INTRODUCTION

Oil sand is a special geomaterial that contains an extremely viscous bitumen which is not recoverable in its natural state by conventional oil well production methods including currently used enhanced recovery techniques. It is actually one kind of unconsolidated sandstone reservoirs that is impregnated with high-content solid or semisolid bitumen and is characterized by loose skeleton that is composed of interlocked solid grains. Bitumen is found filling pores and crevices of oil sand, but it plays different roles in oil sands of different regions: In the Karamay terrestrial sand-in-bitumen oil sand, it chiefly functions as cement as well as framework that can withstand considerable effective stresses, while in the Alberta marine bitumen-in-sand oil sand, it mainly functions as filler. No matter what kind of oil sands it is, the bitumen will make a significant contribution to the reservoir geomechanical response during thermal stimulation, because of its special mechanical behaviors that are very sensitive to temperature. The bitumen in virgin reservoir conditions possesses a dramatically high viscosity, which indicates a considerable elasticity/viscoelasticity at a low temperature.
But the heated bitumen at more than 250°C is just like water, which possesses a perfect fluidity and bears no shear stress. In this regard, the existence of bitumen between solid grains makes a significant contribution to the elastic properties of oil sand, especially for the sand-in-bitumen oil sand, commonly seen in Karamay. The evaluation of reservoir deformation and its induced ground subsidence during thermal simulation is a focused issue for field engineers. To obtain a good evaluation result, determination of elastic properties of oil sand reservoir is very important. Through laboratory experiments, Lin et al. measured elastic and plastic deformation of Karamay oil sand, which revealed that there is a possibility the stress conditions and pressure levels implemented in the field are not adequate enough to trigger plastic deformation. In aspect of numerical simulation of water injection and process of SAGD, nonlinear elastic, elastoplastic, and viscoelastic models were used to depict the mechanical responses of oil sands. In these models, elastic parameters are essentially required. Hence, it is very important to clarify the elastic properties of oil sand.

Up to date, laboratory static mechanical and ultrasonic experiments have been usually used to study the temperature-dependent elastic properties of oil sand. For the laboratory mechanical experiments, oil sand samples collected from Faja (Venezuela), Athabasca, Cold Lake (Canada), and Karamay (China) were employed to conduct the triaxial drained compression tests for observing their stress–strain responses. Because the oil sands in different regions possess different skeleton structures, pore characteristics, mineral compositions, bitumen content, and viscosity, the effects of temperature on these kinds of oil sands may be somewhat different. Blair et al. studied the mechanical properties of Faja oil sands at 23, 125, and 250°C and found that the uniaxial compressive strength is lower in a higher temperature, but they did not get a clear conclusion about the effects of temperature on oil sand's elastic properties because of great petrophysical differences among different samples. Agar et al. used the oil sands collected from McMurray formation, Athabasca, to test the mechanical behaviors at temperatures of 20, 125, and 200°C and at an effective confining pressure 4~8 MPa, and concluded that the stiffness and shear strength at 125°C are higher than that at 20°C when the effective confining pressure is 4 MPa. Kosar used the oil sands cored from UTF formation, Athabasca, to see the deformation at temperatures of 20, 125, and 225°C and at an effective confining pressure 1~7 MPa, and considered that the initial stiffness and shear strength will be higher with temperature rising because of thermal consolidation of clay mineral. The oil sands in Clearwater formation, Cold Lake, were also employed by Kosar to investigate the effect of temperature on mechanical parameters, and he held an idea that the shear strength will be slightly lower in a higher temperature. Wong et al. used the oil sands in Esso Leming trial district, Cold Lake, to test the elastic properties at temperatures of 20, 65, 110, and 200°C and at an effective confining pressure of 1~8 MPa by cyclic loading, and they found that the elastic modulus under the same effective confining stress will increase at a higher temperature. The experimental studies exhibited above are all focused on the marine bitumen-in-sand oil sands. As a terrestrial sand-in-bitumen oil sand, Karamay oil sands were seldom investigated, especially about their properties in high temperature. Li et al. obtained the stress–strain curves of Karamay oil sands at temperatures of 20, 75, and 125°C and found that the elastic modulus at effective confining stresses of 0.5 and 5 MPa is highest at 70 and 125°C, respectively. Lin et al. conducted the experiments for Karamay oil sands at temperatures of 20, 45, and 70°C and at an effective confining stress of 0.5~5 MPa, and deemed that the stiffness will decrease with temperature increasing. For the ultrasonic experiments, the P- and S-wave velocities of the oil sands at varying pressures and temperatures were measured, and elastic properties can be calculated from the ultrasonic measurements based on Gassmann equation. Kato et al. measured ultrasonic P- and S-wave velocities on oil sand core samples collected from Hangingstone, Alberta, and found that the calculated shear modulus rapidly decreases with increasing temperature from 10 to 40°C, and then gradually decreases from 40 to 80°C; the bulk modulus obviously decreases at lower temperatures than 80°C. The measured dependence of ultrasonic velocity in Cold Lake oil sands on temperature is compared in Eastwood's study to theoretical model predictions for seismic wave propagation in porous media, and theoretical and experimental P-wave velocities agree within 5% for temperatures between 22 and 125°C and effective stresses of 1 and 8 MPa. Wang and Nur tested the wave velocities in hydrocarbon-saturated rocks and concluded that the largest changes in velocities with temperature are associated with the melting of solid hydrocarbons in rocks just like oil sands. Javanbakhti et al. discuss the relationship between temperature, apparent shear modulus, frequency, and velocity dispersion, and they used a linear relationship to model bulk modulus decline with temperature. Neither the static nor ultrasonic experiments can express the elastic properties as a continuous function of temperature, because of few test data and poor homogeneity among different samples. These empirical equations derive from several test data are in a low accuracy.

At present, it is a desired work to predict the elastic properties of oil sand by the individual elastic properties of the solid grains/bitumen, porosity, and microstructure, so that we can make the artificial oil sand cores possessing the desired elastic properties as accurately as possible and evaluate elastic properties of oil sand reservoir according to geophysical exploration methods. The changes of elastic properties of oil sand with temperature are due to the sensitive responses of bitumen to temperature (the bitumen is viscoelastic, so it can
be regarded as a temperature- and time-dependent nonlinear elastic material). When temperature changes, the changes of elastic properties of solid grains can be neglected compared with that of bitumen. In this regard, to find a relation of bitumen’s and oil sand’s elastic properties is an accessible approach, because the theoretical studies on bitumen’s properties were relatively mature. For example, the nomograph for determining the stiffness of bitumen proposed by Van Der Poel$^{27}$ was conveniently employed to obtain the elastic modulus of bitumen, if the bitumen’s softening temperature and penetration index were known. The oil sand can be viewed as a composite geomaterial, whose matrix and inclusion phases are bitumen and solid grains, respectively. Knowing the individual elastic properties of the bitumen/solid grains at any temperature, if the reservoir porosity was known, the oil sand’s effective elastic properties can be evaluated by the Eshelby, Mori–Tanaka, self-consistent, and differential methods. $^{28-32}$ The sand obtains the effective elastic properties by FEM. In these theoretical methods mentioned above, at least two elastic properties are needed, such as elastic modulus and Poisson’s ratio. The time- and temperature-independent elastic modulus and Poisson’s ratio of solid grains can be obtained from literatures, $^{33}$ and the time- and temperature-dependent elastic modulus of bitumen can be calculated from Van Der Poel’s nomograph, $^{27}$ but the Poisson ratio of bitumen was seldom considered as a function of temperature and time, which may lead to a poor theoretical prediction. In fact, the results predicted maybe cannot agree with test data, because there are fundamental assumptions in the theoretical methods, so the theoretical method must be combined with the test data.

