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Feasibility Analysis of Municipal Wastewater Reinjection Technology

Haijie Hu*(**), Huan Zhang*, Lei Han**, Le Zhang****, Tao Yu**(*****)† and Chengtun Qu****

*Shaanxi Zhiyuan Siyuan Environmental Protection Technology Co. Ltd., Xi'an 710065, PR China
**Xi'an Shiyou University, Shaanxi Provincial Key Laboratory for Environmental Pollution Control and Reservoir Protection, Xi'an 710065, PR China
***Weinan Normal University, School of Chemistry and Materials, Weinan 714099, PR China
****Xi'an Aeronautical University, Institute of Energy and Architecture, Xi'an 710077, PR China
*****Yan'an Oil and Gas Field Environmental Pollution, Low-carbon Collaborative Control Technology and Reservoir Protection Key Experiment, Shaanxi Fuquan Environmental Protection Technology Co. Ltd., Yanan 727500, PR China
†Corresponding author: Tao Yu; 569775931@qq.com

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ABSTRACT

To study the feasibility of using municipal sewage as a reserve water source for oilfield reinjection, the water sample treated by the municipal sewage treatment plant and the produced water of the Chang 2 reservoir were taken as the research objects. Through the analysis of water quality and compatibility, the optimal ratio of reinjection water samples was determined. At the same time, the clay swelling experiment and reservoir damage experiment were carried out. The experimental results show that the salinity of municipal sewage is low, and the content of scale ions is low. When the ratio of produced water to municipal sewage is 7:3, the scale formation amount can reach 42.5 $mg.L^{-1}$, and when the scale inhibitor is added, the scale formation amount can be reduced to 10.4 $mg.L^{-1}$. The mixed water sample will not cause clay expansion. Meanwhile, Chang 2 reservoir is moderately weak water sensitive and weak acid sensitive. The oil content, suspended solids content, and median particle size of the mixed water sample during reinjection should be controlled at 5 $mg.L^{-1}$, 5 $mg.L^{-1}$, and 5 μm to ensure that the reinjected water sample does not cause damage to the reservoir.

INTRODUCTION

Water injection development in oil fields is an important way to achieve efficient reservoir development. Reliable water sources and stable water quality are the basic requirements for water injection development. However, with the continuous expansion of the water injection scale, the contradiction between the demand for water injection and water supply in oil fields has become increasingly prominent (Ge et al. 2017, Ye et al. 2016). At present, the injected water in most oilfields is mainly produced water, and some water injection stations use circulating water from the boiler in the station and treat domestic sewage in the station as supplementary water sources for reinjection (Xin 2021, Gao et al. 2016). However, in some water injection sites, the amount of water injected is low, resulting in lower formation pressure, which seriously affects the oil recovery. Therefore, it is particularly important to select the appropriate supplementary water source. At present, the national sewage discharge index is increasingly strict, and direct sewage discharge after treatment is also a waste of resources. In 2020, urban sewage discharge in our country reached 57.1 billion m^3 (Zhang et al. 2022). In Northern Shaanxi Province, water resources are especially precious because of drought and less rain. If the treated municipal sewage is used for oilfield reinjection, it can effectively slow down the pressure of oilfield water injection and reduce the cost of oilfield water injection. At the same time, the reuse of municipal sewage is of strategic significance to reduce pollutants, reduce environmental pollution, and alleviate water shortage (Zhang et al. 2020).

Chang 2 reservoir in Yanchang Oilfield is a tight reservoir with low permeability and a small pore throat (Xing 2009, Du et al. 2015, Yang 2002). The treated municipal sewage contains a large number of suspended particles with large particle sizes. The biochemical process is generally used to degrade organic matter in the treatment of municipal sewage, and the bacterial content in the treated water sample exceeds the standard (Liu et al. 2020). If direct injection is made, suspended matter, emulsified oil, dissolved oxygen, bacteria, and other substances injected into the water will block the reservoir, which will seriously decrease the water absorption capacity of the injection well and increase the water injection pressure, thus affecting the liquid output of the oil well (Wang 2021, Yang 2015, Wu et al. 2012). At the same time, the salinity of produced water is relatively high (Ding et al. 2019). If it is not compatible with municipal sewage, the scale crystals generated will also cause pore throat blockage of the reservoir (Bu et al. 2022). Therefore, the compatibility of reinjection water and reservoir fluids should be considered during reinjection. At the same time, according to the characteristics of reinjection water and the reservoir damage mechanism, the water injection development system and water quality standards in line with the reservoir characteristics should be standardized (Bu et al. 2022, Chang et al. 2017). In this paper, the municipal wastewater and the produced water of Chang 2 reservoir are taken as the research objects, and the water quality analysis, compatibility research, clay swelling experiment, and reservoir damage rate experiment are carried out. The feasibility evaluation of the injected formation of Chang 2 reservoir produced water and municipal wastewater is also carried out, which provides a basis for the injected formation of municipal wastewater and produced water.

