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A COMPARATIVE STUDY OF PHYSICAL AND MECHANICAL PROPERTIES OF NATURAL AND SYNTHETIC WAXES FOR DEVELOPING MODELS FOR DRILLING APPLICATIONS

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ABSTRACT

Natural and synthetic waxes are used in laboratory to simulate the rock waterjet drilling. The main objectives of this study are to investigate the physical and mechanical properties of wax materials using uniaxial compressive strength test and ultrasonic nondestructive testing (NDT). This study explores the potential of diametral stress-strain behavior of natural wax (beeswax) and synthetic (paraffin) wax by the uniaxial compressive test to scale its strength. The average density of beeswax and paraffin wax samples is measured as 0.854961 g/cc and 0.7855 g/cc respectively. Experimental results show that the compressive strength of beeswax and paraffin wax samples is 526.7 and 658.4 kPa respectively whereas the modulus of elasticity of beeswax and paraffin wax samples is 39.0 and 55.7 MPa respectively. The stress-strain curves show that beeswax is analogue to rock and paraffin wax is similar to steel material. Moreover, empirical correlations show that natural wax can be a good replacement of reservoir rock for waterjet drilling during laboratory experiments. In this study, ultrasonic NDT is used to detect damage after waterjet drilling in beeswax and paraffin wax samples.

Keywords: waterjet; beeswax; paraffin wax; physical properties; ultrasonic nondestructive testing, uniaxial compressive strength test.

1. INTRODUCTION

The natural waxy materials are being used for different purposes from ancient time. Its importance is increasing day by day. Beeswax is one of the natural waxy materials found in nature easily. The diversity of the natural waxes gives a range of usages (Hossain, 2008). Synthetic waxes are also used in many purposes after the beginning of industrial revolution

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throughout the world. Paraffin wax is a synthetic waxy material come from petroleum refinery.

We know that the use of hard rock drilling or excavation machines is increasing in recent years in the field of drilling, mining and civil engineering. Therefore, it is important to pay our attention to improve the existing technology or look forward an alternative of drilling technique. In existing technology, the questions about the ability of drilling machines to operate and cut effectively in hard rock are well known (Bilgin, 2006). These difficulties are limited by the system stiffness and the ability of cutting tools to withstand high forces. Moreover several factors such as cutting forces, force acting on a cutting tool, chipping out, and brittle nature of rock are the governing criteria for drilling in rock formation. The high force acting on formation rock may damage the machine components and exceed the machine’s torque and thrust capacities. All these short comings can easily be solved by waterjet drilling. However, the problem behind the waterjet is how to develop a tremendous energy to drill rock material in nature and laboratory. The uses of soft and waxy materials are very limited in the available literature as a substitute of rock in laboratory. Moreover, the researcher’s attention did not pay on an alternative way how to solve this problem. There are very few literature which deals with the physical and mechanical properties of the beeswax and paraffin wax. The below sections give a literature review of the present work.

Craig et al. (1967) studied the paraffin, beeswax, and carnauba waxes. They determined the modulus of elasticity, compressive strength, and proportional limit for those waxes. Mancktelow (1989) used the waxes as an analogue material for rocks in order to study the deformations undergone by geological structures. He presented stress–strain relationships based on experimental data. The stress–strain curve for paraffin wax in the solid state has a clear elastic range, a rounded yield segment, and a stress-flow segment which, for a specific temperature range and confining pressure, approximates steady state. The results in the paper were focused on the stress-flow deformation regime for which it was found that the stress–strain relationship for paraffin wax in the solid state is accurately described by a power-law. However, the results are applicable only for small temperature ranges.