In this contribution, some improved methods were proposed. First, a model for predicting time- and temperature-dependent Poisson’s ratio of bitumen was established. The Eshelby, Mori–Tanaka, and differential methods were adopted to analyze the effects of reservoir porosity, temperature, and time on the effective elastic properties of oil sand. Second, a new definition of the equivalent static time was proposed to eliminate the effect of time, so as to write the oil sand’s elastic properties as a function of only temperature. Third, a temperature transform was used to adjust the model to fit the experimental data. A case study was given to exhibit temporal and spatial distributions of elastic modulus and Poisson’s ratio of oil sand reservoir in the process of SAGD steam circulation. The method proposed not only can help the researchers obtain the artificial oil sand cores possessing the elastic properties they desired, but also can provide a guidance for the engineers in charge of field operations or numerical simulations to properly evaluate the elastic properties of these oil sand reservoirs lack of adequate laboratory experiments.

2 | PETROPHYSICAL PROPERTIES OF KARAMAY OIL SANDS

The elastic properties are the natural properties of a material, which are only determined by the compositions and structures of this material under the conditions of a certain environment like temperature and pressure. Oil sand is composed of four phases: mineral solids, water, bitumen, and gases.$^{2}$ The oil sands in Karamay are filled with the rich viscous bitumen, which keeps a solid state in initial reservoir conditions. Bitumen filled in pores is also viewed as the skeletons; therefore, it can make a significant difference to the elasticity of the oil sand. The skeleton of oil sands is viewed as a granular assembly with the cements including the clay and bitumen at the reservoir temperature of 18.5°C, $^{4,5,34}$ and pore fluids including the water and gases filled the pores under formation pressure. The mechanical behaviors of oil sands are very dependent on their compositions, microstructures, and other petrophysical properties. In this study, the composition, porosity, microstructure, and bitumen characteristics of Karamay oil sands were investigated. These experiments lay the foundation for subsequent analysis and discussion. All the used samples were collected in Qigu formation of the Fengcheng oilfield, Karamay, Xinjiang, China. All the experiments were conducted in the State Key Laboratory of Petroleum Resources and Prospecting, Beijing, China.

2.1 | Mineral compositions

The X-ray spectrometer (OXFORD Link ISIS300) was used for analyzing the mineral compositions of Karamay oil sands. The bitumen in the oil sand samples (with 6.6% bitumen) was first washed, and pure inorganic mineral substances including the common minerals as well as clays were used for the analyses. The results are shown in Table 1.

As shown in Table 1, the Karamay oil sand consists of twelve minerals, of which they were divided as common

| Minerals | Quartz | Feldspar | Dolomite | Siderite | Calcite | Pyrite | Anhydrite | Plaster |
|----------|--------|---------|----------|----------|---------|--------|-----------|---------|
| Contents (%) | 34.9 | 20.3 | 6.3 | 3.2 | 1.6 | 1.4 | 1.3 | 0.3 |

| Minerals | Chlorite | Illite | Kaolinite | Illite–smectite mixed layer |
|----------|----------|-------|-----------|----------------------------|
| Contents (%) | 11.1 | 9.8 | 8.3 | 1.5 |

TABLE 1 Mineral compositions of Karamay oil sands
minerals (from quartz to plaster) and clay minerals (from chlorite). The main minerals of Karamay oil sands are quartz, feldspar, dolomite, illite, kaolinite, and chlorite, of which the quartz and feldspar are the two most compositions, accounting for 35% and 20%, respectively. The high-content quartz means that the Karamay oil sand is a high-hydrophilic instead of an oleophilic geomaterial. The low contents of smectite and illite–smectite mixed layer make the Karamay oil sand possess a weak water sensitivity. The clay mineral accounts for 30.7%, which means a possibly low permeability.

The test results show that the Karamay oil sand has more than two-thirds of common minerals and one-third of quartz, indicating that there are adequate oil sand grains. The high quartzitic nature sand grains ensure that the elastic modulus of solid grains is very high, and little grain crushing occurs.

The studies for the mineral compositions were used to analyze the elastic properties. On one hand, the high quartzitic nature sand grains mean a high elastic modulus and a low Poisson's ratio. On the other hand, the shear dilation-induced porosity change has considerable effect on the overall elastic properties of the oil sand, which is regarded as a composite geomaterial.

### 2.2 Porosity characteristics

The particle size and porosity properties were investigated. The laser nanoparticle size analyzer (Zetasizer Nano ZS) was used for determining the particle size distributions of Karamay oil sand after the bitumen in pores being washed. Wet method, dispersing the pulverous oil sand samples in the liquid, was adopted. The particle size distributions are shown in Figure 1. The particle size distributions are shown in Figure 1. The porosity of Karamay oil sand with bitumen was tested by the automatic ratio surface and aperture analyzer (ASAP2020M). It is worth noting that the porosity of Karamay oil sand reservoir under water injection is much lower than that under oil production, because the solid bitumen plays a role of structures instead of pore fluids. The porosity test results of three samples are shown in Table 2.

From Figure 1, another studied oil sand sample (without bitumen) has about 20% clay, 60% silt, and 20% sands. The mass of oil sand grains with particle size ≥10 μm is more than 80%, which means the oil sands in Karamay have an excellent dilation potential if some adequate measures are taken for a reservoir stimulation by artificial operations.

The high-content oil sand grains make the Karamay oil sands have a high porosity including bitumen. The average porosity including bitumen is from 0.33 to 0.37, and the bitumen-rich oil sands seem to exhibit a higher value than regular and mud-rich oil sands. However, the bitumen under reservoir condition and even under the operation of water injection (normally from 20 to 80°C) is too viscous to flow, so another porosity named the porosity excluding bitumen is always used for reservoir geomechanical analyses. The average porosity excluding bitumen ranges from 0.13 to 0.17, and the bitumen-rich oil sands show a lower value than others.