MATERIALS AND METHODS

Materials

The municipal sewage used in the experiment was taken from the treated water sample of the Wuqi sewage Treatment plant. The produced water used is the produced water of Chang 2 formation in Wuqi Oil Production Plant. The core used in the experiment was taken from well 10-40 of the resource perimeter in Chang 2 Reservoir.

LDY50-180 multi-functional core flow tester, Nantong Yichuang Experimental Instrument Co., Ltd. Uv-visible spectrophotometer, Shanghai Youke Instrument Co. Ltd.

Analytical Methods

According to the oil and gas industry standards, "Water Quality Index and Analysis Method for Clastic Reservoir Injection" (SY/T 5329-2012), "Oil and gas field water Analysis Method" (SY/T 5523-2016) and "Water and Wastewater Monitoring and Analysis Method" (Fourth edition) for the detection and analysis of total ion content, oil content, suspended matter content, corrosion rate and bacterial content (SY/T 5523-2000, SY/T 5329- 2012).

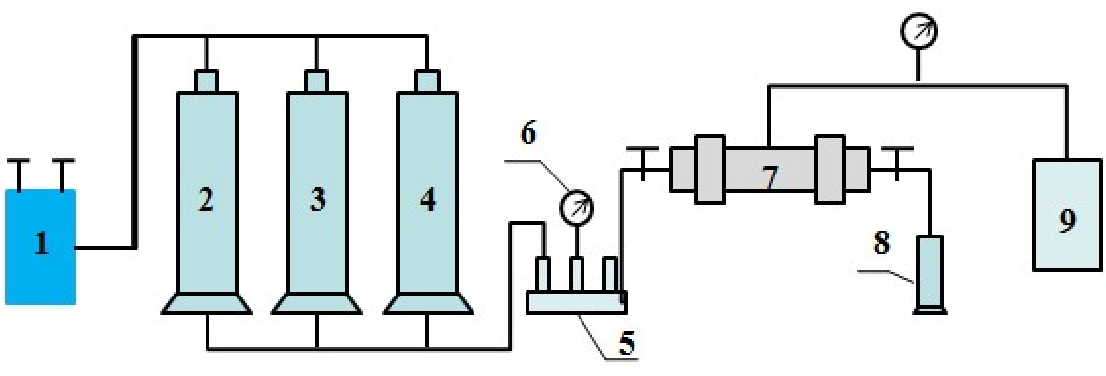
The produced water from the oil field was mixed with municipal sewage in a certain proportion (9:1-1:9), and the simulated formation temperature was placed at 60°C for 72 h. After the placement, the appearance of the water sample was observed, and the experimental phenomenon was recorded. The compatibility was evaluated by measuring the calcium loss rate and scale amount in the mixed water, and the calcium loss rate was calculated according to the formula:

$$\text{Calcium loss rate} = \frac{C_{\text{before mixing}} - C_{\text{after mixing}}}{C_{\text{before mixing}}} \times 100\%$$

The clay swelling experiment was conducted according to the "Evaluation Method of Clay Stabilizer Performance for Fracturing Acidification and Water Injection in Oil and Gas Fields" (SY/T 5971-2016). 1 g sodium-based bentonite was mixed with a 10 mL water sample, poured into a 10 mL centrifuge tube, and stood at 25°C for 2 h. Then, centrifuged at 1500 $r.min^{-1}$ for 15 min to measure the bentonite volume V_1, and 3%KCl solution was used instead of the reinjection water sample to measure the expansion volume V_2. Calculation formula of relative expansion rate:

$$\text{Relative expansion rate} = \frac{V_1 - V_2}{V_2} \times 100\%$$

Where V_1 represented the expansion volume (mL) of the reinjection sample mixed with clay; V_2 represented the expansion volume of 3% KCl mixed with clay, mL.



