared to Multiple Linear Regression analysis, which obtained  $R^2$  of 0.82. Additionally, the results of the current study were compared with literature. It was however observed that the optimum return permeability of 46% was reached at 361<sup>st</sup> iteration which corresponded to the pressure of 21 psi and 6 ml/hr flowrate. Overall, return permeability prediction and optimization is best with ANN ( $R^2 = 0.99$ ) and pressure

value of 21 psi respectively. Extension of the return permeability study could consider the formation damage before and after nano-based breaker treatment.

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## **1. Introduction**

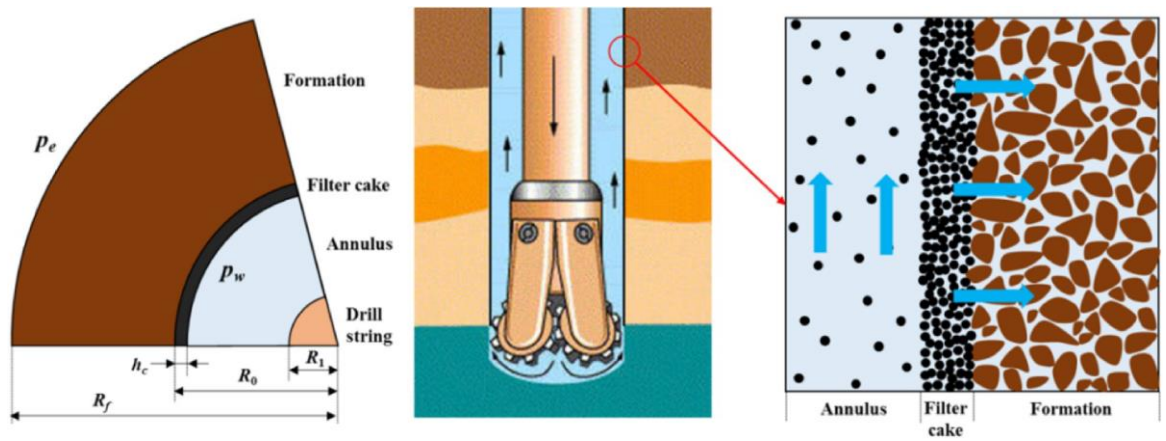
### **1.1 Background**

Drilling fluids, also known as drilling mud, are an essential component of the drilling process in the oil and gas industry. These fluids are used to lubricate and cool the drill bit, maintain pressure in the wellbore, and carry cuttings to the surface. They are critical for the success of drilling operations, as they help to ensure the stability of the wellbore and prevent formation damage. There are several types of drilling fluids, each with its own specific properties and advantages: gaseous, aqueous (water-based) and nonaqueous (oil-based). The selection of the appropriate fluid for a particular drilling operation is a crucial decision. In this context, it is essential to understand the characteristics and behavior of drilling fluids, including their rheological properties, density, and chemical composition.

In drilling operations, filter cakes refer to the layer of solids that are deposited on the surface of the wellbore during the drilling process (Fig. 1). This layer is created as drilling mud flows through the formation and carries the cuttings and other debris generated by the drill bit with it. The filter cake serves as a barrier between the drilling fluid and the formation.

The thickness and properties of the filter cake can vary depending on the drilling conditions, the properties of the drilling mud, and the characteristics of the formation being drilled. The filter cake must be managed carefully to optimize drilling and production operations as it helps to prevent the loss of drilling fluid into the formation and the invasion of formation fluids into the wellbore. If the filter cake is too thin, it may not be effective at preventing fluid invasion, whereas if it is too thick, it can impede the flow of oil or gas into the wellbore during production.

In addition, the properties of the filter cake can affect the efficiency of the drilling operation. The filter cake must be able to withstand the pressure of the drilling fluid, and it should be able to maintain its integrity even in the presence of formation fluids. The formation of an effective filter cake can also help to reduce the risk of wellbore instability and formation damage.



**Fig. 1.** Filter cake formation during drilling (Ma et al., 2020)

The use of nanoparticles (NPs) to remove filter cake is an emerging technology in the petroleum industry. Nanoparticles, which are particles with sizes between 1 and 100 nanometers, have unique properties such as high surface area, high reactivity, and unique surface chemistry, which make them promising candidates for removing filter cakes from wellbores.

Studies have shown that nanoparticles can effectively penetrate and break down filter cakes, resulting in improved wellbore cleanup and enhanced well productivity. For example, in a study made by (Prakash et al., 2021), researchers tested the effectiveness of silica nanoparticles in removing filter cake from a wellbore. They found that the nanoparticles were able to reduce its thickness by up to 49% compared to drilling fluid with no additives. Similarly, Cheraghian et al. (2013) investigated the use of titanium dioxide nanoparticles to remove filter cake from a wellbore. The authors found that the nanoparticles were effective in upgrading drilling fluid performance and improving the recovery factor.

Nanoparticles can be used in a variety of ways to remove filter cake from wellbores, including as additives to drilling fluids, as pre-flush or post-flush treatments, or as standalone treatments. The selection of the appropriate nanoparticle and treatment strategy depends on the specific properties of the filter cake, the drilling conditions, and the objectives of the wellbore cleanup.

## **1.2 Problem Statement**

The removal of filter cakes from the wellbore has been a long-standing issue in the drilling, with numerous attempts to find effective and cost-efficient solutions. Existing solutions, such as acidizing or application of oxidizers, seem to be expensive and difficult to formulate and analyze. In some cases, the application of traditional methods is not possible due to high cost of chemicals, compatibility issues and environmental concerns. One novel approach introduced in the literature is the use of nanoparticle-based breakers. However, there are not many studies related to numerical analysis estimating the flow of nanoparticle-based breakers. Therefore, this thesis answers to following questions: how effective are nanoparticle-based breakers in removing synthetic filter cakes from the wellbore and what is the best way to optimize their flow using numerical analysis?

## **1.3 Aims and Objectives**

The research focuses on using numerical analysis to validate the empirical results and to optimize decision-making in terms of application of nanoparticle-based breakers. To achieve the main goal of this work, the following sub-objectives have to be met:

- To predict return permeability using artificial neural network (ANN) and multiple linear regression (MLR) and compare the results.
- To estimate the effect of pressure and flow rate on return permeability.

## **1.4 Thesis Structure**

The structure of thesis includes five chapters with first chapter introducing the background to the topic, the problem statement and aims and objectives of the research. Chapter 2 presents the literature review in mechanisms of filter cake formation and methods of filter cake removal. The materials, experimental setup and methodology used to achieve the objectives of the research are developed in Chapter 3. Numerical simulation results are shown and discussed in Chapter 4. Finally, Chapter 5 highlights the main findings of thesis and provides recommendations for further research.

## **2. Literature Review**

### **2.1 Synthetic Drilling Muds**

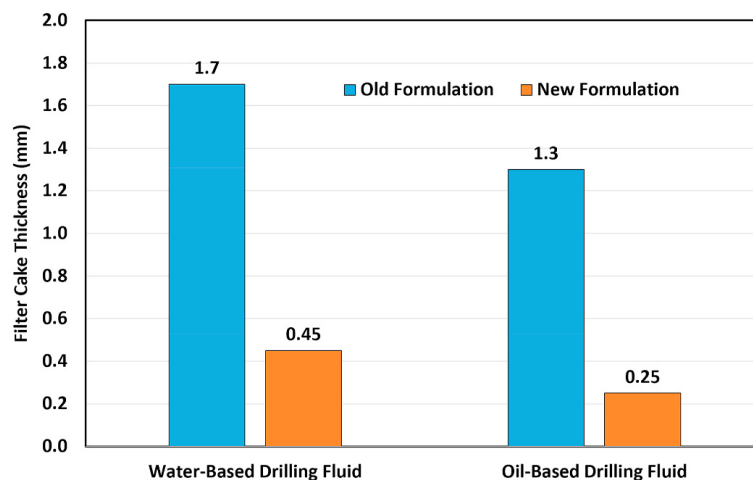
Unlike traditional drilling mud, synthetic-based mud (SBM) is typically made synthetic base fluids including esters, olefins, and other synthetic hydrocarbons or from water with clays and polymeric additives. Synthetic drilling mud offers several advantages over traditional drilling mud, including better thermal stability, reduced toxicity, and improved lubricity. These properties make it particularly well-suited for use in deepwater and high-temperature drilling operations, where traditional muds may break down or become less effective.

