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FACTORS AFFECTING PARTICLE RETENTION IN POROUS MEDIA

C. Gao

Petroleum Engineering Department, Curtin University of Technology, Australia
Email: cnusau@yahoo.com.au

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تترسب حبيبات التربة في الصخور أو الطبقات العميقة المنفذه مما يؤثر بصورة كبيرة على معامل النفاذية. وقد تأثرت العدد من آبار الحقن بتدهور معدلات الحقن نتيجة للحبيبات العالقة في التربة. ويرجع نقص معامل النفاذية إلى معامل الإمتصاص، حجم الحبيبات ومعدل ترسيب الحبيبات بواسطة قوة الجاذبية في الأوساط المسامية. ودلت التجارب السابقة على أن تركيز الحبيبات وسرعة السائل وحجم الحبيبات والمعامل الأيوني للسائل يؤثرون على تدهور معامل النفاذية. وأوضحت تحاليل بيانات الاختبارات السابقة أن التركيز العالي للحبيبات وانخفاض سرعة السائل وكبر حجم الحبيبات لهم التأثير الأكبر على نقص معامل النفاذية. كما أن الحجم الصغير للحبيبات والسرعة العالية للسائل يؤديان إلى نقص قليل في النفاذية ولكن على أعماق كبيرة في حين يكون نقص النفاذية كبيراً في الطبقات السطحية حينما يزداد حجم الجزيئات ويقل معدل السريان.

Particles can deposit in reservoir rocks or deep-bed filters and cause severe damage to their permeability. Several water injection wells experienced severe injectivity loss induced by the suspended particles in injected water. The mechanisms of permeability damage are attributed to adsorption, size exclusion and gravity settling of particles in porous media. Previous experimental studies show that particle concentration, fluid velocity, particle size and fluid ionic strength all have significant effects on permeability decline. The analysis on previous test data reveals that high particle concentration, low fluid velocity, and large particle size lead to more severe permeability reduction. Small particle size and high flow rate lead to deep but less severe permeability loss, and the damage tends to be shallower and more severe with increasing particle size and decreasing flow rate.

Keywords: Literature review, particle deposition, porous media

1. INTRODUCTION

Particle retention in porous media has been a concern for many industries. Reservoir rocks that bear oil and gas are porous media and can be severely affected by particle invasion. In petroleum industry, impairment of rock caused by particles is referred to as an aspect of formation damage and it can happen in many operations.

Drilling, completion, and workover fluids generally contain large amounts of particles in order to balance reservoir pressure. Once these fluids come in contact with the reservoir, these particles may invade and clog the pores, reducing the permeability of the rock and causing severe loss of productivity.

In water flooding, produced water re-injection (PWRI), or water disposal projects, suspended particles in the injected water can cause the injection wells to become impaired. Even though the solid concentration in injected water is much lower than that in drilling fluid, the quantity of injected water is usually very large and these solids may still lead to serious damage on rock permeability.

Moreover, once formation damage has occurred, it is unlikely to be completely removed by subsequent treatment. As a result, the composition of any fluid that comes in contact with the reservoir formation has to be carefully selected to minimize the potential for causing formation damage.

In water treatment process, deep-bed filters have been in common use for more than 100 years. Deep bed filtration removes impurities in waste water by flowing it through a packed bed of solids. Its greatest application is in drinking water filtration and final filtration of waste water before discharge into natural environment[1]. Researchers have been studying the filtration process to improve efficiency of deep bed filters.

Despite that research on particle retention in porous media has been conducted for many years, its understanding is still limited. Formation damage takes place in the near wellbore region. The reservoir simulators in the market cannot quantify the severity of formation damage and the user simply applies an overall skin factor to the near wellbore region to account for the damage.

Many experiments have been conducted to investigate the factors that affect the complex process of particle retention in porous media. It is meaningful to summarize the findings from previous experiments to gain better understandings.

2. FIELD EXPERIENCES

Several authors reported injectivity declines for PWRI projects. Mature fields produce large amounts of water. Produced water can be from natural water drive, injected water, or usually a combination of both. As oil and gas production declines, water production increases and water cuts can exceed 90% in many mature fields.

Produced water contains various impurities and pollutants, including organic and inorganic particles, hydrocarbon droplets, and treatment chemicals. As such, to avoid or reduce environmental impact, produced water needs to be carefully treated before being released into the environment. It thus presents significant costs and potential risks for oil and gas producers. Alternatively, produced water is injected back into the reservoir to maintain reservoir pressure. This is especially the case in onshore fields.