1 - advection pump; 2,3,4 - high pressure tank; 5-6. 6 - pressure gauge; 7 - core gripper;
8 - measuring cylinder; 9 - ring pump
Fig. 1: Flow chart of core damage experiment.

According to the petroleum industry standard SY/T 5358-2010 "Experimental Evaluation Method of Reservoir Sensitivity flow," various sensitivity evaluation experiments were conducted on the Chang 2 reservoir. At the same time, the influencing factors of reservoir damage are analyzed (SY/T53588-2010). The experimental process is shown in Fig. 1.

RESULTS AND DISCUSSION

Water Quality Analysis

Total ion analysis of water quality was carried out on water samples after municipal sewage treatment and oil field-produced water. The experimental results are shown in Table 1.

It can be seen from Table 1 that the scale-forming ions of municipal sewage are relatively low, and the scale-forming ions in the produced water of Chang 2 reservoir are significantly higher than that of municipal sewage. If the two water samples are mixed, scale formation may occur. The dissolved oxygen content in the municipal sewage water sample is significantly higher than that in the produced water, mainly because the municipal sewage treatment process contains aeration. Meanwhile, the dissolved oxygen content in the water will be significantly higher if the municipal sewage is in contact with the atmosphere for a long time (Chi et al. 2021). Therefore, the damage to the reservoir caused by scale formation and suspended matter should be strictly considered when using municipal sewage as a reinjection sample.

Table 1: Water ion composition.

Test items		Produced water	Municipal wastewater
Ca^{2+} [$mg \cdot L^{-1}$]		669.34	8.42
Mg^{2+} [$mg \cdot L^{-1}$]		226.08	7.78
Fe^{2+} [$mg \cdot L^{-1}$]		0.08	0.07
Fe^{3+}[$mg \cdot L^{-1}$]		0.14	0.08
Cl^{-} [$mg \cdot L^{-1}$)		20893.52	402.54
CO_3^{2-} [$mg \cdot L^{-1}$)		0.00	0.00
HCO_3^{-} [$mg \cdot L^{-1}$]		280.69	244.08
S^{2-} [$mg \cdot L^{-1}$]		3.67	0.14
SO_4^{2-} [$mg \cdot L^{-1}$]		759.76	263.40
K^{+} Na^{+} [$mg \cdot L^{-1}$]		1280851	454.49
Salinity [$mg \cdot L^{-1}$]		35641.79	1381.00
Water type		Calcium chloride	Sodium bicarbonate
pH		6.5	6
Oil content [$mg \cdot L^{-1}$]		1.25	0
SS [$mg \cdot L^{-1}$]		3.15	8.76
Median particle size [um]		0.80	1.81
Dissolved oxygen content [$mg \cdot L^{-1}$]		0.37	3.42
Mean corrosion rate [$mm \cdot a^{-1}$]		0.0249	0.0527
Bacteria [per cell·mL^{-1}]	SRB	6	0
	FEB	0.6	0.6
	TGB	2.5	6

Mixed Compatibility

The produced water from the oilfield and municipal sewage were mixed. The compatibility of the mixed water sample was analyzed. The experimental results are shown in Fig. 2.

As can be seen from Fig. 2, when the ratio of produced water and municipal sewage is low, the water sample has good compatibility and can reach the reinjection index. The ratio of produced water and municipal sewage is 7:3, the maximum scaling amount reaches 42.5 $mg.L^{-1}$, and the calcium loss rate reaches 15.90%. After adding a scale inhibitor to the mixed water sample, the scale formation amount of the mixed water sample can be reduced to 10.4 $mg.L^{-1}$, and the calcium loss rate can be reduced to 4.22%. Therefore, in the later reinjection process, the corresponding scale inhibitor can be added to the mixed water sample to avoid the blockage of the reinjection pipeline, equipment, and reservoir void caused by the scale formation of the mixed water sample, which will affect the reinjection effect (Liu et al. 2015, Wang et al. 2021).