Despite these benefits, synthetic drilling mud can be more expensive than traditional muds and may require specialized equipment and expertise to handle. As such, its use is typically reserved for more challenging drilling operations where its unique properties can provide significant benefits (i.e., in shale drilling). Rana & Saleh (2022) investigated the inhibition effect of polymer-modified activated carbon (AC-PAD) in water-based drilling mud. According to FTIR and TGA analysis, AC-PAD caused plugging of nanopores in shale structure and hydrophobization of shale surface. The results of immersion test showed that mud ball dived in AC-PAD solution had lower dispersion and saved its initial form compared to the mud ball placed in in the water. Application of AC-PAD allowed to reduce clay swelling by 50% and 23% compared to water and water-based mud with no additive.

Paul & Adewale (2018) developed a new type of drilling fluid based on canola oil. The researchers used enzymatic interesterification to modify the fatty acid composition of canola oil, resulting in improved physical and rheological properties that make it suitable for use as a drilling fluid. According to results, interesterification reduced the viscosity and density of canola oil to fit SBM standards. FTIR analysis detected no presence of aromatics in the newly synthesized drilling fluid making it environmentally friendly. Another group of researchers (Yusof & Hanafi, 2015) estimated the impact of silica nanoparticles on SBM rheological properties and filtration process. Increasing nanoparticle concentration yielded in lower viscosity and higher gel strength compared

to SBM without nanoparticles. Furthermore, HPHT filtration experiments showed that addition of nanoparticles resulted in lesser filtration lose and thinner filter cake due to low size nanoparticles tending to plug the pores. Overall, nanoparticle-based mud had a good efficiency in HPHT conditions.

Many researchers studied the removal of barite filter cakes as barite is the most common additive in drilling fluids. Tariq et al. (2021) suggested a new formulation of water-based and oil-based drilling fluids to remove barite filter cake. According to methodology of this study, sodium nitrite ( $\text{NaNO}_2$ ) and ammonium chloride ( $\text{NH}_4\text{Cl}$ ) thermochemical fluids (TCF) were added to conventional drilling muds in encapsulated form. The micro-reactor system was preheated to  $100^\circ\text{C}$ , which caused the thermochemical reaction to occur. The start of the reaction was determined by the jump in pressure and temperature values during the stability test. The results also revealed that TCF had no effect on rheological properties of drilling fluids making TCF a good candidate as additive. Overall, new formulation of drilling fluids yielded in 70% and 80% filter cake thickness reduction for water-based and oil-based muds respectively (Fig. 2). Oil dissolution was considered as the determining factor in greater removal efficiency of oil-based mud compared to water-based. Researchers expected high efficiency in field conditions due to greater reservoir pressures and temperatures than used in the experiments.



**Fig. 2.** Filter cake thickness after filtration of conventional (old) and new formulation of drilling fluids (Tariq et al., 2021)

Similar to Tariq et al. (2021), Rostami & Nasr-El-Din (2010) investigated the self-destruction of filter cake formed by water-based drilling fluid. In this study, Polylactic acid (PLA) was used as acid lactic acid precursor. Firstly, PLA was added to water-based drilling fluid with suspended calcite particles. Due to chemical reaction between PLA and water, lactic acid was generated. Then lactic acid dissolved calcite particles which mainly made up the filter cake. The researchers estimated the effect of temperature, soaking time and particle size on filtration loss and filter cake removal. Filter cake removal efficiency increased with temperature, however, the temperature rise also caused thickening of drilling fluid due to enhanced hydrolysis reaction of PLA and subsequent dehydration of the mud. Furthermore, soaking tests showed that PLA required considerable time (20 hours) to remove 80% of the filter cake. The authors also noted that high concentrations of calcium carbonate were found in solutions containing  $\text{CaCO}_3$  particles of lower size, which evidenced the higher dissolution of those particles by lactic acid.

Mahmoud & Elkatatny (2019) proposed a single- and multistage treatment to remove barite scale and filter cake using converters and catalysts. Normally, barite is insoluble in water and acids and can dissolve to some extent in chelating agents such as EDTA (Mahmoud & Elkatatny, 2019). In this study,  $\text{K}_2\text{CO}_3$  converter was used to transform barite ( $\text{BaSO}_4$ ) into  $\text{BaCO}_3$ . The conversion was possible only in high pH environment provided by KOH catalyst. After conversion, the newly formed  $\text{BaCO}_3$  could be dissolved by either HCl or EDTA. However, authors advised rather to use EDTA than HCl due to toxicity of HCl reaction byproducts. During single stage barite removal EDTA served as both catalyst making high pH and acid dissolving  $\text{BaCO}_3$ . The results showed that barite solubility in EDTA was temperature dependent and additionally increased in combination with potassium carbonate ( $\text{K}_2\text{CO}_3$ ). Additionally, the composition of the drilling fluid in the experiments depended on the type of base fluid, as the water-based fluid contained a polymer breaker to wash out polymer coating of barite, when oil-based fluid included oil solvents and water-wetting surfactant. Another application of EDTA was reported in earlier studies by Shaughnessy & Kline (1983), where EDTA was applied to remove calcium carbonate scale in the

wells. According to results, EDTA demonstrated good efficiency in dissolving and chelating the calcium ions, which positively affected the productivity of wells.

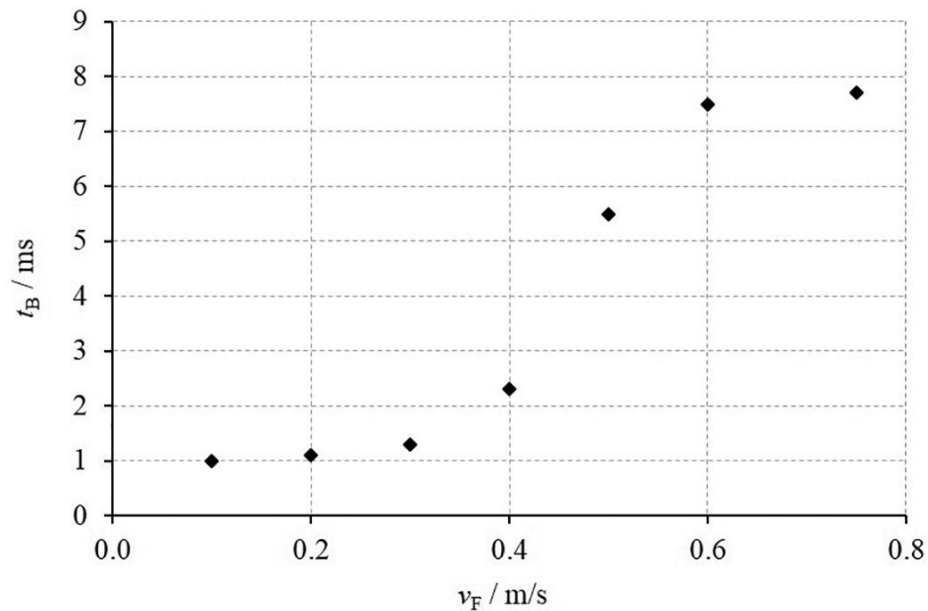
In high-pressure vertical wells, wellbore cleaning is possible by natural flow back, whereas horizontal wells with low pressure require cleanup treatments (Al-Ibrahim et al., 2015). However, using reactive inorganic acids and oxidizers during treatments may cause the formation damage, leading to a search for slower-acting chemicals like acid precursors, enzymes, and chelating agents. Al-Ibrahim et al. (2015) tested two chelating agents, namely NTA and EDTA, in removing filter cake formed by oil-based mud. The experiments were conducted in HPHT cell to simulate reservoir conditions. Compatibility test showed that both chemicals were compatible with formation oil. However, NTA appeared to be incompatible with mud brine according to number of precipitates in the solution. Similarly, EDTA formed a miscible mixture with formation water containing precipitates. Filter cake removal efficiency of NTA and EDTA strongly depended on soaking time. The results showed that NTA reached 90% removal efficiency in 24 hours, while it took 90 hours for EDTA to achieve such result.

## **2.2 Filter Cake Formation**

Filter cake formation is a common phenomenon that occurs during filtration process. When a fluid containing suspended particles or contaminants is passed through a porous medium, the particles can accumulate on the surface of the medium, forming a layer of material known as the filter cake. This cake layer acts as a physical barrier between wellbore and reservoir fluids.