Filtration is usually used to reduce the concentration of suspended solids in water prior to injection, but the high costs of water treatment should be justified against other alternatives, such as periodic well stimulation. In many mature fields, untreated water is injected to reduce the costs. Also due to the high costs, water can only be filtered to a certain level, generally between 10 and 50 microns. Smaller impurities are carried by the water and injected into the formation. These impurities can still cause severe injectivity decline.

A field case is the offshore Siri field in the southern Persian Gulf[2]. The oil in this field is produced from the Mishrif formation which is common to both Iran and the United Arab Emirates. To maintain reservoir pressure and to increase oil recovery, water injection was started in 1984 at rates of 9100 bbl/day. However, the injectivity declined rapidly, until the injection was stopped in 1990, when the water injection rate had dropped to only 2200 bbl/day as shown in Figure 1.

Another 5 wells in the Gulf of Mexico demonstrated even faster decline[3]. The water injection rate declined from 7000 BBL/day to less than 1000 bbl/day in just 200 days, as seen in Figure 2. In these cases, the particles in injected water were filtered to 10 microns, yet the decline was very severe.

In the above cases, suspended particles in the injected water were identified as the cause of injectivity decline. As we can see, the severity of injectivity decline varies from case to case, depending on the particle sizes, solid concentrations, and different reservoir properties. A reservoir with high porosity and high permeability tends to sustain its injectivity longer.

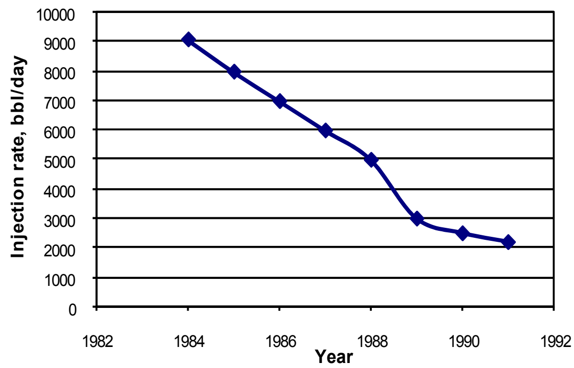

Figure 1. Water Injection History of a Well in the Siri Oil Field

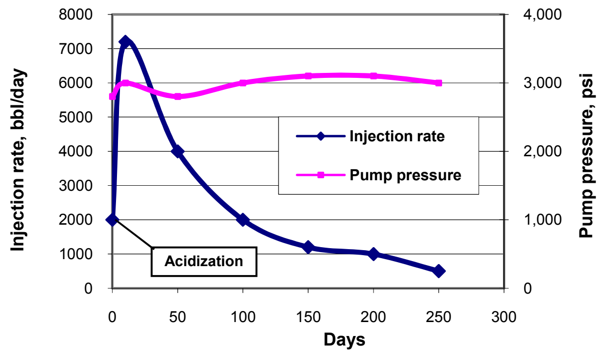

Figure 2. Water Injection History of Well A09 in the Gulf of Mexico

3. MECHANISMS OF FORMATION DAMAGE DUE TO SUSPENDED PARTICLES

Particle movement in porous media is a very complex process due to the complexity of porous media and forces governing solids movement in porous media. The paths of the solids are determined by numerous factors, such as the shape of the particles and their surface properties, the morphology of the medium, the chemistry of the carrying fluid, the flow field in the pore space, and various interaction forces between the particle and the medium. These factors acting together significantly affect the particle transportation, adsorption or deposition and the resulting reduction in the permeability of the porous medium.

Once entrained by the fluids flowing through porous media, the various particles can be captured by three primary mechanisms[4]: (1) adsorption of the particles because of the Brownian motion, and the electrostatic interaction between the migrating particles and the solid surface of the pores; (2) size exclusion when the effective size of the pores are smaller to those of the migrating particles; (3) sedimentation or gravity settling when the densities of the moving particles and the carrying fluid are very different. These mechanisms illustrated in Figure 3.