Clay Swelling

When the injected water enters the formation, it will react with the clay material in the formation. Due to the difference in the salinity of the water samples, the clay will produce

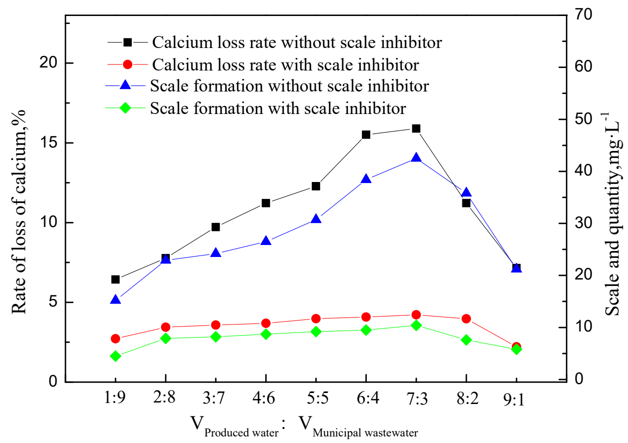


Fig. 2: Experimental analysis of compatibility between municipal sewage and produced water.

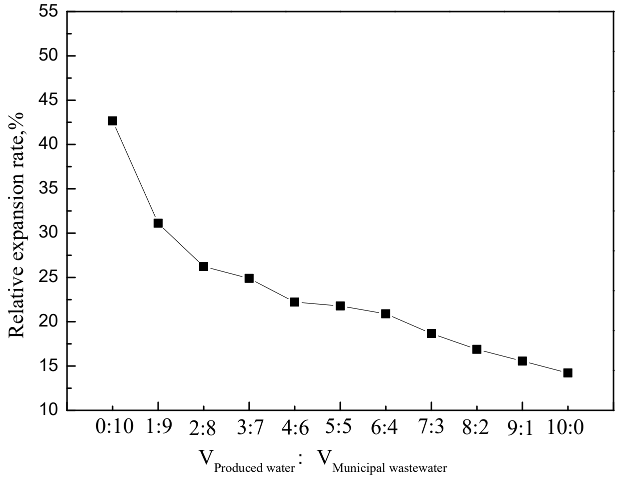


Fig. 3: Effect of reinjection sample on the clay swelling.

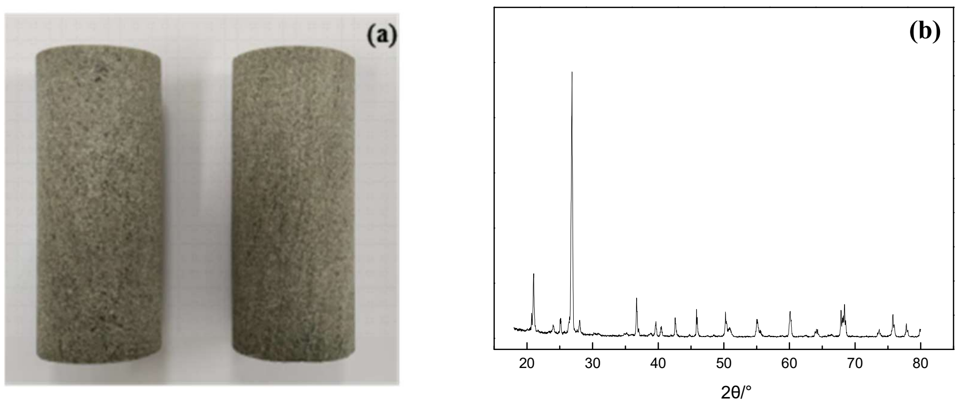


Fig. 4: (a) Core photo of Chang 2 reservoir Group and (b) XRD patterns of Chang 2-layer cores.

hydration expansion and disperse migration. The mixed water samples of produced water and municipal sewage were analyzed by clay swelling experiment. The experimental results are shown in Fig. 3.

It can be seen from Fig. 3 that with the increase in the proportion of produced water in the reinjection sample, the clay swelling rate gradually decreases. The clay swelling rate of produced water is 14.22%, while that of municipal sewage is 42.67%, which is relatively large. The salinity of produced water is relatively high, and divalent ions such as Ca^{2+} and Mg^{2+} in the water sample diffuse to the interlayer of clay, which inhibits the hydration and swelling of clay and makes the mixed water sample with a large proportion of produced water has a relatively low swelling rate (Kang et al. 2019).

Reservoir Damage

Reservoir injury refers to the damage to the natural capacity of the reservoir caused by various human factors during the opening and subsequent development of the reservoir. The causes of reservoir damage mainly include sensitivity factors, clogging factors, and corrosive factors (Ren et al. 2010).