Some experiments were conducted to find evidences that the porosity (excluding bitumen) increase exists under the operation of water injection. The dilation mechanisms in this process are proven to be shear- and tensile parting-induced dilations. From the test results, the regular and bitumen-rich oil sands show a very significant dilation capability under both shear and tensile parting. Especially, the shear dilation-induced porosity increases by 0.05 for the regular oil sand, and the tensile parting-induced porosity increases by 0.08 for the bitumen-rich oil sand. The mud-rich oil sand shows a lower shear dilation capability for this tested specimen. The discussions above show enough evidences for considerable shear dilation capability or potential for Karamay oil sands.

### 2.3 Microstructure characteristics

Oil sand samples including a bitumen-rich oil sand and a regular oil sand were used. The experiment for the bitumen-rich oil sand was used to focus on the in situ distributions of solid grains and bitumen, and to find which materials the inclusions are (solid grains or bitumen). The regular oil sand is used to observe the microfracture induced by dilation during water or steam injection. The microstructures were investigated by the environmental scanning electron microscope (ESEM, FEI Quanta 200F). The ESEM experiments can obtain the origin Karamay oil sands with water and bitumen, so it can embody the real microstructures of oil sands. Figure 2 shows the microstructures of Karamay bitumen-rich oil sands. Figure 2A-D is both the initial oil sand structures before shear, and their magnifications are 60, 75, 90, and 120 times, respectively.

From Figure 2, it is obvious that the grains are surrounded by the continuous bitumen (sand-in-bitumen mode).

![Figure 1](image-url) **Figure 1** Particle size distributions of Karamay oil sands
Therefore, if the oil sand is regarded as a composite material, the bitumen and solid grains are the matrix and inclusions, respectively. These solid grains are in an irregular arrangement and relatively loosely packed. The Karamay oil sand grains are interlocked just like the Canadian oil sand, but the presence of intergranular rich bitumen lowers the capability or potential of dilation.

2.4 Bitumen characteristics

The bitumen in the Karamay oil sand is in a semisolid or solid state in the initial condition, so it cannot flow at all before steam injection. The roles of bitumen in Karamay oil sand can be played as the pore fluid, skeleton, and cement. The role of the pore fluid can be easily understood, though bitumen cannot flow. The roles of skeleton and cement are due to its super high viscosity. The initial viscosity of Karamay bitumen ranges from $10^5$ to $10^6$ mPa·seconds. Temperature increase through steam injection can effectively decrease the viscosity of bitumen, and the relation of the viscosity and temperature of bitumen collected from a SAGD well is shown in Figure 3. In general, the bitumen viscosity in a certain temperature is determined by its components. The more content the macromolecule (asphaltenes and resins) is, the more viscous the bitumen is. To know the components of the bitumen abstracted from the Karamay oil sands, the mass contents of asphaltenes, resins, aromatics, and saturates are tested according to ASTM D4124-09. The test results are shown in Table 3.

As shown in Figure 3, the viscosity of Karamay bitumen drops sharply with the temperature increase. In the reservoir condition, the viscosity of bitumen dramatically reaches as high as $3 \times 10^6$ mPa·seconds. This means that the Karamay bitumen cannot flow at all and always stay in the initial positions under the water injection temperature of 20–80°C. In the SAGD process, when the viscosity of

| Sample                  | Average porosity including bitumen | Average porosity excluding bitumen | Dilation-induced porosity by experiments |
|-------------------------|------------------------------------|-----------------------------------|----------------------------------------|
| Regular oil sand        | 0.33                               | 0.17                              | 0.23→0.28                              |
| Mud-rich oil sand       | 0.33                               | 0.16                              | 0.22→0.23                              |
| Bitumen-rich oil sand   | 0.37                               | 0.13                              | 0.18→0.20                              |

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crude oil drops to a critical value of 1000 mPa·seconds, the drained zone forms and it is not very difficult for the pore fluids to flow under some driving forces. For achieving this, the reservoir temperature should be at least 140°C. The viscosity of Karamay oil drops to a value of less than 10 mPa·seconds, which is absolutely favorable for oil production rate. The bitumen in the process of water injection plays a role of skeleton and cement, and it can affect the shear dilation capability in some degree. The sliding of oil sand grains forces the intergranular mixtures of clay and bitumen to be dislocated, leading to the collapse or expansion of primary pores. The degree of this behavior is dependent upon the intergranular cementing strength, which is related to the content of asphaltenes and resins. Table 3 shows the separation of Karamay bitumen into four fractions. As shown in Table 3, the asphaltenes and resins of Karamay bitumen account for 20.87% and 27.42%, respectively. It means that the cementing strength caused by viscous bitumen is very high.

2.5 | Composite material model

According to previous studies, the grain-in-bitumen Karamay oil sand can be viewed as a particle reinforced composite material, of which the matrix phase is bitumen and the inclusion phase is solid grains, just as shown in Figure 4. In this study, the solid grains are assumed as spheres with different diameters and are randomly distributed in bitumen. The clay is mixed with bitumen, and it will not be treated as an individual phase for simplicity.

Water and gas are neglected in the composite model for its low content. The porosity is equal to the volume ratio of bitumen. It is assumed that the matrix phase (bitumen) has not be squeezed out of pores during steam circulation phase, because of relatively high viscosity of bitumen as well as no production differential between SAGD wells. When switching to SAGD production phase, the heated bitumen will flow into the production well, and most of solid grains will contact with each other. It is noted that the elastic properties of oil sands in this study were predicted when the bitumen stays in the original position.

3 | MATHEMATICAL MODEL FOR ELASTIC PROPERTIES OF KARAMAY OIL SAND

The oil sand consists of solid grains (including clay), bitumen, water, and gas. Water and gas have no effect on the elastic properties in a drained condition. The solid grains are absolutely elastic until the yield stress under the condition of a certain effective confining stress. The bitumen is viscoelastic in most of conditions. In the thermal stimulation, the reservoir temperature changes from the initial reservoir temperature to a high temperature of more than 250°C. During this process, the property changes of bitumen are absolutely considerable. The virgin bitumen is in a solid state, but the heated bitumen is a Newton fluid just like the pore water. In a relatively lower temperature, the bitumen possesses an elastic or viscoelastic property, but the elasticity would weaken a great deal with temperature increasing (time would also affect the viscoelasticity of bitumen). The effects of temperature and time on the bitumen elasticity are described in Figure 5.

Figure 5 shows the bitumen property changes from pure elasticity to pure viscosity under different ranges of temperature and time. When the temperature is lower than $T_1$ and the time is shorter than $t_1$, the bitumen tends to show pure elasticity. When the temperature is higher than $T_2$ and the time is longer than $t_2$, the bitumen shows pure viscosity. $T_1$,

| Components | Asphaltenes | Resins | Aromatics | Saturates |
|------------|-------------|--------|-----------|-----------|
| Mass contents (%) | 20.87 | 27.42 | 17.61 | 34.10 |

FIGURE 3 Relation of viscosity and temperature of Karamay bitumen

FIGURE 4 Composite material model for Karamay oil sands

TABLE 3 Separation of Karamay bitumen into four fractions
FIGURE 5  Bitumen property changes under varying temperatures and times

$T_2$, $t_1$, and $t_2$ are all critical values related to natural properties of material studied. The bitumen shows viscoelasticity in other remaining conditions. In this study, the elasticity and viscosity of bitumen are viewed as two extreme conditions of viscoelasticity. The effects of temperature and time on elastic properties of solid grains were neglected.