The formation of filter cake can be influenced by various factors, including the properties of the fluid being filtered, the characteristics of the filter medium, the flow rate, and the pressure applied during the filtration process. Piroozian et al. (2012) investigated the influence of drilling fluid viscosity, velocity and hole inclination on drilling fluid performance. Researchers found that the highest number of cuttings was recovered at high velocities and high viscosity. However, the increase of viscosity under constant flow velocity and well inclination led to change of flow regime from turbulent to laminar, which negatively affects the ability of mud to carry out the cuttings.

Alternatively, Hund et al. (2020) used numerical simulation to study the influence of suspension concentration and inlet flow velocity on the bridging time and resistance of a filter medium. Increasing suspension concentration caused faster bridging due to an increased particle flow rate. Moreover, the effect of inlet flow velocity on bridging time at constant particle flow rate was studied. Until flow velocity value of 0.3 m/s was reached, bridging time increased slowly due to insufficient flow resistance, then rose rapidly due to hindrance caused by high flow velocities (Fig. 3). The inlet velocity also had effect on the interference factor and porosity of filter cake. The filter cake formed at high filtration velocities ( $> 0.6$  m/s) yielded tighter particle packing and lower porosity of the formed cake resulting in increase of the specific filter cake resistance.



**Fig. 3.** Bridging time  $t_B$  depending on the inlet flow velocity  $v_F$  for constant particle flow rate (Hund et al., 2020)

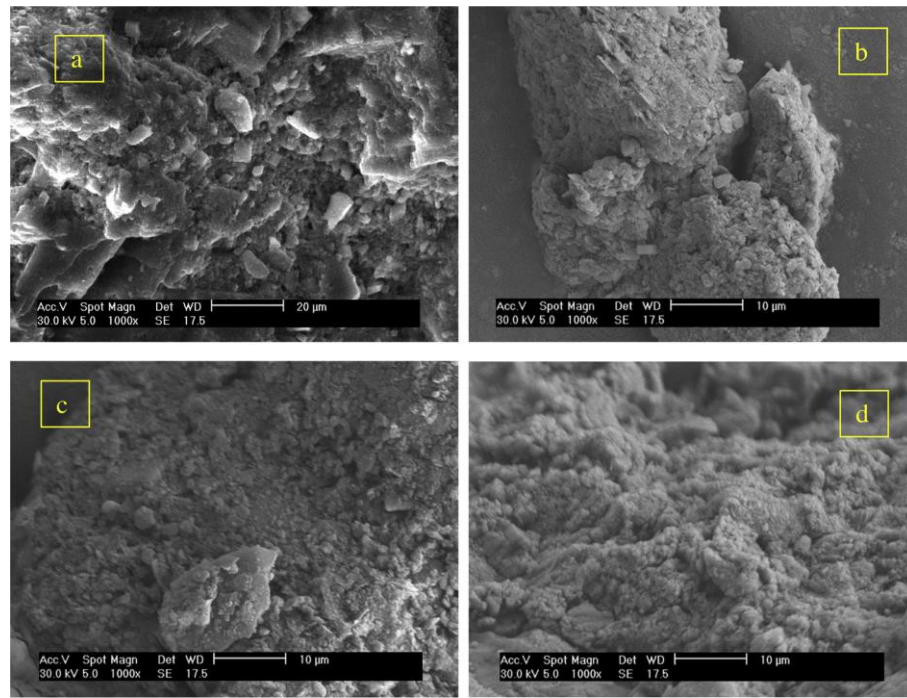
Ofei et al. (2021) analyzed the effect of drilling fluid density on barite sag formation. The density of drilling fluid was varied by different barite concentrations. The results showed that the increase of barite concentration led to increase of viscosity. However, when two drilling fluids with equal barite concentration were compared, it was noted that the fluid containing sieved barite particles yielded in lower viscosity compared to the same with coarse particles. Moreover,

sedimentation of barite occurred faster in fluids with low barite concentration. All samples followed the same destabilization kinetics with top section of the fluids being more prone to destabilization than the bottom part.

Usually, researchers assume the size distribution of solids suspended in drilling fluids to be uniform, which is not common in real cases. Ma et al. (2020) studied the impact of normal and logarithmic distribution with varying standard deviation on the mud cake formation. The lower was the mean value of particle size the thicker filter cake was formed. Furthermore, filter cake formed faster with standard deviation increasing. In addition, the influence of formation permeability was also estimated. The authors' findings demonstrated that filter cake formation process is extremely sensitive in low-permeable formation as rapid changes in filter cake thickness and filtrate invasion were observed.

### **2.3 Nanoparticle-based Breakers**

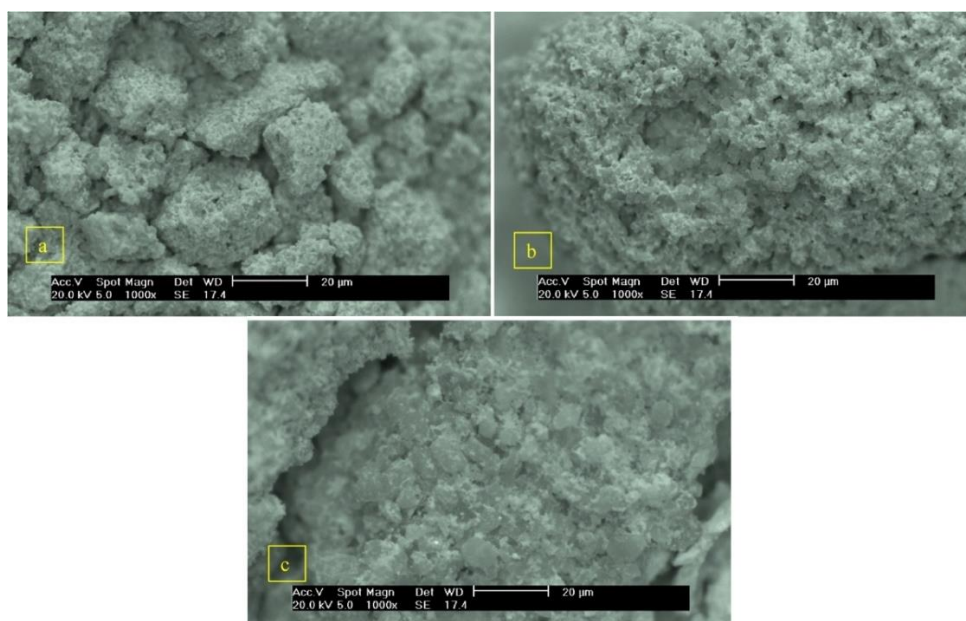
One of the potential applications of nanoparticles in drilling fluids is to avoid clay swelling caused by drilling mud during shale production. Bayat & Shams (2019) evaluated the effect of titanium oxide, silica and zinc oxide nanoparticles on rheological properties of water-based temperatures at two temperatures. All three nanoparticles slightly increased the plastic viscosity of base fluid having  $\text{TiO}_2$  and  $\text{ZnO}$  as major influencers of viscosity increase at low and high temperatures respectively. Similarly,  $\text{TiO}_2$  and  $\text{ZnO}$  demonstrated lower value of filtration loss compared to silica. However,  $\text{SiO}_2$  showed better efficiency in increasing yield point at low temperature. The key point in effect of nanoparticles on filtration was their distribution in filter cakes. As can be seen in Fig. 4, the surface of the cake formulated by base mud had irregular dents and bumps, while nanoparticles brought smooth and less rough surface. Moreover, researchers observed that all three nanoparticles positively affected on shale recovery resulting in up to 49% value. The higher was concentration of nanoparticles, the higher recovery was achieved.