Reservoir Characteristics Analysis

As can be seen from Fig. 4(a), the overall color of the Chang 2 reservoir core in Wuqi Yanchang is light and gray. Its main composition is quartz, kaolinite, chlorite, illite, calcite, feldspar, etc. (Fig. 4(a) and Fig. 4(b)). Based on the analysis of core sample data of Chang 2 reservoir in the study area, Chang 2 reservoir in Yanchang Oilfield is a typical medium-low porosity and ultra-low permeability reservoir. The main distribution range of its porosity is 2.19%~16.4%, and the average porosity is 10.8%. The permeability distribution range was $0.12\sim8.63\times10^{-3}\mu m^2$, and the average permeability was $1.25\times10^{-3}\mu m^2$. Due to the small porosity and low permeability of the Chang 2 reservoir, incompatibility between injection water and formation water will lead to scaling and precipitation, which will easily block the pore throat, cause reservoir damage, and reduce the water absorption capacity of the injection well. Therefore, it is necessary to conduct research and analysis on injection water compatibility (Yang & Wang 2021).

Reservoir Sensitivity Factors

When the injected water is not compatible with the reservoir rock, the clay in the rock will expand, disperse, and migrate to damage the formation, which usually includes water-sensitive, velocity-sensitive, salt-sensitive, acid-sensitive, and alkali-sensitive (Liu et al. 2020, Hu 2015). The sensitivity test was carried out to analyze and evaluate the core of the Chang 2 reservoir in Yanchang Oilfield, and the experimental results are shown in Fig. 5.

Based on the sensitivity analysis of different cores in the long two layers, it can be seen from Fig. 5(a) that the rate of speed-sensitive damage in the long two layers is 0~25%, which is weak speed-sensitive, and the critical average flow rate is 0.5 mL.min^{-1}. Therefore, the zone is not prone to speed-sensitive damage, and the mining rate can be appropriately increased during water injection and mining. However, due to the shear action of fluid, the clay in the reservoir rock will be dispersed to form particles, which will block the pore throat and cause speed-sensitive damage. As can be seen from Fig. 5(b), the water sensitivity index