3.1 Elastic properties of bitumen

The Karamay oil sand bitumen in virgin reservoir conditions keeps a solid state, and it possesses a considerable high elasticity (or viscoelasticity) in a relatively low temperature. To deduce the mechanical properties of a given viscoelastic bitumen in the whole range of temperatures and times of loading that are of practical interest, Van Der Poel\textsuperscript{27} proposed a simple extension of the concept of Young’s modulus. The parameter was denoted as stiffness (modulus) $S$:

$$S = \left( \frac{\sigma}{\varepsilon} \right)_{T,t},$$  
(1)

where $\sigma$ is the load on bitumen samples in the static creep test, MPa; $\varepsilon$ is the resulting deformation, %; $T$ is the temperature, °C; and $t$ is the time, s. When the material is purely viscous (that happens when the temperature is high enough, or the time is long enough), its stiffness can be written as:

$$S = \frac{3\eta(T)}{t},$$  
(2)

where $\eta(T)$ is the dynamic viscosity at $T$, Pa-seconds. However, when the reservoir temperature is relatively lower than a critical temperature (softening temperature), the Karamay bitumen is viewed as the solid skeleton. For example, the bitumen during the phase of SAGD startup by water injection and early phase of steam circulation has a considerable elasticity,\textsuperscript{4,5,7,8,10} so Equation (2) is not suitable for predicting the stiffness of bitumen under a low temperature. In this regard, Van Der Poel\textsuperscript{27} provided the engineers with a nomograph for determining the stiffness of bitumen by a large number of experiments. However, the nomograph is not convenient for analytical or numerical analyses, so Zeng et al\textsuperscript{38} proposed a general formulation for predicting the stiffness modulus of asphalt using routine test data of Van Der Poel\textsuperscript{27} This relation is as follows:

$$S = \frac{S_g}{1 + \left[ \frac{t}{10} \left( \frac{T - T_1}{500} \right) + \frac{T - T_2}{10} \right]^2}$$  
(3)

where $S_g$ is the stiffness of glass-state bitumen, MPa, $S_g =$ 3000 MPa; PI is the penetration index; $\Delta T$ is the difference of the actual and softening temperatures, °C; $A = 500$; $T_1 = 0.2060$, $k_2 = 4.996$, $k_3 = 0.1710$; $t_1 = 0.6000$ seconds; $t_2 = 1.260$, $t_3 = 0.7346$; $t_4 = -6.0535$; $T_1 = 1^\circ $C; $c_a = -0.9413$; $c_b = 36.61$; $c_c = 18.40$, $c_d = 4.616$, $c_e = 443.8^\circ $C.

In Equation (3), the stiffness $S$ under any $T$ and $t$ can be obtained if the PI and $T_{R&B}$ are measured by experiments. The $T_{R&B}$ can be directly obtained according to ASTM D36/D36M-14e1.\textsuperscript{39} The PI can be calculated by

$$PI = \frac{20 - 500A}{1 + 50A}$$  
(4)

The stiffness of Karamay bitumen in virgin reservoir conditions keeps a solid state, and it possesses a considerable high elasticity (or viscoelasticity) in a relatively low temperature.
\( \nu = 0.5 \). But, for the lower temperatures, Poisson’s ratio may change down to \( \nu = 0.3–0.33 \). In this paper, the ring-and-ball softening temperature \( T_{\text{R&B}} \) is viewed as the critical value. The Poisson ratio is \( \nu = 0.33 \) under the initial reservoir temperature \( T_i \). Considering that the change rate at a lower temperature range is absolutely more sensitive than that at a high temperature, this paper proposed two methods to model the evolution of Poisson’s ratio with varying temperatures \( \nu(T) \). The first method is modeled by a parabolic form

\[
\nu(T) = \begin{cases} 
\frac{0.17}{(T_i-T_{\text{R&B}})}(T-T_{\text{R&B}})^2+0.5, & T_i \leq T \leq T_{\text{R&B}} \\
0.5, & T \geq T_{\text{R&B}} 
\end{cases} . \tag{6}
\]

The second method is a sine form

\[
\nu(T) = \begin{cases} 
0.33 + 0.17 \sin \left( \frac{\pi}{2} \times \frac{T_i-T}{T_{\text{R&B}}-T_i} \right), & T_i \leq T \leq T_{\text{R&B}} \\
0.5, & T \geq T_{\text{R&B}} 
\end{cases} . \tag{7}
\]

The curves of the two modeling are exhibited in Figure 7. Both two curves reasonably expressed the change of Poisson’s ratio from 0.33 to 0.5, when the temperature ranges from the initial reservoir temperature to a high temperature. The bitumen is viewed as a liquid under a temperature of more than the melting point, and its Poisson’s ratio is 0.5. That the slope under a lower temperature exceeds that under a high temperature is consistent with experiments, in which the Poisson ratio is more sensitive to temperature in a lower temperature range than a high temperature range.\(^{23}\) Therefore, the two methods both achieved good modeling results.

Apart from the temperature, the effect of time on Poisson’s ratio was discussed when the temperature \( T \) is a constant, in general as a room temperature or initial reservoir temperature \( T_i \). In this paper, an exponential form was used to model the relation of Poisson’s ratio \( \nu(t) \) and \( t \) using the method of Tschoegl.\(^{43}\)

\[
\nu(t) = 0.5 - Ae^{-\frac{t}{T}}, \tag{8a}
\]

where \( A \) and \( B \) are parameters related to material properties, and they can be acquired by experiments. In this study, the \( A \) and \( B \) were 0.167 and 1, respectively.\(^{42,43}\)

\[
\nu(t) = 0.5 - 0.167e^{-t}. \tag{8b}
\]

Figure 8 shows changes of Poisson’s ratio under varying temperatures in a semilogarithmic coordinates. For the bitumen, a loading time shorter than 0.1 seconds (regarded as transient loading in an undrained condition) means a weak lateral deformation capacity just like these hard rocks, so its Poisson’s ratio is around 0.33. When the loading time exceeds 10 seconds, the bitumen is regarded as an incompressible liquid, and its Poisson’s ratio reaches 0.5.