**Fig. 4.** SEM images of the filter cakes formed after filtration test from four different mud samples: a-base mud, b-mud with 0.1 wt% TiO<sub>2</sub> NPs, c-mud with 0.1 wt% SiO<sub>2</sub> NPs, d-mud with 0.1 wt% ZnO NPs (Bayat & Shams, 2019)

Similarly, the performance of graphene oxide (GO) nanoparticles in water-based drilling fluids was explored by Kosynkin et al. (2012). The results showed that stability of GO in seawater was increased by methylating making the mud applicable in fresh-water and brine. The GO used in this study was synthesized from the mixture of large-flake and powder GO, which demonstrated lower filtration loss and thinner layer of filter cake compared to bentonite-polymer based mud. Alternatively, GO nanoparticles could be used as shale inhibitors. Wang et al. (2020) conducted a comparative study with GO, silica nanoparticles and conventional inhibitors. Linear swelling and imbibition tests demonstrated that GO solution significantly decreased the swelling of clay material and filtrate invasion. This was explained by the unique structure of GO sheets, which deformed under the pressure to fit in nanosized pores of shale and formed the durable filter cake. In addition, uniaxial shale compression experiments revealed that shale compressive strength of core immersed in GO solution slightly differed from the dry core value, which was in agreement with previous test results.

In further research, Bayat et al. (2021) compared the performance of polymeric water-based mud in presence of SiO<sub>2</sub> and TiO<sub>2</sub> nanoparticles. The researchers found that both silica and titanium nanoparticles decreased plastic viscosity and upgraded gel strength of the base mud at three temperatures. However, TiO<sub>2</sub> nanoparticles reduced plastic viscosity in larger extent than SiO<sub>2</sub>, while SiO<sub>2</sub> yielded in higher gel strength. Moreover, lower filtration loss was observed in drilling fluid with SiO<sub>2</sub> nanoparticles and, hence, tighter filter cake was formed in that case. The pore clogging by nanoparticles in mud cake was also proved by SEM images, where filter cake surface treated by nanoparticles had smoother surface. (Fig. 5 b, c). The same mechanism was identified in research of Beg et al. (2020) where titanium dioxide nanoparticles were added to polymer-based drilling fluid. The findings of this study revealed that TiO<sub>2</sub> nanoparticles provide thermal stability to PAC and HEC polymers in the drilling fluid and preserved the rheological and filtration properties of the mud from thermal degradation.



**Fig. 5.** SEM images of filter cake before and after treatment: a – base mud, b – mud with 0.1% wt. TiO<sub>2</sub> nanoparticles, c – mud with 0.1% wt. SiO<sub>2</sub> nanoparticles (Bayat et al., 2021)

Nanoparticle dispersions were also successfully used to remove filter cakes formed by polymers and paraffins (Mcelfresh et al., 2012). Due to their small size nanoparticles tended to

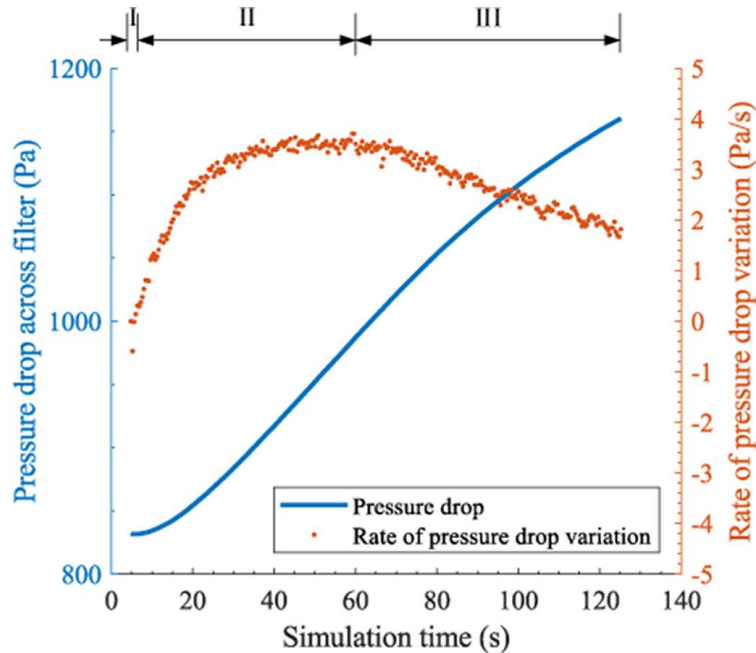
squeeze between organic solid particles and push them into liquid phase. This phenomenon was explained by disjoining pressure and electrostatic repulsion forces. The researchers also mentioned that surface modification enhanced the filter cake removal efficiency and the stability of nanodispersions.

## **2.4 Numerical Simulation**

Many researchers studied the mechanisms of filter cake formation using numerical simulation methods, such as computational fluid dynamics (CFD) and discrete element method (DEM). Zhang et al. (2019) introduced combination of CFD-DEM approach to study the mechanism of slurry infiltration and filter cake formation processes. The researchers considered solid phase (slurry particles) as discrete particles and Newtonian fluid (water) as liquid phase. The properties and performance of filter cake were found to be affected by the applied pressure, friction coefficient, and cohesion energy density. When the applied pressure was higher, the filter cake became more compressed, resulting in a larger pressure drop. However, the cake porosity and pressure drop changed slightly when the applied pressure reached certain value (70 kPa). Having the friction coefficient less than 1, the porosity of cake rose considerably, while the pressure drop declined as the friction coefficient increased.

Similarly, Liu et al. (2019) used CFD simulation to identify three stages of pressure drop variation in a ceramic candle filter (Fig. 6). In the first stage, when particles were firstly added into flow some negative pressure drop rates were observed. The second stage occurring between 8 and 60 seconds showed a rapid increase in pressure drop due to more deposition dust in the less dust loading area with low flow resistance. As radial velocity dropped close to the ceramic candle surface in the third stage, the increase rate of the pressure drop gradually slowed down. After the simulation time exceeded 60 seconds, a relatively uniform dust cake layer formed in the center of the filter candle. Additionally, this study analyzed the dust cake distribution of the front-end and back-end filter candles, revealing the formation of less-particle-deposition-zones (LPDZs) at the lower portions of candles. The specific parameter called the radius of convergence ( $R_c$ ) was used

to explain the formation of LPDZs. Particles did not adhere to the candle surface when the distance between the candle center and the particles exceeded  $R_c$ , and the deposition density on the candle's lee side was significantly lower than on its windward side.



**Fig. 6.** Pressure drop and rate of pressure drop variation by time (Liu et al., 2019)

Numerous research papers considered the effect of size and shape of the particles suspended in drilling mud. For instance, Deshpande et al. (2020) utilized DEM-CFD coupling to simulate the behavior of non-spherical particles in sedimentation and filtration processes. The simulation results were compared to experimental data and showed that the method could predict not only particle velocity but also orientation. The simulations also demonstrated that the void fraction of filter cakes increased with decreasing sphericity and decreasing coefficient of sliding friction. The pressure gradient across a filter cake was found to depend on both void fraction and sphericity, and the study demonstrated the complex interdependence of these factors. In addition, filter cake consolidation increased with sphericity decreasing. In earlier research, Kabir & Gamwo (2011) used CFD to study the filter cake formation process with 45  $\mu\text{m}$  and 7  $\mu\text{m}$  at shallows and deep drilling conditions. The results showed that filter cakes formed in upper part of the wellbore

are thicker than in the bottom due to large vortices in the bottom region. Moreover, vortices caused a non-uniform distribution of solid particles forming filter cake. The study also showed that thick filter cake is formed by larger particles at high pressure due to compaction of particles in filter cake structure.

Rabbani & Salehi (2017) used numerical simulation to model mud cake formation in sandstone and predict the formation damage. It was noted that the higher was porosity of the sandstone sample, the wider pores in the filter cake were formed. Also, more filtration loss and thicker filter cake were observed in high permeable formations. After 30 min filtration test, Michigan sandstone, which had the highest permeability among four core samples, showed sharp increase in filter cake thickness with further potential of thickness growth. The results of modeling were in good agreement with experimental study of Salehi et al. (2015).

Sören & Jürgen (2012) applied DEM-CFD solution to compare the structure of filter cakes generated from stable and flocculated suspensions. When attractive forces dominated, flocculation occurred, resulting in a loose packing of filter cake with high compressibility and increased porosity. This led to a 43% decrease in filtration time compared to stable suspensions. The permeability of flocculated suspensions was 10 times higher than the same of stable suspensions, which was explained by high compressibility of the former.

Jeirani & Mohebbi (2006) predicted filtration properties of drilling fluid, namely filtrate volume and mud cake permeability, using Artificial Neural Network modeling (ANN) in MATLAB. 154 datasets were used to train the model, while the rest 51 datapoints were tested by the model. The design of ANN model included 4 inputs and 2 outputs such as filtrate volume and mud cake permeability processed by one hidden layer with 30 neurons. The  $R^2$  value during testing was 0.94 for permeability, which proves good performance of applied method. In addition, the ANN showed better fitting with actual experimental data compared to empirical correlation-based results.