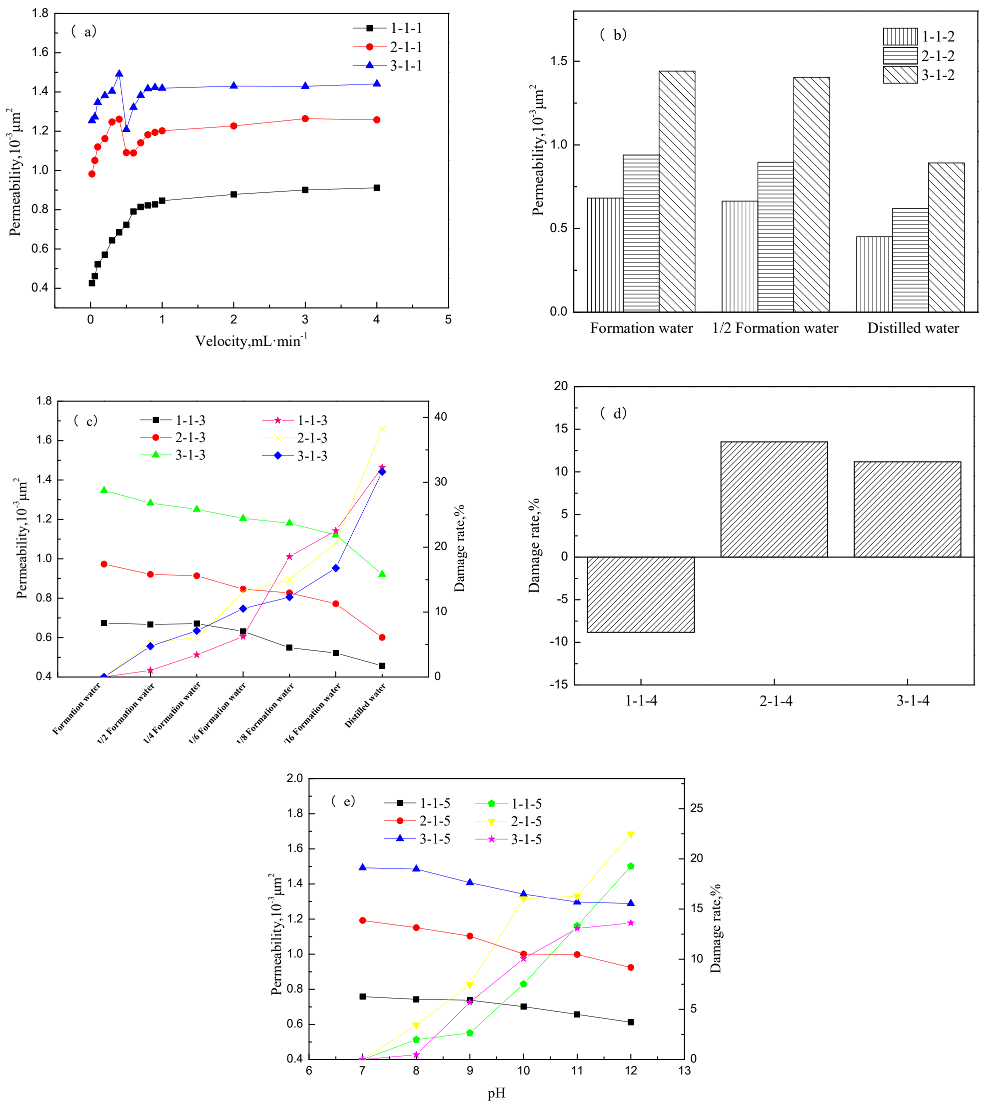


Fig. 5: Results of core velocity sensitivity (a), core water sensitivity (b), core salt sensitivity (c), petrocardiic acid sensitivity (d), and core alkali sensitivity (e).

of the long second layer is 33%-38%, which is moderately weak. The main reason is that there are a large number of clay minerals, such as kaolinite and illite, in the cracks of the Chang 2 reservoir. When the injected water enters the Chang 2 reservoir, the lattice expansion, dispersion, and migration of clay minerals occur, resulting in the blockage of the pore throat, reducing the migration channel of the reservoir, resulting in the reduction of reservoir permeability and water-sensitive damage. As can be seen from Fig. 5(c), when the injected water salinity is 1/16 formation water, the damage rate to the Chang 2 reservoir is greater than 20%. Therefore, the critical salinity of the Chang 2 reservoir is 4455.23~35641.79 mg.L^{-1}. As can be seen from Fig. 5(d), the acid sensitivity index of hydrochloric acid in the Chang 2 reservoir ranges from -8% to 13%, which is moderately weak acid sensitivity. This is because hydrochloric acid solution reacts with acid-sensitive minerals in the core after entering the core, resulting in secondary precipitation or releasing particles to block the pore throat, resulting in a decrease in reservoir permeability. As can be seen from Fig. 5(e), with the increase of pH value of injected water, its damage rate to the reservoir gradually increases. When the pH value is 12, the damage rate to the reservoir is lower than 20%, which is weak alkali sensitive. Therefore, the water-sensitive damage should be considered when the salinity of reinjection water or reinjection water is less than 4455.23 mg.L^{-1}.

Effect of Oil Content

Based on the mixed water sample of municipal sewage and Chang 2 reservoir produced water, injected water with different oil content is prepared to conduct a core damage experiment. Permeability and damage rate of injected water to the reservoir are taken as the investigation objects to determine the maximum oil content of injected water (Zhao 2020). The experimental results are shown in Fig. 6.

As can be seen from Fig. 6(a), with the increase in injection volume, the reservoir permeability will gradually decrease, and the damage rate to the reservoir will gradually increase. With the increase of the oil content in the mixed water sample, the permeability decreases greatly, and the damage rate to the reservoir increases gradually [Fig. 6(a)]. When the oil content is greater than 10 mg/L, and the injection volume increases to 30 PV, the damage rate to the core is greater than 20%, mainly because the crude oil in the water sample will adhere to the pipeline when entering the water injection pipeline. With the increase of the injection volume, the crude oil in the water sample will enter the core, resulting in the blockage of the pore throat of the core and the reduction of core permeability. When the oil content in the water sample is lower than 5 mg.L^{-1}, the permeability of the reservoir gradually decreases, but the damage rate to the reservoir is lower than 20%. This is because, with the increase of injection volume, impurities in the water sample will accumulate and block part of the pore throat, resulting in a slight decrease in core permeability and a low damage rate to the reservoir (Zhang et al. 2001, Cui 2021). Therefore, the oil content in the reinjection water sample should be kept below 5 mg.L^{-1}. However, the oil content in the water sample after mixing municipal sewage and produced water is 0.5 mg.L^{-1}, lower than 3 mg.L^{-1}, and the damage to the reservoir is less than 20%, which can be directly injected back into the Chang 2 reservoir.