Kotsiomiti and McCabe (1997) measured mechanical properties for 26 blends of paraffin wax, beeswax, and inorganic filler for dental applications. They measured the dental waxes properties such as plastic-flow stress, linear thermal expansion, elastic modulus, and flexural strength. Plastic-flow tests were conducted in accordance with the corresponding ISO specification (ISO Standard 1561, 1975). The flow test measurements were usually conducted by calculating the percent height decrease of cylindrical specimens of 10 mm diameter and 6 mm height which were kept at the testing temperature for 10 min under a load of 2 kg. The flow stress of paraffin and beeswax binary mixtures did not vary with the addition of beeswax. The addition of filler particles to beeswax even in small amounts was found to dramatically reduce flow of the beeswax, an effect that is termed hardening. It was observed that the degree of purity and constitution of waxes drastically affected the material’s mechanical properties (Kotsiomiti and McCabe, 1997). Morgan et al. (2002) studied the mechanical properties of beeswax and measured these properties as a function of temperature. They used a variety of techniques and compared with each other. In the study, the coefficient of friction of beeswax was measured and compared with that of plasticine and Nylon 6–6. They found that the frictional behavior of beeswax departs from Amonton's laws and behaves instead as a classic soft, elastic polymer.

To analyze the effectiveness and sustainability of waterjet as a drilling technique, a series of laboratory tests were conducted and justified the results using natural and synthetic waxes in laboratory (Hossain et al., 2007a; Hossain et al., 2007b; Hossain, 2008). A detail procedure and experimental analysis of waterjet drilling are shown in those papers. The authors proposed empirical models for rate of penetration (ROP) and depth of penetration (DOP) based on laboratory findings to simulate rock materials. The other experimental works are also conducted to investigate the structural and chemical properties of natural and synthetic waxes (Hossain et al., 2009a; Hossain et al., 2009b). In literature, there exists the structural and chemical analysis of beeswax and paraffin wax. A detail overview of its analysis and usages are well explained by Hossain et al. (Hossain et al., 2009a; Hossain et al., 2009b). An elaborate literature review is also completed by them. They presented the structural and chemical analysis and established the results and findings by SEM and NMR test. The scale up models from laboratory to field scale is also established by Hossain et al. (2007a). In continuation of these researches, the present study has been conducted and measured the physical and mechanical properties based on uniaxial compressive strength test, density test and ultrasound test.

Microstructural weakening begins when any load (compressive or tensile) is applied to any material. Therefore, the impact of load on rock samples is essential to get the proper information during the drilling activities. However, the studies on physical and mechanical properties on waxes are very limited and rare in available literature. The objective of this study is to identify a substance which can be used as a rock sample in laboratory instead of real reservoir rock. The reason behind this research is that it is very difficult to cut a rock by waterjet drilling in laboratory. To cut or drill a rock, a high energy pump with establishment is necessary for developing huge pressure on the tip of drill bit. Therefore, selection of a substance is required to save laboratory energy, money and time as well which should be an analogue to rock materials. This research presents the different stress-strain relationship of beeswax, paraffin wax to simulate the behavior of reservoir rock in the field application.

2. DENSITY MEASURE

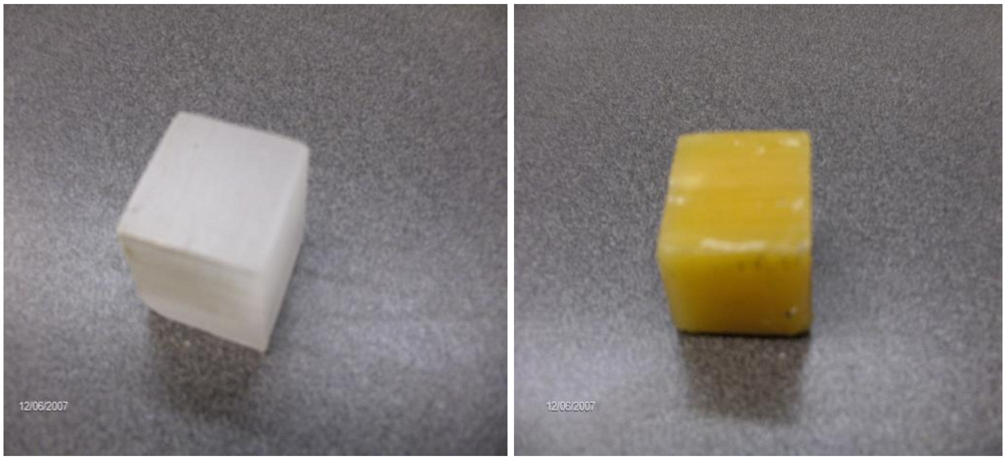
To measure the density of beeswax and paraffin wax, the wax samples were sized into $1'' \times 1'' \times 1''$ cubes as shown in Figure 1. A cylindrical scaled borate of $3''$ diameter is used to measure the density of the waxes. Table 1 shows the density values of beeswax and paraffin wax for different samples.