### 3. Methodology

#### 3.1 Modeling parameters

Permeability is ability of a material or medium to allow the flow of a substance, such as a fluid or gas, through its pores or interstices. Henry Darcy firstly developed the rock permeability equation, which became the basic concept for fluid flow in the porous media. In this study, the permeability was calculated using Darcy equation (1).

$$Q = \frac{KA \Delta P}{\mu L} \quad (1)$$

where K is the permeability of the media (ceramic disc), mD

Q is flow rate, cm<sup>3</sup>/sec

$\mu$  is fluid viscosity, cP

A is cross-sectional area, cm<sup>2</sup>

$\Delta P$  is the differential pressure, psi

L is thickness of ceramic disc with filter cake, cm.

In terms of permeability, the equation (1) can be rearranged to:

$$K = \frac{Q\mu L}{\Delta P A} \quad (2)$$

The typical view of filter cake is presented in Fig. 7.



**Fig. 7.** Ceramic disc with formulated filter cake (Rostami & Nasr-El-Din, 2010)

Finally, the return permeability after nanofluid breaker treatment was predicted using numerical modeling.

### 3.2 Experimental setup

In Wayo (2022) experiments, four breaker solutions containing EDTA, silica, titanium and graphene oxide nanoparticles were tested to remove synthetic filter cake from ceramic disc. Firstly, filter cake was formulated using OFITE HPHT filter press. Basic rheological properties of drilling fluid used in filter cake formation were determined by OFITE 900 viscosimeter. Pure ceramic disc and formulated filter cakes were further processed in soaking, infectivity and filter cake removal tests. During injectivity test, 200 ml of base oil were filtered through ceramic disc under 20 psi pressure. The filtration time and volume of filtered oil were also recorded and considered as benchmark or initial condition. Additionally, the test was repeated on eight ceramic discs with formulated cakes. The difference between actual and benchmark test results were referred as return permeability (RP).

$$RP = \frac{K_2}{K_1} \quad (3)$$

where RP is the return permeability after treatment, %

$K_1$  is the permeability of pure ceramic disc, mD

$K_2$  is the permeability of ceramic disc after filter cake treatment, mD

By measuring weights of clean ceramic disc ( $W_1$ ), ceramic disc after filter cake build up ( $W_2$ ) and after treatment ( $W_3$ ) Wayo (2022) calculated the removal efficiency (RE) of breakers:

$$RE = \frac{W_2 - W_3}{W_2 - W_1} * 100\% \quad (4)$$

### 3.3 Synthetic Data

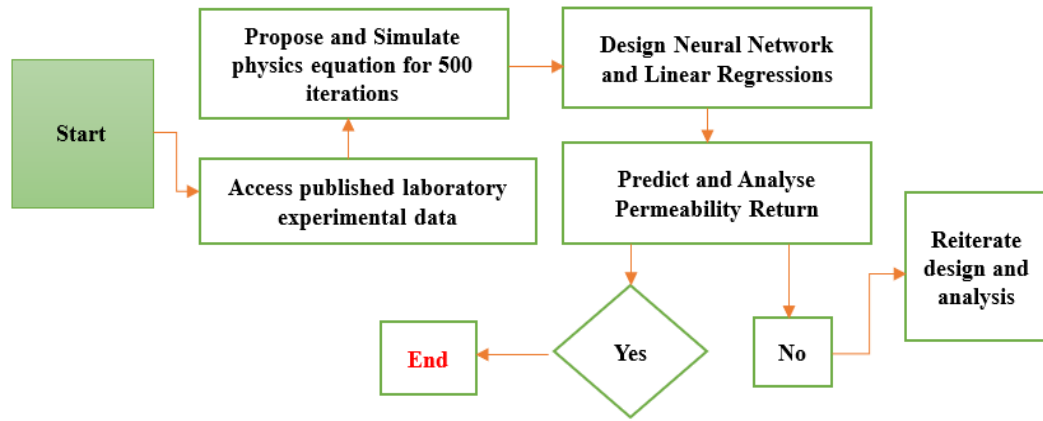
The synthetic data was generated based on the laboratory experiments conducted on silica and titanium dioxide breakers by Wayo (2022), and as shown in Table 1. Subsequent numerical computations based on fluid flow equations made emphasis on pressure, flow rate, viscosity and permeability return. It is however indicated that the permeability returns as against the existing

pressure-viscosity profiles and the viscosity of the nanofluids in question yielded an applicable result where silica and titanium dioxide after 24 hours and 42 hours of filter cake treatment obtained 49.79, 50.58% and 53.13, 51.51% respectively.

**Table 1.** Return permeability from TiO<sub>2</sub> and SiO<sub>2</sub> filter cake breakers (Wayo, 2022)

Chemical Concentration	Soaking Time, hrs	Ceramic Disc #	Weight of Ceramic Disc, W <sub>1</sub> (g)	Weight of Disc + Filter Cake, W <sub>2</sub> (g)	Weight after treatment, W <sub>3</sub> (g)	Removal Efficiency, weight %	Return Permeability, %
SiO <sub>2</sub>	24	2	41.60	71.30	55.20	54.21	49.79
TiO <sub>2</sub>		3	41.66	74.10	57.00	52.71	50.58
SiO <sub>2</sub>	42	6	41.71	72.10	51.09	69.13	53.13
TiO <sub>2</sub>		7	41.67	72.09	54.00	59.47	51.51

The physics-driven synthetic dataset consisting of 500 samples (iterations) as presented in Table 2 expounds the induced pressure for filtration, the density of nanoparticles under fluidity and permeability return based on the chemical treatment of the filter cakes. Flowrate, viscosity and pressure ranges were created based on laboratory data, while values for filter cake thickness were taken from the literature. It could be noticed that at 361<sup>st</sup> iteration, pressure at 21 psi yielded the highest return permeability (RP) of 46% and subsequently, the lowest RP was determined at the 446<sup>th</sup> iteration with 1% value at a pressure of 92 psi. Moreover, studies (Al-Yasiri et al., 2019), (Zhou et al., 2020) have shown that nanoparticle breakers increase the tendency of interacting with loose-packed filter cakes originating from synthetic-based muds because the void space of these nanoparticle breakers is smaller, and they find their way in between larger particles in the cakes under the influence of rigorous pressure. When data generation is finished, the design of neural network and linear regression analysis begins (Fig. 8).



**Fig. 8.** ANN and MLR methodology flowchart

**Table 2.** Permeability values for treated filter cakes

Iteration	Flow rate [mL/30 mins]	Viscosity [cP]	Thickness [mm]	Pressure [psi]	Final Permeability K <sub>2</sub> [mD]	Return Permeability, %
1	5	3	7	22	4188.39	20.94
2	5	5	7.2	49	3223.72	16.12
3	3	4	7.5	58	1361.74	6.81
4	6	4	7.8	74	2220.01	11.10
5	5	2	7.6	40	1667.38	8.34
6	6	4	7.6	25	6402.73	32.01
7	3	3	7.7	93	653.93	3.27
8	5	4	7.5	29	4539.14	22.70
9	6	4	7.2	43	3526.60	17.63
10	2	3	7.7	26	1559.37	7.80
11	4	4	7	65	1512.12	7.56
12	5	3	7.6	63	1587.98	7.94
13	6	3	7.4	39	2997.23	14.99
14	6	5	7.1	98	1907.37	9.54
15	2	2	7.3	69	371.38	1.86
16	5	2	7.2	79	799.81	4.00

17	4	5	7.6	45	2964.23	14.82
18	4	5	7.4	46	2823.48	14.12
19	6	5	7.2	75	2527.39	12.64
....	....					
500	6	4	7.6	98	1633.35	8.17

### 3.4 Nanoparticle Density and Size Distribution

Nanoparticles has great influence in determining filtration and rheological properties of drilling mud and this study focuses on the permeability return of the filter cakes treated by silica and titanium dioxide breakers. However, the 1.87 g/cm<sup>3</sup> density of the nanoparticles (Kimoto et al., 2017) under investigation enhances optimum fluid-particle propagation. However, the size distribution of the nanoparticles can impact the structure and properties of the resulting filter cake. If the nanoparticles have a narrow size distribution, the resulting filter cake may have a more uniform structure with fewer defects. On the other hand, if the nanoparticles have a broad size distribution, the resulting filter cake may have a more heterogeneous structure. Additionally, the size of nanoparticle can also affect the porosity and permeability of the filter cake. Small size nanoparticles may be able to fill in the pores between larger particles, resulting in a denser filter cake with lower permeability.