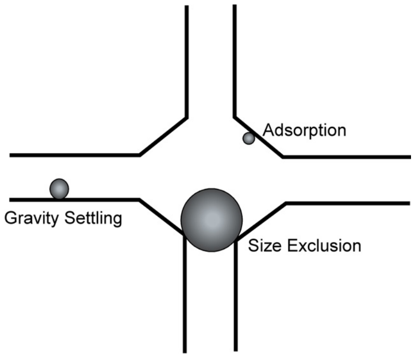

Figure 3. Particle Capture Mechanisms

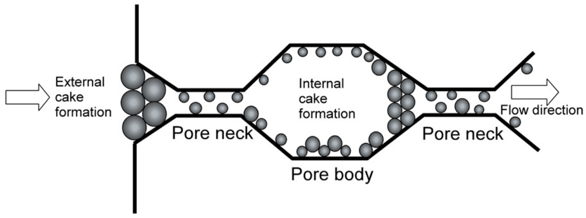

Figure 4. Formation of Filter Cake

When multiple particles invade the porous media at the same time, the issue becomes more complicated. Deposited particles reduce the flowing path inside the porous media, thus increasing the possibility of bridging. Large particles may form a filter cake on the face of the rock, namely external cake formation. Small particles may invade the formation, bridge, and form an internal filter cake, namely particle invasion, internal cake formation or deep bed filtration. Since the solids are of various sizes, the damage can be attributed to more than one mechanism, as shown in Figure 4.

For sub-micron particles, adsorption due to Brownian motion is dominant. For the particles with sizes comparable to or bigger than pore neck, size exclusion is dominant. The particles with sizes in between are likely to settle down due to gravity.

4. REVIEW OF SELECTED EXPERIMENTS

The research in particle transport in porous media has been active since 1950s. Two types of experimental methods have been developed to test the permeability impairment caused by suspended solids. In the early years, membrane filter tests were used. In the recent years, core flowing tests have become the standard method. In this section, some well-documented tests are reviewed.

Different researchers used very similar test apparatus, as illustrated in Figure 5. A stirrer keeps the particles suspended in the tank. A pump sends the mixture through the core holder. And the differential pressure transducer monitors the pressure loss across the core, which translates into permeability decline.

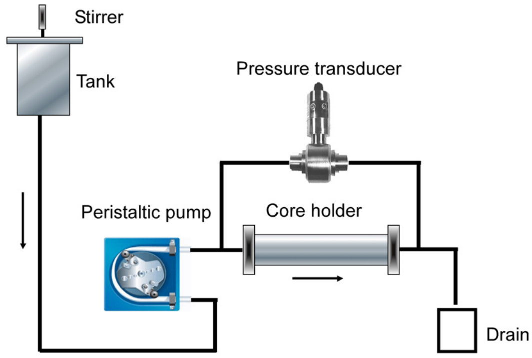

Figure 5. A Typical Test Apparatus

Todd et al.[5] injected aluminum oxide particles through Clasach and Lochaline cores. The test conditions are listed in Table 1. To quantify the damage at different depth, they measured pressures along the 3 inch (7.6 cm) long core. The cores damaged by particles of 0 to 3 microns exhibit damage throughout their entire lengths, and no external filter cake was observed; The particles with sizes of 4 to 6 microns caused more severe damage to the first 12 mm of the core, and no external filter cake was visible; The 8-10 micron particles caused the first 5mm of the core to lose 90% of its permeability, and filter cake was apparent.

Vetter et al.[6] conducted particle-filtration tests to study the effects of particle sizes, flow rates, particle concentration and particle charges. The test conditions are listed in Table 1. It was concluded that particles of all sizes (from 0.05 to 7 microns) cause formation damage. The larger particles cause a rapid decline in permeability with shallow damage. Smaller particles (in the sub-micron range) enter the core and cause a gradual permeability decline. Fluid flow rate is another important factor. The higher the linear flow rate, the less severe is the damage to the core plug. Third, higher particle concentration causes more severe damage. Fourth, NaCl, anionic and cationic surfactants were added to the suspensions and the resulted damages were much more severe. This shows the ionic strength of the fluid also has effects on particle retention in porous media.

Baghdlklan et al.[7] injected kaolin and bentonite clay suspensions through packed sand. The sizes of clays in the suspension are mostly in the sub-micron range. The test conditions are shown in Table 1. Their reported data were among the most complete, including measurements of particle size and pore size distributions. The authors tested the effects of flow rate, solid concentration, pH and ionic strength. The results showed that clay suspensions at low flow rates, high particle concentrations, high ionic strengths and low pH cause more rapid permeability reduction, which agrees with the findings of Vetter et al.[6].

Table 1. Test Parameters Used by Todd et al., Vetter et al., and Baghdlklan et al.