Table 1. Beeswax and paraffin wax density values for different samples

Sample	Beeswax			Paraffin wax		
	Mass (g)	Volume (cc)	Density (g/cc)	Mass (g)	Volume (cc)	Density (g/cc)
1	18.2	20.0	0.91	15.4	20.0	0.77
2	14.8	17.0	0.870588	15.8	20.0	0.79
3	15.0	18.0	0.833333	15.7	20.0	0.785

Table 1. (Continued)

Sample	Beeswax			Paraffin wax		
	Mass (g)	Volume (cc)	Density (g/cc)	Mass (g)	Volume (cc)	Density (g/cc)
4	15.0	17.0	0.882353	16.3	20.0	0.815
5	15.3	17.5	0.874286	15.1	20.0	0.755
6	19.6	21.0	0.933333	15.6	20.0	0.78
7	15.2	10.0	0.80	15.8	20.0	0.79
8	18.2	20.0	0.91	15.9	20.0	0.795
9	14.1	17.5	0.805714	15.8	20.0	0.79
10	14.6	20.0	0.73	15.7	20.0	0.785
Average	16.0	17.8	0.854961	15.71	20.0	0.7855



(a) (b)

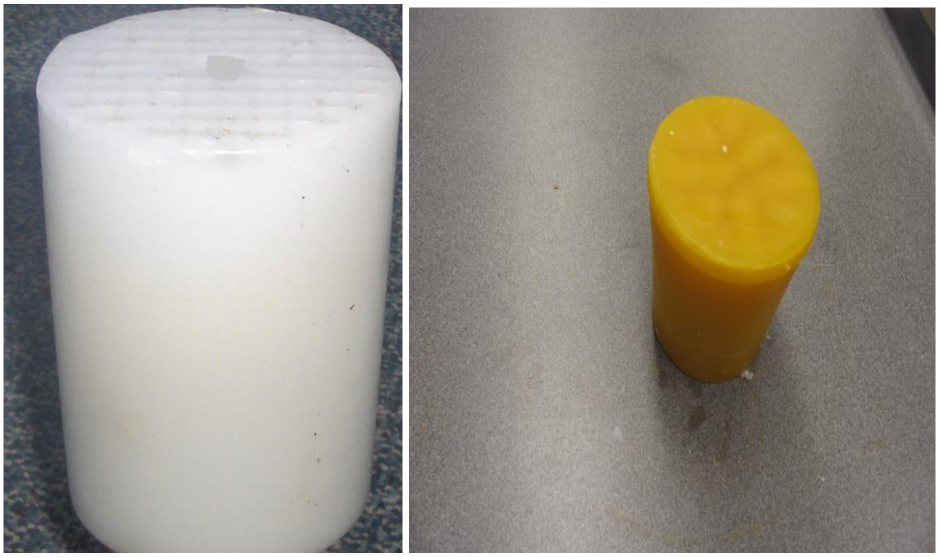
Figure 1. Paraffin wax (a) and beeswax (b) samples used in density measurement.

3. UNIAXIAL COMPRESSIVE STRENGTH TEST

Uniaxial compression tests were performed on beeswax and paraffin wax samples, which had a diameter of 2” (50.8 mm) and a length of 5” (127 mm) (see Figures 2). The length-to-diameter ratio is 2.5. The stress rate was applied within the limits of 0.5 –1.0 MPa/s.