### 3.5 Assumptions

The following assumptions were made during numerical simulation:

- Size and distribution of nanoparticles were assumed to be spherical and at equal propagation on the surface of the filter cake.
- Specifications of commercial ceramic disc, including thickness, diameter and permeability, were taken from OFI Testing Equipment website (*Ceramic Filter Disk, 55 Micron - OFI Testing Equipment, Inc., n.d.*).
- The ceramic disc is considered as porous media with uniform pore size distribution.

- Initial permeability  $K_1$  which comprises of the oil and the ceramic disc under pressure equals to 20 D.

### 3.6 Numerical Investigation

In this research, two statistical methods were utilized to predict the permeability values after nanobreaker treatment. Flow rate, viscosity and pressure were considered as independent (input) parameters in both methods, while permeability return was set as dependent (output) variable. The numerical simulation was carried out using MATLAB software. The compatibility of the models was estimated by coefficient of determination ( $R^2$ ). In statistics,  $R^2$  is a statistical measure which represents the proportion of variance in the dependent variable explained by the independent variables in a regression model. It is a value between 0 and 1 and is often expressed as a percentage where 1 indicates that the model explains all of the variation. However, it is rare to have an R-squared value of 1 in practice, as there is always some degree of random variation that cannot be explained by the model. The formula for calculating the coefficient of determination is the following:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \quad (5)$$

where  $SS_{res}$  is the sum of the squared residuals (the difference between the predicted and actual values of the dependent variable), and  $SS_{tot}$  is the total sum of squares (the difference between the actual values and the mean of the dependent variable).

#### 3.6.1 Artificial Neural Network Method

Artificial neural network modeling is a technique used in machine learning to simulate and solve complex problems. It involves the creation of an artificial neural network that is composed of multiple interconnected processing nodes or neurons. These neurons are organized into layers, with each layer performing a specific computation.

The basic architecture of an ANN consists of an input layer, one or more hidden layers, and an output layer. Each neuron in the input layer receives an input signal and passes it to the

neurons in the next layer. The neurons in the hidden layer perform computations on the input signals and pass the output to the next layer until the output layer is reached. The output layer produces the final output of the network. The process of ANN modeling involves the following steps:

1. **Data Preprocessing:** The first step is to prepare the data for modeling. This includes data cleaning, normalization, and feature scaling.
2. **Network Architecture:** The next step is to define the architecture of the neural network, including the number of layers, nodes, and activation functions. This is important as it affects the performance of the network.
3. **Training:** After defining the network architecture, the network is trained using the training data. During training, the weights of the network are adjusted to minimize the difference between the predicted output and the actual output.
4. **Validation:** Once the network is trained, it is validated using the validation data. This helps to ensure that the network is not overfitting the training data and is generalizing well to new data.
5. **Testing:** After validation, the network is tested using the testing data to evaluate its performance.

Artificial neural network model was built by implementing Neural Net Fitting app in MATLAB.

### **3.6.2 Multiple Linear Regression Analysis**

Multiple linear regression (MLR) analysis is a statistical method used to model the relationship between a dependent variable and two or more independent variables. The basic idea of multiple linear regression is to fit a linear equation to a set of data points. The equation takes the form:

$$Y = b_0 + b_1X_1 + b_2X_2 + \dots + b_NX_N \quad (6)$$

where  $Y$  is the dependent variable (also called the response variable),  $X_1, X_2, \dots, X_N$  are the independent variables (also called the explanatory variables or predictors),  $b_0$  is the intercept, and  $b_1, b_2, \dots, b_N$  are the regression coefficients.

The regression coefficients represent the change in the dependent variable that occurs when the corresponding independent variable changes by one unit, while holding all other independent variables constant. The intercept represents the expected value of the dependent variable when all independent variables are zero.

The process of fitting a multiple linear regression model involves estimating the regression coefficients and the intercept that best fit the data. This is typically done using a method called ordinary least squares regression, which minimizes the sum of the squared errors between the predicted values and the actual values of the dependent variable.

Multiple linear regression analysis can be used for both prediction and inference. In prediction, the goal is to use the model to predict the value of the dependent variable for new observations based on the values of the independent variables. In inference, the goal is to use the model to test hypotheses about the relationship between the dependent variable and the independent variables.

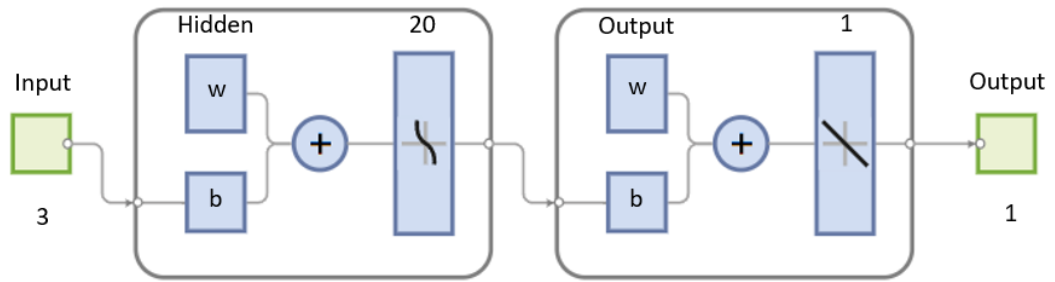
Multiple linear regression analysis has been done using Regression Learner app in MATLAB.

## **4. Results and Discussion**

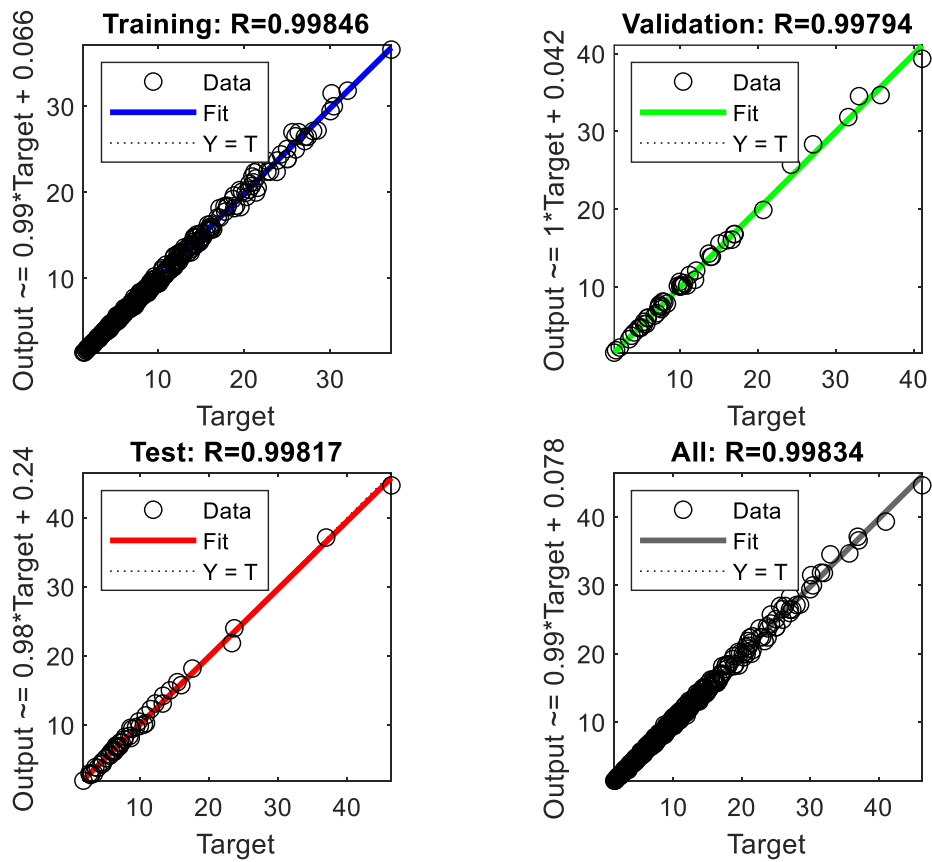
### **4.1 Prediction of Return Permeability Using Artificial Neural Network**