To embody the effects of both temperature and time on Poisson’s ratio, the geometric mean was used to express the Poisson ratio as a function of temperature and time in a form as

\[
\nu(T,t) = \begin{cases} 
\sqrt{0.33 + 0.17 \sin \left( \frac{\pi}{2} \times \frac{T_i-T_{\text{R&B}}}{T_{\text{R&B}}-T_i} \right)} \left( 0.5 - 0.167e^{-t} \right), & T_i \leq T \leq T_{\text{R&B}} \\
\sqrt{0.5 \times (0.5 - 0.167e^{-t})}, & T \geq T_{\text{R&B}} 
\end{cases} . \tag{9}
\]

or

\[
\nu(T,t) = \begin{cases} 
\sqrt{\frac{0.17}{(T_i-T_{\text{R&B}})}(T-T_{\text{R&B}})^2+0.5} \left( 0.5 - 0.167e^{-t} \right), & T_i \leq T \leq T_{\text{R&B}} \\
\sqrt{0.5 \times (0.5 - 0.167e^{-t})}, & T \geq T_{\text{R&B}} 
\end{cases} . \tag{10}
\]

According to Equations (9) and (10), the Poisson ratio under any \( T \) and \( t \) can be determined. In this paper, the changes

![Figure 6](image-url) Stiffness of Karamay bitumen under varying temperatures

![Figure 7](image-url) Poisson’s ratio of Karamay bitumen under varying temperatures
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FIGURE 8 Poisson's ratio of Karamay bitumen under varying time

of Poisson's ratio under varying temperatures (when \( t = 0.01 \), 1, and 100 seconds, respectively) are plotted in Figure 9. The time can be adjusted as per the field practice, and the effect of temperature is mainly focused on in this study.

3.2 Effective elastic properties of oil sands

In this paper, the oil sand is viewed as a composite geomaterial. This composite material is composed of matrix and spherical inclusions. Oil sand microstructures by ESEM revealed that the oil grains are surrounded by bitumen. The bitumen is continuous, and the particle is isolated. The volume of initial water and gas is neglected. Therefore, for this geomaterial, the bitumen is the matrix, and the solid grains are the inclusions. The solid grains are assumed as an isotropic perfect ideal elastic plastic material. The bitumen under the condition of a certain temperature and time is regarded as an equivalent elastic material.

For the grain-in-bitumen oil sands, the matrix phase is bitumen, and the inclusion phase is the solid grains. It is assumed that all the solid grains are spherical and randomly distributed in the matrix; the solid grains and bitumen are all isotropic materials. The elastic stiffness tensor of bitumen at any \( t \) and \( T \) is

\[
L_0 (T, t) = \left[ 3k_0 (T, t), 2\mu_0 (T, t) \right]
\]

The elastic stiffness tensor of solid grains is

\[
L_1 = \left( 3k_1, 2\mu_1 \right)
\]

where \( k_i \) and \( \mu_i \) are the bulk modulus and shear modulus, respectively (\( i = 0 \) and \( 1 \) denote the matrix and solid grains, respectively). The volume ratio of the solid grains is \( c_1 \), so the porosity of oil sand is \( 1 - c_1 \). Up to date, four methods including the Eshelby method, Mori–Tanaka method, self-consistent method, and differential method were usually used to predict the effective elastic properties of a composite material. Because the solid grains are nearly rigid compared with the bitumen, the self-consistent method cannot properly predict the elastic properties of a composite material whose porosity (matrix volume ratio) is <0.5.\(^3\)\(^\text{10} \) Therefore, the remaining three methods were employed to predict the effective elastic properties of oil sands. The predicted results using the Eshelby method were\(^2\)\(^8 \)

\[
k_{\text{Es}} = k_0 + \frac{c_1}{3} \frac{(k_1 - k_0)(3k_0 + 4\mu_0)}{3k_1 + 4\mu_0}
\]

\[
\mu_{\text{Es}} = \mu_0 + \frac{5c_1\mu_0}{3k_0(3\mu_0 + 2\mu_1)} \frac{(3k_0 + 4\mu_0)}{4\mu_0 (2\mu_0 + 3\mu_1)}.
\]

The predicted results using the Mori–Tanaka method were\(^3\)\(^1 \)

\[
k_{\text{MT}} = k_0 + \frac{c_1}{3} \frac{(k_1 - k_0)(3k_0 + 4\mu_0)}{3k_0 + 4\mu_0 + 3(1 - c_1)(k_1 - k_0)}
\]

\[
\mu_{\text{MT}} = \mu_0 + \frac{5c_1\mu_0}{5\mu_0 (3k_0 + 4\mu_0) + 6(1 - c_1)(\mu_1 - \mu_0)(k_0 + 2\mu_0)}
\]

The predicted results using the differential method were\(^3\)\(^2 \)

\[
\frac{dk_{ds}}{dc_1} + \frac{(k_{ds} - k_1)}{(1 - c_1)(3k_1 + 4\mu_0)} = 0
\]

FIGURE 9 Poisson's ratio of Karamay bitumen under varying temperatures and time
Equations (13-20) can be written as a function of the two

different methods, respectively. The reason can be attributed to the different assumptions of each method. First, the Eshelby method does not take

In this regard, if the elastic modulus and Poisson's ratio of bitumen and solid grains are known, the elastic modulus and Poisson's ratio of oil sand can be calculated by Equations (13-22). The solid grains are mostly comprised of quartz, so the time- and temperature-independent elastic's modulus and Poisson's ratio of inclusions are 124 GPa and 0.077, respectively. The elastic modulus (stiffness $S$) of bitumen at any $T$ and $t$ can be determined by Figure 6. The Poisson ratio of Karamay oil sand bitumen at any $T$ and $t$ can be obtained by Figure 9. Next, the three methods were adopted to predict the changes of elastic properties ($E/E_0$ and $\mu/\mu_0$) of the oil sand in the SAGD phase, including the startup by water injection and thermal stimulation (steam circulation and injection).

### 3.2.1 Effective elastic properties induced by porosity changes during SAGD startup phase

The porosity change occurs when the oil sand is under dilation induced by water or steam injection, just as discussed in our published paper and exhibited in Table 2. Figure 10 shows the effects of dilation-induced porosity changes on the elastic properties of oil sands. The modeling temperature is the initial reservoir temperature $T_i = 18.5^\circ C$, and the modeling time is 0.01 seconds. The initial porosity of Karamay oil sand reservoir is 0.33 according to Table 2. It was assumed that a theoretical maximum porosity of 0.476 can be achieved after dilation.

From Figure 10, it can be concluded that the effective elastic modulus predicted by three methods decreases with porosity increasing, while the Poisson ratio shows an opposite trend. When the porosity changes from 0.33 to 0.476, the effective elastic modulus reduces to 13%, 37%, and 52% by the Eshelby, Mori–Tanaka, and differential methods, respectively; meanwhile the effective Poisson's ratio increases to 1.2%, 2.9%, and 10% by three methods, respectively. These changes reveal that the volumetric dilation under water injection has important influence on the reservoir.