Author Information	Todd et al. [5]	Vetter et al.[6]	Baghdlklan et al. [7]
Tested Porous Media	Sandstone cores	Berea sandstone cores	Ottawa sand pack
Media Length (cm)	7.62	3.8 to 5.1	32.2
Media Diameter (cm)	2.54	2.54	6.3
Media Porosity (%)	15.9 and 19.8	21	37.5
Media Permeability (Darcy)	0.562 to 2.012	0.1 to 0.2	8.0
Test Particle	Aluminum Oxide particles	Chromium Oxide and Cerium Oxide particles	Kaolin and Bentonite clay
Particle Diameter (micron)	0 to 10	<0.06, 0.05, 1.0 and 7.0	Mostly < 1 micron
Particle Concentration (ppm)	5	90, 250 and 500	200 to 4000
Flow Rate (ml/s)	1.8	0.033 to 0.167	0.09 to 0.36

Table 2. Test Parameters Used by Todd et al., Roque et al., and Moghadasi et al.

Author Information	Todd et al.[8]	Roque et al. [9]	Moghadasi et al. [2]
Test Media	Clashach sandstone core	Sandstone cores	Packed glass beads
Media Length (cm)	8	About 10	58
Media Diameter (cm)	2.54	5	3.2
Media Porosity (%)	14.5	10.2 to 17.4	38
Media Permeability (Darcy)	0.2 to 1	0.224 to 3	161
Test Particle	Alumina particles	Latex particles	Aluminum Oxide particles
Particle Diameter (micron)	0 to 3	0.8 to 7.6	7 and 16
Particle Concentration (ppm)	1, 5, 10 and 15	2 to 20	500, 1000 and 2000
Flow Rate (ml/s)	0.45 to 1.80	0.012 to 1	0.42 and 0.83

In another studyby Todd et al. [8], suspended solids were injected through pressure-tapped Clasach sandstone cores to study the effects of flow rates and particle concentrations similar to North Sea situations. The test conditions are listed in Table 2. The injection duration was very large, up to 144 hours or 60000 pore volumes. They first compared the tests results for broken-faced core and cut-faced core. For cut-faced cores, the scanning electron micrographs taken before core flowing tests showed the presence of fine particles at the core face resulted from cutting the end face with a saw. At the end of the experiments, an external filter cake is clearly seen on the inlet face of the cut-faced core, but is not so obvious on that of the broken faced core. Their experiments for the first time revealed a simple semi-log relationship between permeability decline and flow velocity, also between permeability decline and particle concentration. Their test results show that smaller velocities and larger particle concentrations result in greater permeability decline. The four pressure transducers along the core indicated that the first 5 mm of the core was most severely damaged, while the damage spread to the whole core.

Roque et al. [9] injected latex particles with various sizes to 15 sandstone cores to study the effect of flow rate. Their test conditions are listed in Table 2. In some cases, the average pore size, the invasion depth and effluent concentration were also measured. The test data agree with previous findings: lower flow rates lead to greater damage. Their test data also revealed an interesting trend: particles under same linear flow velocity caused very similar damages, regardless of the particle diameters and particle concentrations.

Moghadasi et al.[2] injected Aluminum Oxide solids through the porous media formed by packed glass beads. The test conditions are listed in Table 2. The glass beads were of a quite large diameter, which resulted in extremely high permeability. The test section has 6 pressure taps along its length, each of them connected to a separate pressure transducer. They tested the effects of flow rates, particle concentrations and particle sizes on permeability reduction. Their results agree with previous findings.

5. SUMMARY OF PREVIOUS FINDINGS

The previous test results have shown that flow rate, particle concentration, particle size, fluid pH and fluid ionic environment all have certain effects on the permeability decline. In this section, these factors are analyzed individually.

5.1 Effect of Flow Rate and Fluid Velocity

Previous tests reveal that lower flow rate causes greater damage, and higher flow rate leads to greater invasion depth. This indicates that particles under low flow rate settle down very quickly, resulting in severe and shallow damage to the core. Higher flow rate can carry the particles further, thus the damage is averaged along the core. This mechanism is easy to understand but difficult to quantify. Each porous medium has unique pathways. As a result there is a very high uncertainty while determining the location where a particle settles. Nevertheless, Figure 6 plots flow rates versus T75 based on the test data by Todd et al. [8]. T75 is defined as the pore volumes injected when the overall permeability of the core decreased to 75% of its original permeability. It is apparent that lower flow rate leads to smaller T75 (i.e., more damage).