In this case study, ANN method was applied to predict permeability of ceramic disc after filter cake formation caused by drilling mud containing silica and titanium nanoparticles. As Fig. 9 shows the ANN model consists of 1 hidden layer with 20 neurons and 1 output layer. The model is trained using Levenberg-Marquardt backpropagation algorithm. Before starting the training, 80% of the initial 500 datasets was randomly selected for training, when the remaining dataset was equally divided to validation and test groups. It can be seen from Fig. 10 that  $R^2$  values for

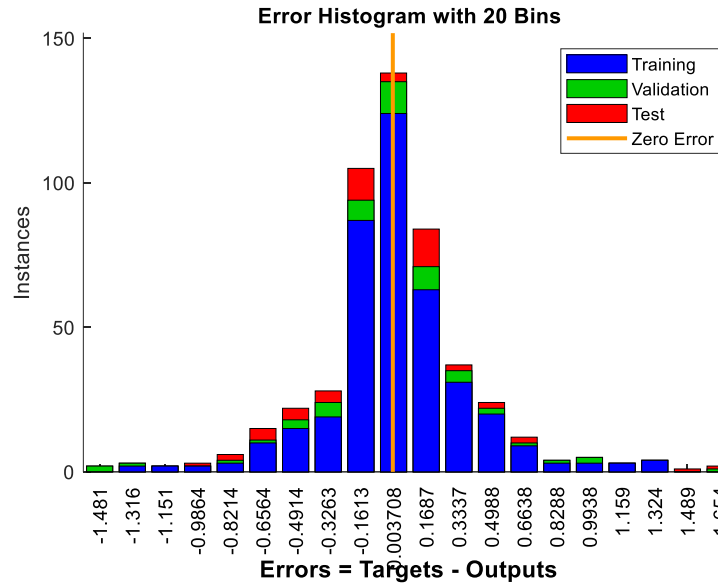
training, validation, testing and all are close to 1, which shows a good fitting. Additionally, due to readjustment of weights ( $w$ ) of values ( $b$ ) in hidden layer, ANN shows its high performance in predicting return permeability. The absolute error for return permeability ranges between -1.481 and 1.654% having the highest number of datapoints with 0.003708 error value (Fig. 11).



**Fig. 9.** ANN model design



**Fig. 10.** ANN regression plot



**Fig. 11.** ANN error histogram

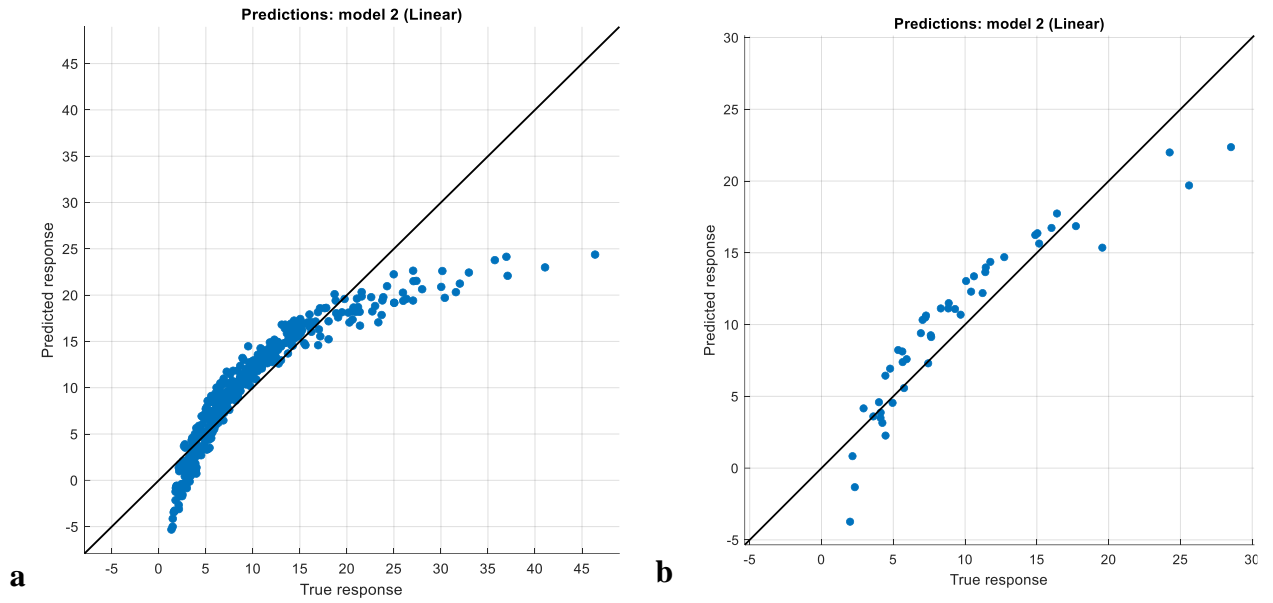
#### 4.2 Prediction of Return Permeability Using Multiple Linear Regression

For multiple linear regression analysis cross-validation option is used dividing validation to four folders to avoid overfitting. Additionally, 10% of the initial data is randomly picked for testing purpose (Fig. 12). In Fig. 12, blue dots represent observed values, while values lying on straight line refer to perfect match between predicted and actual data. The  $R^2$  values for validation and testing are 0.80 and 0.83 respectively, which is lower than in ANN model. During validation, for return permeability values less than 20% the residuals lie in range of [-5; 5] (Fig. 13a). However, at higher permeabilities the predicted values are significantly overestimated. The similar trend is observed in testing stage (Fig. 13b). The regression equation for MLR has the following form:

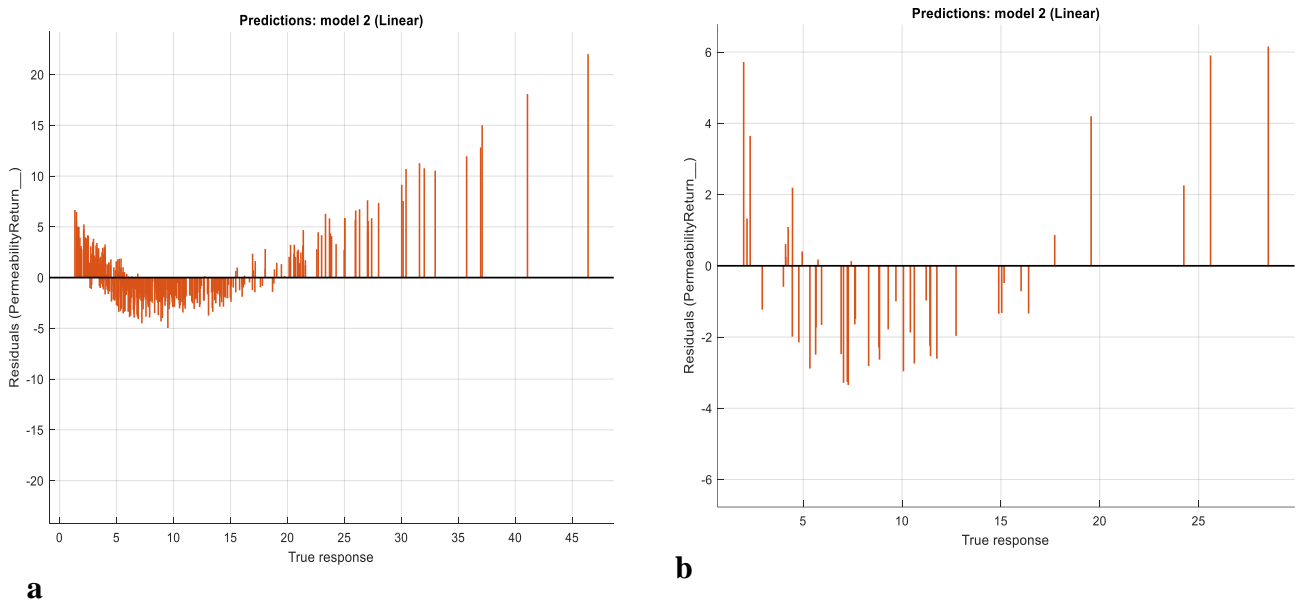
$$RP = 1.9338 + 2.4324 * Flow\ rate - 0.1833 * Pressure + 2,4718 * Viscosity \quad (7)$$

According to  $R^2$  values of ANN and MLR models, applying ANN model to predict return permeability after nanoparticle breaker treatment is preferable. The current results of prediction using ANN and MLR methods are compared with the literature (Jeirani & Mohebbi, 2006), (Mahdi & Holdich, 2017). The  $R^2$  values of this research and studies from the literature are matched in Table 3. However, it should be noted that Jeirani & Mohebbi (2006) and Mahdi & Holdich (2017)

studied the formation of filter cake with conventional drilling fluid not covering the nano-based breakers.