The trends of predicted elastic modulus and Poisson's ratio by the Eshelby, Mori–Tanaka, and differential methods are quite different by increasing porosity. Differential method is much more sensitive to porosity than the other two. The reason can be attributed to the different assumptions of each method. First, the Eshelby method does not take
the interaction between the inclusions into consideration, so the change in porosity only leads to a change in the ratio of inclusions to the volume of matrix. Thus, porosity shows less impact on the effective elastic parameters predicted by the Eshelby method. Second, the Mori–Tanaka method takes the interaction between inclusions into account by far-field equivalent stress. In addition to the change in the ratio of inclusions and matrix volume, the change in porosity also affects the interaction between inclusions, which results the porosity sensitivity of the Mori–Tanaka method is higher than the Eshelby method. Finally, the differential method always maintains the state of single inclusion, which avoids the impact of the interaction between inclusions. This assumption is more reasonable than the assumption of the Eshelby method. The calculation method of differential method is simpler than the Mori–Tanaka method, by using a theoretically true far-field stress, rather than a far-field equivalent stress. Hence, the differential method is most sensitive to porosity.

3.2.2 Effective elastic properties induced by temperature propagation during thermal stimulation

The temperature change occurs when the hot water or steam is injected into the oil sand reservoir and the reservoir is heated to a high temperature as high as more than 250°C. Figure 11 shows the effects of temperature changes on the elastic properties of oil sands. The modeling porosity is 0.33, and the modeling time is 0.01 seconds. The modeling temperature is from the initial reservoir temperature $T_i = 18.5-250°C$.

From Figure 11A, all the predicted methods gave almost the same results of evolutions of effective elastic modulus with temperatures. Compared with porosity, the elastic properties are more sensitive to the temperature. It can be seen that the elastic modulus decreases by 50% when the temperature drops from 18.5 to 25°C. When the temperature increases to 35°C, the elastic modulus is only less than 10% of the initial elastic modulus. When the temperature is more than the softening temperature, the oil sand is more like a liquid instead of a solid. Figure 11B shows that the effective Poisson’s ratio will rise when the reservoir is heated. There is little difference between the predicted results of the three methods. A small drop exists for the ultimate evaluation by the differential method because of numerical fluctuation.

3.2.3 Effective elastic properties induced by injection time

Considering the time has an influence on the stiffness of bitumen, the elastic properties are absolutely related to time. The field operations (water or steam injection) usually last for a time as long as several months. Figure 12 shows the effects of time changes on the elastic properties of oil sands. The modeling temperature is 18.5°C, and the porosity is 0.33. The modeling time ranges from 0.001 seconds to 2 months.

From Figure 12A, the elastic modulus drops sharply with the time increasing. All the results predicted by the three methods were almost the same with each other. When the time changes from 0.001 to 0.004 seconds, the elastic modulus decreases by 50%. The elastic modulus will be <10% of initial value with a longer time of more than 0.1 seconds. The elastic modulus of oil sand under a loading time of more than 10 seconds was very low, and its elasticity can be neglected compared with the solid grains. Figure 12B shows that the Poisson ratio will be higher with a longer time. When the time ranges from 0.001 to 0.1 seconds, the Poisson ratio changes very slowly. Thereafter, it will rise sharply until around 10 seconds, and the ultimate value will be 1.27–1.29 times of the initial value. A small drop exists for the ultimate
evaluation by the differential method because of numerical fluctuation.

3.2.4 | Equivalent static time \( t_{eq} \) and temperature transform \( f_{teq} \)

In previous sections, the effects of both temperature and time were discussed. However, the reliability of the model proposed was difficult to be supported by conventional uniaxial or triaxial compression tests. At present, these rheological experiments for oil sands considering high temperature are very hard to be conducted; and rheological experiments were only mentioned in a few literatures, like Wang and Wong\(^{44} \) and Blair et al\(^{17} \). In conventional tests, the mechanical behaviors are time-independent or so-called static, and only the test temperature can be controlled. That is to say, if the effect of time can be eliminated, the theoretical model can be combined with the conventional compression tests to give a practical evaluation approach.

In this contribution, we achieved it by defining an equivalent static time \( t_{eq} \) and by using a transform for the temperature \( f_{teq} \) to eliminate the effects of time and to coincide with the actual experimental data.

First, the equivalent static time \( t_{eq} \) was defined and determined by tested data. The use of this concept is to establish the relation of the theoretical model and conventional experimental data. It was defined just as follows: When the loading time is \( t = t_{eq} \) and \( T = T_0 \) (\( T_0 \) is the reference temperature, and let \( T_0 = 20^\circ C \)), the elastic modulus and Poisson’s ratio predicted by theoretical models are equal to those measured by experiments. By our methods, when \( t_{eq} = 0.001s \), the predicted elastic modulus of bitumen at 20°C by three methods was 196, 426, and 790 MPa, respectively; the predicted Poisson’s ratio of bitumen by three methods was 0.27, 0.33, and 0.31, respectively. These data agreed very well with our triaxial compression experiments under varying temperatures\(^{4,7,8} \) as shown in Table 4. Hence, \( t_{eq} = 0.001s \) was used in this study.

Table 4 lists our test data of elastic modulus and Poisson’s ratio at the temperatures of 20, 45, and 70°C, respectively.

Unfortunately, the evolutions of elastic properties under varying temperatures shown in Figure 13 were very different to the test data represented by circles. For instance, when the temperature changes from 20 to 45°C, the elastic modulus decreases by 37%, and the Poisson ratio does not change according to our experiments. But the elastic modulus decreases more than 90%, and the Poisson ratio increases to 1.13–1.15 times of the initial value, using the curves in Figure 13.

In fact, the predicted difference between the curves in Figure 13 and test data was because of the elimination of time and the introduction of \( t_{eq} \). In this paper, the method of temperature transform was used to express the elastic properties as the function of only temperature. This process can be exhibited as

\[
 g_{test}(T) = g_{theory}(T', t_{eq}'),
\]  

where \( g_{test}(T) \) is the elastic properties at temperature \( T \) by experiments; \( g_{theory}(T', t_{eq}') \) is the elastic properties at

| Temperature | Elastic modulus | Poisson’s ratio |
|-------------|-----------------|-----------------|
| \( T \) (°C) | \( E \) (MPa) | \( E/E_0 \) (−) | \( ν \) (−) | \( ν/ν_0 \) (−) |
| 20          | 663            | 1               | 0.3   | 1               |
| 45          | 421            | 0.63            | 0.3   | 1               |
| 70          | 388            | 0.59            | 0.4   | 1.33            |
temperature $T'$ and time $t_{\text{eq}}$ predicted by curves in Figure 13. Here, let $t_{\text{eq}} = 0.001\text{s}$, and $T'$ can be found by Figure 13A. So, there is a transform from $T$ to $T'$, which is induced by the elimination of time.

$$T' = f_{\text{eq}}(T), \quad (24)$$

where $f_{\text{eq}}$ is a function related to $t_{\text{eq}}$.

In this paper, the data of elastic modulus were used to obtain the $f_{\text{eq}}$, because the changes of Poisson’s ratio by experiments did not show a clear tendency, just as Table 4 and Figure 13B show. In fact, the Poisson ratio is usually more difficult to be accurately measured compared with the elastic modulus, because of many factors like the manual operations in the test process and the parameter determination derived from the complex axial strain–lateral strain curves, especially for these soft rocks such as oil sand.