Effect of Suspended Matter Content

Based on the mixed water sample of municipal sewage and Chang 2 reservoir produced water, injected water with different suspended solids content was prepared to conduct core damage experiment (Wang et al. 2016, Yang 2012). Permeability and damage rate of injected water to the reservoir were taken as the investigation objects to determine

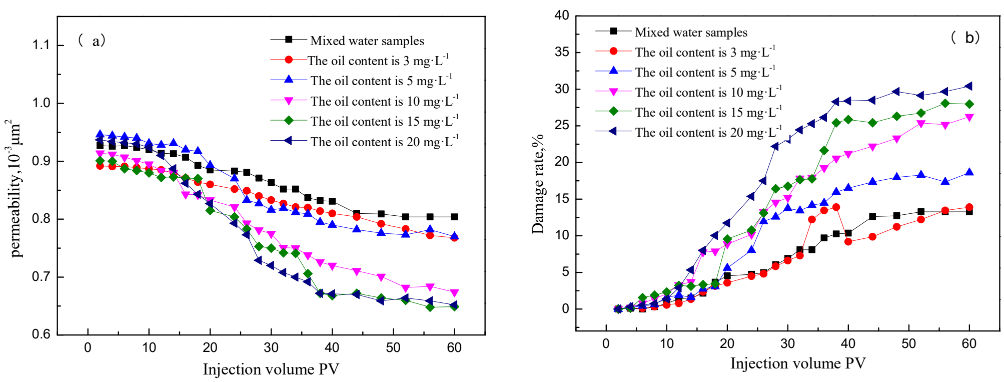


Fig. 6: Effect of oil content on reservoir.

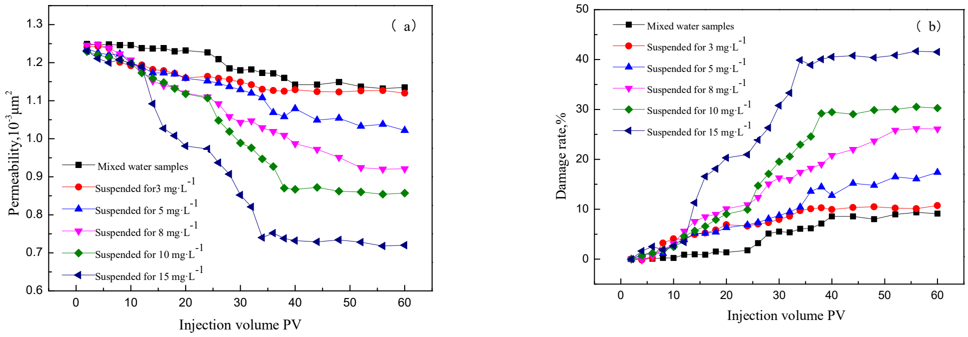


Fig. 7: Influence of suspended matter content on reservoir.

the maximum suspended solids content in injected water. The experimental results are shown in Fig. 7.

As can be seen from Fig. 7(a), with the increase of the content of suspended solids in the reinjection water sample, the permeability of the Chang 2 reservoir gradually decreases with the increase of the injected water volume. The damage rate of injected water to the core gradually increases with the increase of the injected water volume (Fig. 7(b)). When the injected volume is 30 PV, and the content of suspended solids in the water sample is 5 mg.L^{-1}, the damage rate of the core is lower than 10%. When the suspended solids increase to 8 mg/L, the damage rate of injected water to the core is higher than 20%. When the suspended solids content increases to 15 mg.$^{-1}$L, the damage rate of injected water to the core can reach more than 40%. The damage degree to the core is relatively large, so the suspended solids content of injected water can not be higher than 5 mg.L^{-1}. After mixing municipal sewage and produced water, the suspended matter content in the water sample is 1.8 mg.L^{-1}, lower than 5 mg.L^{-1}, and the damage to the reservoir is far less than 20% so that it can be directly injected back into the Chang 2 reservoir.

Effect of Particle Size of Suspended Matter

Based on the mixed water samples of municipal sewage and Chang 2 reservoir produced water, clay with different particle sizes was used to prepare solutions with a suspended solids content of 5 mg.L^{-1}, and core damage experiments were carried out. The maximum particle size of suspended solids in injected water was determined based on the permeability and damage rate of injected water to the reservoir. The experimental results are shown in Fig. 8.