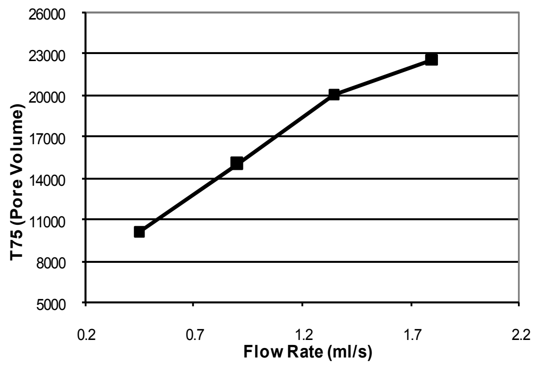

Figure 6. Effect of Flow Rate

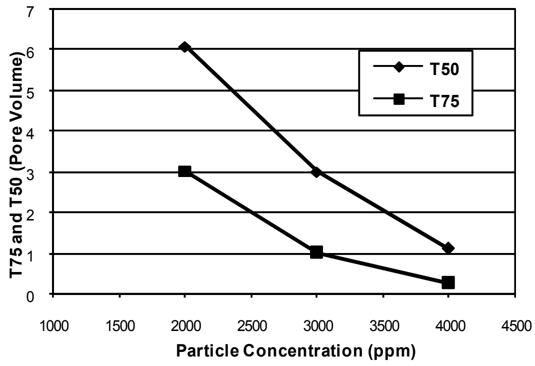

Figure 8. Effect of Particle Concentration for Colloidal Particles

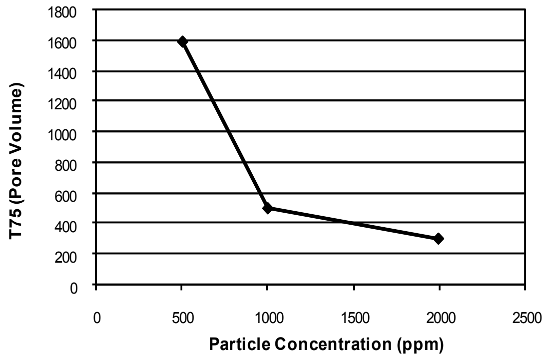

Figure 7. Effect of Particle Concentration for Large Particles

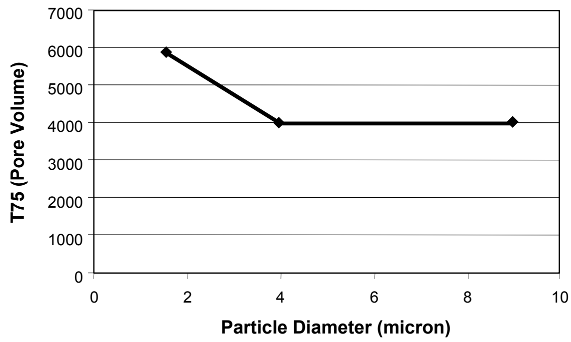

Figure 9. Effect of Particle Size

5.2 Effect of Particle Concentration

It is obvious that higher particle concentration leads to greater damage. Higher concentration leads to more deposition and also increases the tendency of pore throat bridging. Figure 7 shows the effect of particle concentration on T75 based on the test data from Moghadasi et al. [2].

Another group of test data[7] with much smaller particles sizes and a sand pack with much lower permeability revealed a close to linear relationship between T75, T50 and particle concentration, as seen in Figure 8. T50 is defined as the pore volumes injected when the overall permeability of the core decreased to 50% of its original permeability.

Figures 7 and 8 indicate that the impairment mechanisms are different for large particles and small particles. For small particles, the damage is almost proportional to increase of particle concentration. This indicates that surface deposition is the main cause of permeability decline, since the amount of deposit increases linearly with time. For large particles, a much greater damage was observed when the concentration increased from 500ppm to 1000ppm, which may be attributed to pore throat bridging as the main cause of permeability reduction.

5.3 Effect of Particle Size

A study[5] shows that bigger particles cause more damage, as seen in Figure 9. Large particles have higher tendency to settle down and block or bridge at the pore throat, causing more severe damage.

Todd et al. also measured the pressure along the core, which translated into the permeability for different sections of the core. For small particles (0 to 3 microns), the first section lost about 50% of its original permeability, and the last section lost about 20% of its original permeability. While for large particles (8 to 10 microns), the first section lost about 90% of its original permeability, and the last section lost only 5% of its original permeability. In other words, large particles have higher settling tendency and cause severe but shallow damage.