According to Figure 13A, when $f_{\text{eq}} = f_{\text{eq}} = 0.001\text{s}$, Equation (24) can be expressed as

$$T' = 7.1373\log_{10}(T) + 10.874. \quad (25)$$

Up to now, the elastic modulus and Poisson’s ratio at any actual temperature $T$ can be calculated by the temperature transform. To fit the maximum Poisson’s ratio of 0.4 by experiments, the ultimate value in Figure 13B was adjusted by enlarging the slope. The calculation of Poisson's ratio under varying temperatures was also based on the temperature transform as Equation (25) shows. For Poisson’s ratio, only evaluation predicted by the Mori–Tanaka method was given, for instance. The evolutions of...
elastic properties of oil sand at varying temperatures are shown in Figure 14.

According to Figure 14, the changes of elastic properties of oil sand reservoir can be evaluated if the temperature propagation during the thermal stimulation was known. In the next section, our mathematical model was employed to predict the elastic property distributions of an oil sand reservoir with a SAGD well pair A-3 under steam circulation.

4 | CASE STUDY

Well pair A-3 corresponds to a recently studied reservoir in area A of the Fengcheng oilfield, Karamay, Xinjiang Province. The depth of the I well and P well is 453 and 458 m, respectively. The oil sand reservoir is thick enough, so the interference of cap and base rocks can be neglected in the process of heat transfer. The in situ viscosity can exceed $5 \times 10^6$ mPa·seconds under reservoir conditions, and the bitumen is essentially a solid. The steam circulation is used to heat the oil sand reservoir between the two wells, so as to establish a thermal communication and to prepare for the SAGD production. Tested results revealed that the initial reservoir temperature was 20°C, and the bottom hole vapor temperature was kept at 260°C. In Fengcheng oilfield, the circulation period was always maintained for about 6–12 months because of the super high viscosity of bitumen.

In this study, the numerical simulation was established by FEM software ABAQUS. The 2D finite element model of SAGD steam circulation in oil sand reservoir was designed as a rectangle with the size of 20 m in length and 10 m in width (in Figure 15). The distance between two wellbores is 5 m. The wellbore size is 0.25 m in diameter. The horizontal section of the well pair was designed to be 370 m in length. It must be notified that the model is symmetric; therefore, only one-half of the model is established and studied, and the other half of the model is in the same situation. In the model, the element type of CPE4T (A 4-node plane strain thermally coupled quadrilateral, bilinear displacement and temperature) was used, and totally, 1107 high-quality meshes were generated.

The heat transfer in oil sand reservoir during the steam circulation phase was discussed in our published paper, and here, the calculation process will not be given. The predicted temperature of oil sand reservoir under varying injection time was exhibited. Figure 16 shows the temperature distributions at 30, 60, 120, and 300 days. In these figures, the temperatures in a profile perpendicular to the borehole axis were given. The midpoint of the two wells was set as the origin of coordinate $X\text{-}Y$. The upper vertical direction is $x$-axis, and the right parallel direction is $y$-axis. The unit of these values in the color bars of Figure 16 is °C.

The temporal and spatial distributions of oil sand reservoir temperature can be obtained by our temperature evaluation model of heat transfer considering the phase change behavior of bitumen. Figure 16 shows the temperature propagation is not so rapid during the steam circulation phase, and the midpoint of two wells can reach about 110°C, which is a signal for switching to SAGD production by letting the P well produce oil instead of steam circulation. Using our model that can predict the elastic properties by temperatures, the fields of elastic modulus and Poisson’s ratio in the process of SAGD steam circulation are shown in Figures 17 and 18, respectively. The units of these values in the color bars of Figures 17 and 18 are MPa and 1, respectively.

From Figures 17 and 18, it can be seen that the changes of elastic properties will be more apparent with the circulation time increasing. In the domain near the wells, the high temperature induces a deterioration of elastic modulus and a rise of Poisson’s ratio. When the oil sand reservoir is heated to 260°C, the elastic property will decrease to 260 MPa, which is less than half of the value in virgin reservoir condition. The Poisson ratio in the reservoir near wells is 0.48, which means the oil sand will show a fluidity when the intergrain
bitumen melts in a high temperature. The ultimate state after circulation for 300 days revealed that the elastic properties of oil sand reservoir in the square area of $20 \times 20$ m (the area of $-10 \leq x < 0$ was not shown) undergo a significant evolution.

Next, the changes of elastic properties of the midpoint $(0,0)$ during the steam circulation will be investigated. The changes of temperature and elastic properties in midpoint with time are plotted in Figures 19 and 20, respectively.

As shown in Figure 19, the temperature of midpoint will increase with time. The temperature increase rate is relatively low in the initial and end sections, but is relatively high in the middle section. There is a temperature mutation when time is about 100 days, because the phase change of bitumen occurs. The ultimate temperature of midpoint is 110°C, which indicates that it is high time for switching to SAGD production. The elastic properties of midpoint are relied on temperature changes, just as Figure 20 shows. The elastic modulus of midpoint drops, while the Poisson ratio increases with time increasing. The elastic modulus drops from 663 to 360 MPa, and the Poisson ratio increases from 0.3 to 0.415 during circulation. The elastic properties change suddenly at the phase change area.

Two straight paths, Path-1 (Figure 16A) and Path-2 (Figure 16B), were established for analyzing the elastic properties of the oil sand reservoir between two wells induced by temperature propagations. If a position in oil sand reservoir can be located by $(x,y)$, the Path-1 is from $(0.2,5)$ to $(0,-2.5)$, and Path-2 is from $(0,0)$ to $(10,0)$. Figures 21 and 22 show the temperature and elastic properties along Path-1, respectively. Figures 23 and 24 show the temperature and elastic properties along Path-2, respectively.

The temperature distributions along Path-1 at varying time shown in Figure 21 revealed that the temperature will...
decrease from the wellbore to midpoint, and the temperature change rate will be lower with the distance. Circulation for a longer time will increase the temperature along Path-1. Elastic properties distributions along Path-1 at varying time shown in Figure 22 exhibited that the elastic modulus reduces, while the Poisson ratio rises from wellbore to midpoint. For example, when circulated for 60 days, the elastic modulus on wellbore is only about 250 MPa, while the elastic modulus at midpoint is 460 MPa; the Poisson ratio on wellbore is as high as 0.49, while the Poisson ratio at midpoint is only 0.32. Circulation for a longer time will decrease the elastic modulus and increase the Poisson ratio along Path-1.