**Fig. 12.** MLR actual vs predicted data: a – validation/training, b – testing



**Fig. 13.** MLR residuals plot: a – validation/training, b – testing

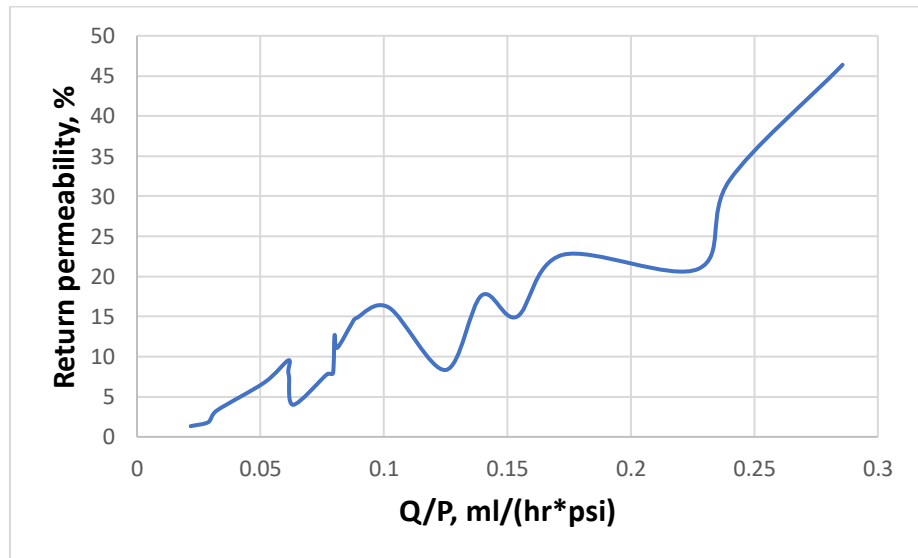
**Table 3.** Comparison of results with the literature

Model	Average $R^2$	Reference
ANN	0.99	Present Study
MLR	0.82	Present Study

ANN	0.94	Jeirani & Mohebbi, 2006
ANN	0.99	Mahdi & Holdich, 2017

### 4.3 Return Permeability Optimization

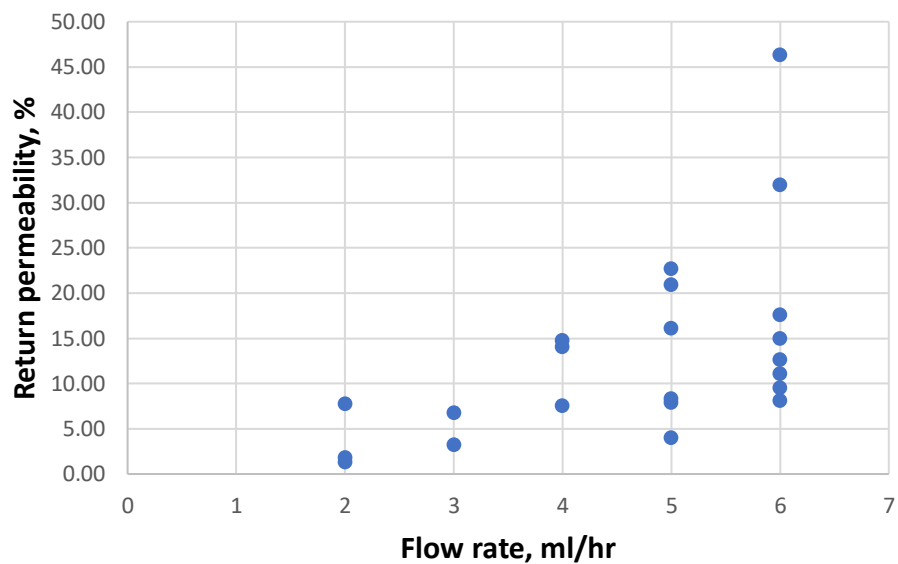
The focus of the numerical study was to optimize permeability return under the influence of pressure, viscosity and flow rate. Figure 14 demonstrates the effect of pressure on return permeability. As both flow rate and pressure are changing, the ratio between them is taken instead of single pressure and plotted against return permeability. As the ratio between flow rate and pressure increases, the return permeability also grows. Thus, variation of flowrate and pressure allows to achieve optimum return permeability. Most importantly, the medium (ceramic disc) for the experiment was assumed to have a uniform pore throat and at maximum pressure the particles turn to clog the throats of the pores, hence reducing the final permeability and preventing the fluid flow.



**Fig. 14.** Pressure-return permeability relationship

As flow rate is in linear relationship with final permeability, according to Darcy equation (1), it will definitely influence RP. Fig. 15 demonstrates that return permeability rises with increase

in flowrate with maximum RP achieved at 6 ml/hr flowrate, when the minimum was reached at flowrate of 2 ml/hr. The physics behind this is the following: as flow rate increases more concentration of nanoparticle breakers gets inside the pores of filter cake pushing the chemical reaction between nanobreaker and filter cake particles.



**Fig. 15.** Flow rate-return permeability relationship

## Conclusions and Recommendations

In conclusion, application of nanoparticle breakers is promising method for filter cake removal. According to the presented data, the return permeability after nanobreaker treatment can reach almost 50% and can be further optimized by varying flow rates and pressures. Furthermore, the statistical analysis (ANN and MLR) presented in the research proposal serve as alternative way to conventional tools to estimate removal efficiency of nanoparticle-based breakers by predicting the return permeability of the media after the treatment.

- Both ANN and MLR models showed a good performance in predicting return permeability from synthetic data. However, ANN performed slightly higher than MLR with  $R^2 = 0.99$  compared to  $R^2 = 0.82$  by MLR. On the other hand, the MLR method had lower  $R^2$  values during validation and testing.
- The study also demonstrated the effect of pressure and flow rate on return permeability and provided insights into the physics behind the phenomenon. Furthermore, flowrate and pressure effect are in agreement with Darcy law utilized as the governing equation in this work.

For further research purposes, the influence of heterogeneous pore geometry on return permeability and accuracy of applied models can be investigated. Moreover, the effect of nonunified nanoparticle size distribution and shape, especially non-sphericity, may be covered by the researchers in order to produce some correlations.

## Nomenclature

### Acronyms and Abbreviations

AC-PAD	=	Activated Carbon with Polyamine Dendrimers
ANN	=	Artificial Neural Network
CFD	=	Computational Fluid Dynamics
DEM	=	Discrete Element Method
EDTA	=	Ethylene Diamine Tetraacetic Acid
FTIR	=	Fourier-transform Infrared Spectroscopy
GO	=	Graphene Oxide
HEC	=	Hydroxyethyl Cellulose
HPHT	=	High pressure – high temperature
LPDZ	=	Less-particle-deposition-zone
MLR	=	Multiple Linear Regression
NP	=	Nanoparticle
NTA	=	Nitrilotriacetic Acid
PAC	=	Polyanionic Cellulose
PLA	=	Polylactic Acid
RP	=	Return Permeability
SBM	=	Synthetic-based Mud
SEM	=	Scanning Electron Microscopy
TCF	=	Thermochemical Fluid
TGA	=	Thermogravimetric Analysis

### Symbols

K	=	Permeability [mD]
$\mu$	=	Fluid Viscosity [cP]

A	=	Cross-sectional Area [cm <sup>2</sup> ]
$\Delta P$	=	Differential Pressure [psi]
L	=	Thickness of Ceramic Disc with Treated Filter Cake [cm]
K <sub>1</sub>	=	Permeability of Pure Ceramic Disc [mD]
K <sub>2</sub>	=	Permeability of Ceramic Disc after Filter Cake Treatment [mD]
R <sup>2</sup>	=	Coefficient of Determination

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