5.4 Effects of pH and Ionic Strength

The effects of fluid pH and ionic strength were not as widely studied. Baghdlklan et al.[7] tested permeability decline under fluid pH numbers of 2.5 and 10. The test results revealed the effect of pH was not significant. Their tests on KCl concentrations showed that the damage was more severe at high salt concentration.

The research on the effect of ionic strength was done by adding salts, commonly NaCl or KCl to the injected fluid. One test showed the permeability damage was much more dramatic after 0.1 mol/Liter of KCl was added to the injected solution [6]. Chang and Vigneswaran[10] added NaCl to the injected solution and observed similar phenomena: more particles deposited when NaCl concentration increased from 0.00086 mol/liter to 0.438 mol/liter. This phenomenon can be explained by the repulsive double layer theory. At high ionic strength, the repulsive double layer is suppressed, resulting in more particles colliding with pore surface.

Stephan and Chase[11] injected Kaolin clay into Berea sandstone cores. The average size of the injected clay was 1.45 microns. The objective was to study permeability decline at various salt concentrations and pH numbers. The test data revealed that permeability decline was much more severe at low salt concentration, which is contradictory to previous findings. An interesting observation was that the effect of pH on permeability decline was insignificant at high salt concentration. While at low salt concentration, low pH leads to more damage. Apparently, the effects of salt concentration and pH are not yet clarified.

5.5 Effect of Presence of Oil droplets

For PWRI projects and deep bed filtration, oil droplets commonly coexist with suspended particles. Few researches were conducted to inject particles together with oil droplets into porous media. Zhang et al.[12] conducted experiments with 40 sandstone cores. The cores had permeability less than 550 mD. The injected oil droplets and solids had mean sizes less than 10 microns. Oil concentration was less than 500 ppm and solids concentration was less than 50 ppm. More severe damages were observed while oil droplets were injected together with particles, and damage spread further along the core. Their findings are supported by Ali et al.[13]. Another study showed that addition of organic substance such as Fulvic acid greatly enhanced capture of particles [14]. However, it is not confident to draw conclusions with the limited studies conducted.

5.6 Invasion Depth

Many factors determined how far a particle travels inside a porous medium. Large particles tend to settle down quicker than small particles. Particles with high density tend to settle down quicker than light one. High flow rate (velocity) can carry particles further inside a porous medium. The surface charges of the particles and pore surface also have effect on how far a particle travels.

Theoretically, the invasion depth is the furthest distance any injected particle can travel in a porous medium. However, the many parameters involved make it impossible to give a definite measurement of invasion depth. Previous tests revealed that the damage generally spread to the whole core. But it was very clear that the rock sections close to the injection entrance are always much more severely damaged than the deeper sections. As such, there is no definite cut-off point for invasion depth. Invasion depth generally refers to the length of the most severely damaged section. The following invasion depths were reported: 12mm [5,8], 12mm [15], 15mm [12], 25mm [2], 35mm [9], and 40mm [16]. Therefore, it may be safe to say the invasion depth is generally less than 50mm.

Thirty years have passed since Abrams first proposed the “1/3-1/7” rule-of-thumb [17]. He proposed that particles larger than 1/3 of the pore diameter can bridge at pore throats and form an external filter cake; Particles smaller than 1/3 but larger than 1/7 of the pore diameter invade the formation and form internal cake; Particles smaller than 1/7 of the pore diameter are carried through and cause no damage. Later, a new rule of “1/3-1/14” was proposed by Van Oort et al.[18] based on new developments.

Unfortunately, both the “1/3-1/7” and “1/3-1/14” rules were proved invalid by many experimental studies. Due to the complex nature of porous media and injected fluids, a simple criterion is unlikely to be sufficient to understand transport of particles in porous media. Prediction of permeability reduction due to capture of particles thus remains a very challenging topic.

6. CONCLUSIONS

- Particle deposition in porous media has been a research topic for both petroleum industry and water treatment industry. It is a complex process due to the complex nature of porous media and the properties of injected particles and fluids.
- Previous test results reveal that fluid flow rate, particle size, particle concentration, and fluid ionic strength all have significant effects on capture of particles. Low fluid velocity and large particle size lead to shallow and severe damage. Higher particle concentration causes more severe permeability damage.
- Most of the previous experimental studies focused on the effects of fluid flow rate and particle concentration. More studies are needed to understand the effects of particle size and fluid ionic strength.

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