As shown in Figure 23, temperature distributions along Path-2 at varying time exhibited that the temperature falls with the distance from midpoint to far reservoir. The temperature decreases slowly at initial and end sections, and very sharply in the middle section. Circulation for a longer time can raise the temperature along Path-2. As exhibited in Figure 24, the elastic modulus increases, while the Poisson ratio drops with the distance. For instance, when injected for 120 days, the elastic modulus at a distance of 5 m is 600 MPa, while the elastic modulus at midpoint is just 425 MPa; the Poisson ratio at a distance of 5 m is as low as 0.315, but the Poisson ratio at midpoint is 0.38.

As analyzed above, the elastic properties of oil sand reservoir will change a lot during steam circulation. As long as the temperature distributions of oil sand reservoir are given, the elastic property fields can be calculated according to the model proposed. It is worth noting that the time- and temperature-dependent elastic properties are very essential to be considered in the prediction of reservoir deformation during thermal stimulation, because the elastic modulus ranges from 260 to 663 MPa and Poisson's ratio ranges from

**FIGURE 17** Elastic modulus distributions when circulation for (A) 30, (B) 60, (C) 120, and (D) 300 d
0.30 to 0.48 at varying temperatures and time, just as analyzed in previous part.

5 DISCUSSION

In this contribution, a model for predicting the time- and temperature-dependent elastic properties was proposed, assuming the Karamay sand-in-bitumen oil sand was a composite geomaterial. A concept of the equivalent static time was defined to try to eliminate the time effect on elastic properties for simplicity of calculation and comparison with conventional static triaixal compression tests. A temperature transform method was used to make the model well fit the experimental data. The elastic property changes in a field practice of steam circulation were calculated according to our models.

This evaluation is relatively theoretical, because these derivations were all based on ideal mathematical approaches. However, it seems to be argumentative with other experimental data for Canadian oil sands exhibited in literatures (eg, Ref.17-20). In Figure 25, the first letter in the legend represents the author of the literature, last number represents the test effective confining stress (MPa), and the middle one or two letters mean the studied oil sands. Specifically, these abbreviations are as follows: B—Blair; A—Agar; K—Kosar; W—Wong; L—Lin; F—Faja oil sands; FS—Faja shales with bitumen; A—Athabasca oil sands; C, C1, and C2—Cold Lake oil sands in different layers; K—Karamay oil sands; L—loading; U—unloading.

As shown in Figure 25, most researchers held the idea that the elastic modulus of Canadian oil sands will increase with temperature increasing (Mode 2), or increase firstly and then decrease (Mode 3). But our theoretical
model and experimental data showed that the elastic modulus of Karamay oil sand drops with an increasing temperature (Mode 1). In reality, this is because the oil sands studied were not the same: The oil sands discussed in this model and tested in this experiment were described as sand-in-bitumen, just as Figures 2 and 4 show, while the oil sands in other literatures were mostly bitumen-in-sand. The composition and structure of different oil sands determine the elastic property change tendency with temperature.

To interpret the difference between this model (experiment) and other experimental data, we took the elastic modulus as an instance to analyze the elastic property evolution with temperature rising. It is noted that the improved stiffness under a higher temperature as well as an enough effective confining pressure (Mode 2) is because of the direct contact of solid grains when the heated low-viscous bitumen was squeezed out of pores. This interpretation was also found in the studies of Blair et al,17 Agar et al18 and Wong et al20. For Mode 3, the elastic modulus firstly increases with temperature because of the adequate grain contacts, then reduces with high temperature because of grain crushing. The phenomenon of grain crushing-induced stiffness deterioration was also found in investigations of Agar et al,18 Kosar19 and Wong et al20. For Mode 1, it only corresponds to the elastic modulus change of Karamay oil sand with temperature. The Karamay bitumen is dramatically viscous, and it cannot be easily squeezed out in a relatively low temperature. In this regard, the elastic modulus
of sand-in-bitumen Karamay oil sand will absolutely drop due to the softening of bitumen before bitumen is squeezed out and enough particle contacts with each other. Once the temperature exceeds a critical value, the solid bitumen is heated to liquid oil, and the contact of sand grains changes the micro-structure of Karamay oil sand into bitumen-in-sand type. That is to say, the mechanical behaviors of Karamay oil sand will be similar to these of Canadian oil sands as after this critical temperature.

Figure 26 describes the elastic modulus change of sand-in-bitumen Karamay oil sand with temperature. There are three possible changes: First, the elastic modulus drops with temperature when the bitumen is in situ and not squeezed out (curve 1); secondly, the elastic modulus rises with temperature when bitumen is squeezed out and solid grains sufficiently contact (curve 2); the third possible occasion is that the elastic modulus will drop again with high temperature (curve 3). The curve 4 tells us that the test points of temperature may be better to be dense for sand-in-bitumen oil sands, especially in the temperature range that the phase change of bitumen occurs. For example, the three test points may just happen to fall on the three points marked by cross, if we select just three test points for temperature. It may cause a wrong view that the elastic modulus will be higher with temperature increasing, but it does not perform so in actual conditions.

The model for elastic properties of Karamay oil sand in this study only takes two parameters of time and temperature into consideration. In fact, mechanical localization behavior may also impact the elastic properties. For example, as pore pressure in the area near wells is higher, the effective confining stress is lower, which is beneficial to the occurrence of shear dilation as well as volumetric expansion. The future work will build the model taking the effects of local mechanical behavior of oil sand into account.

Last but not least, we must declare that the so-called elastic properties of Karamay oil sand in this paper were discussed based on the assumption of bitumen being in situ and not squeezed out. This occasion reasonably occurs before SAGD production, because there is not adequate differential pressure for putting the viscous heated bitumen out to the production well, and the bitumen still occupies most of pores. The case study in this paper is to evaluate the elastic modulus and Poisson's ratio propagation during steam circulation, so only the curve 1 in Figure 25 was used in the application.

6 | SUMMARY AND CONCLUSION

In this study, a model for predicting the time- and temperature-dependent elastic properties of sand-in-bitumen Karamay oil sand was derived with considering the viscosity and thermal impacts from bitumen. The Eshelby method, Mori–Tanaka method, and differential method were employed to calculate the elastic properties of Karamay oil sand as a function of both temperature and time. The equivalent static time was proposed to eliminate the effect of time. The model was improved by temperature transform based on the results of laboratory experiments and used for case study to predict the elastic property fields of oil sand during SAGD steam circulation.

Future work will be conducted in three directions:

1. Elastic property changes in a heterogeneous reservoir during thermal stimulation;
Effects of the shear dilation and temperature induced fractures on the elastic property;

Model validation through FEM mechanical modeling through oil sand digital cores.

ACKNOWLEDGMENTS

We sincerely appreciate the funding provided by the National Natural Science Foundation of China (Nos. 51325402 and 51404281). We also owe gratitude to Xinjiang Oilfield Corporation for providing the field-collected oil sand samples and the field injection data.

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How to cite this article: Pang H, Jin Y, Gao Y. Evaluation of elastic property changes in Karamay oil sand reservoir during thermal stimulation. Energy Sci Eng. 2019;7:1233–1253. https://doi.org/10.1002/ese3.342