As can be seen from Fig. 8(a), with the increase of the particle size of suspended solids in the reinjection water sample, the permeability of the Chang 2 reservoir gradually decreases with the increase of the injected water volume. The damage rate of injected water to the core gradually increases with the increase of the injected water volume (Fig. 8(b)). When the particle size of a water sample is less than 0.45 µm, with the increase of injection volume, the core has no damage. When the injection volume is 30PV, and the particle size of suspended solids increases from 3 µm to 5 µm, the damage rate of the core increases from %14 to %21. This is because the pore throat of the core will be blocked by the increase of the particle size of suspended solids in the water

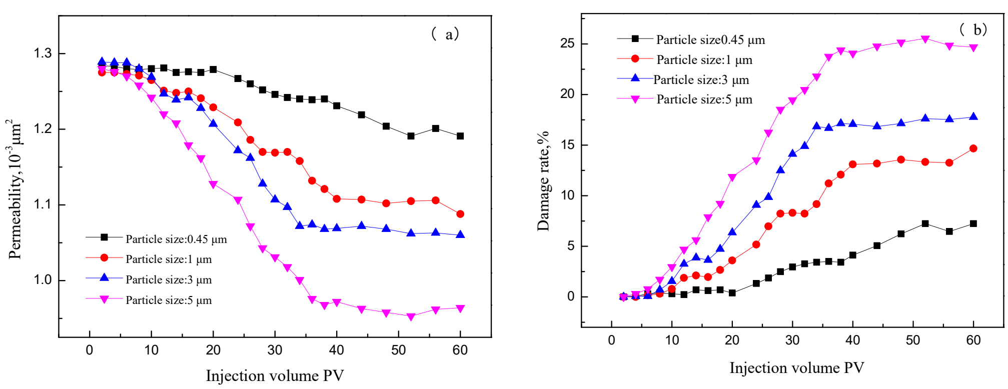


Fig. 8: Influence of particle size of suspended solids on reservoir.

Table 2: Recommended water quality indicators for reinjection.

Project	Recommended indexes
pH	6-9
Oil content [$mg.L^{-1}$]	≤5
Suspended matter content [$mg.L^{-1}$]	≤5
Median particle size [μm]	≤5
Corrosion rate [$mm.a^{-1}$]	≤0.067

sample, resulting in the decrease of reservoir permeability and the increase in damage rate. Therefore, the particle size of suspended solids in injected water is larger than 5 μm, which will cause serious damage to the core. The particle size of suspended solids in reinjected water should be controlled below 5 μm. The particle size of the water sample after mixing municipal sewage and Chang 2 reservoir-produced water is 0.8 μm, so the mixed water sample can be injected directly without harming the reservoir.

Indicators of Reinjection of Water

Through the compatibility test, clay swelling test, and reservoir damage test of municipal sewage and produced water, it can be confirmed that municipal sewage can be used as a reserve water source for oilfield reinjection water. Combined with Recommended Indicators and Analysis Methods for Water Quality of clastic Reservoir Injection (SY/T 5329-2012), the injection standard of mixed water samples of municipal sewage and produced water injected into the Chang 2 reservoir is proposed, and the results are shown in the following table.

CONCLUSION

(1) The water type of municipal sewage is sodium bicarbonate, with a salinity of 1381 mg/L and low-scaling ions. The produced water from the Chang 2 reservoir belongs to the calcium chloride type, with a high content of scaling ions and a mineralization degree of 35641.79 $mg.L^{-1}$. The static corrosion rate of municipal sewage and produced water is less than 0.076 $mm.a^{-1}$, which meets the reinjection standard.

(2) When the ratio of produced water to municipal sewage is 7:3, the maximum scaling amount is 42.5 $mg.L^{-1}$, and the calcium loss rate is 15.90 %. After adding a scale inhibitor, the scaling amount of the mixed water sample is reduced to 10.4 $mg.L^{-1}$, showing good compatibility. The clay swelling rate of the mixed water sample of produced water and municipal sewage is low, which meets the reinjection effect.

(3) The water sensitivity factor should be considered when the mixed water sample is reinjected into reservoir Chang 2. The contents of oil, suspended solids, and the median particle size of the reinjected water samples should be controlled at 5 $mg.L^{-1}$, 5 $mg.L^{-1}$, and 5 μm to avoid the damage of the reinjected water samples to the reservoir when reinjecting mixed water samples.

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