Figure 3 and 4 show the paraffin wax and beeswax sample attached with a compressive strength test machine along with a strain meter (linear traveling dial machine). It shows the setup before starting the experiment.

Figure 5 and 6 display the paraffin wax and beeswax sample after compressive strength test. It presents the rupture of both wax samples. There is a shear failure due to compressive load.



a) Paraffin wax b) Beeswax

Figure 2. Paraffin wax (a) and beeswax (b) samples.

Figure 3. Paraffin wax sample for compressive strength test.

Figure 4. Beeswax sample for compressive strength test.

Figure 5. Paraffin wax sample after compressive strength test.

Figure 6. Beeswax sample after compressive strength test.

4. ULTRASOUND NONDESTRUCTIVE TESTING

Ultrasonic nondestructive testing (NDT) introduces high frequency sound waves into a test object to obtain information about the object without altering or damaging it. Sound generated above the human hearing range (typically 20 KHz) is called ultrasound. However, the frequency range normally employed in ultrasonic testing and thickness gaging is 100 KHz to 50MHz. Although ultrasound behaves in a similar manner to audible sound, it has a much shorter wavelength. This means it can be reflected off very small surfaces such as defects inside materials. Two basic quantities are measured in ultrasonic testing; they are time of flight or the amount of time for the sound to travel through the sample and amplitude of receiver signal.

Based on velocity and round trip time of flight through the material the material properties can be evaluated. Measurements of the relative change in signal amplitude can be used in sizing flaws or measuring the attenuation of a material. The new phased array technology generates an ultrasonic beam with the capability of setting beam parameters such as angle, focal distance, and focal point size through software. With phased array one can vary the angle of the beam to scan a part without moving the probe itself. Phased array also allows the replacement of multiple probes and even mechanical components. Almost all current ultrasonic inspection methods require the use of a couplant between the transducers and the material to be inspected. Typical couplants include water, air, glycerin and a variety of oil or water based pastes.

The most common water coupling can be done with squirters where the sound travels through a jet of water or by immersing the transducer and test object in a tank of water. Both techniques are called immersion testing. In immersion testing, the transducer is placed in the water, above the test object, and a beam of sound is projected.

4.1. Ultrasonic Technique

Among various NDT techniques, the ultrasonic technique has been most widely applied to various engineering problems. Improvement of accuracy of the ultrasonic method has been one of critical issues in the NDT field. Selection of proper transducers, water scan or air scan, pulse echo or through transmission, longitudinal, shear or plate waves, spike pulse or tone burst signal and reference standards are all key parameters in ultrasonic method of damage detection. Ultrasonic methods offer a unique potential of detecting surface as well as internal damage states, while many others like replication, magnetic measurements and eddy currents merely inspect the surface or near-surface region of materials, while radiography detects only the state of internal damage.

4.2. Ultrasonic Image Acquisition

Ultrasonic NDT uses high frequency sound energy to conduct examination of the material. Ultrasonic inspection can be used for flaw detection and evaluation, dimensional measurements, and material characterization, to name a few. With appropriate equipment it is possible to perform sensitive inspections for defects such as voids, cracks and delaminations in a wide variety of water-incompatible materials.

A typical Ultrasonic NDT inspection system consists of several functional units, such as the pulsar/receiver, transducer, and display devices. A pulsar/receiver is an electronic device that can produce high voltage electrical pulse. Driven by the pulsar, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into electrical signal by the transducer and is displayed on a screen. Signal travel time can be directly related to the distance that the signal would travel. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.

Ultrasonic data can be collected and displayed in a number of different formats. The three most common formats are known in the NDT world as A-scan, B-scan and C-scan presentations. Each presentation mode provides a different way of looking at and evaluating the region of material being inspected. Modern computerized ultrasonic scanning systems can display data in all three presentation forms simultaneously.

4.3. C-Scan Presentation

The C-scan presentation as shown in Figure 7 provides a plan-type view of the location and size of test specimen features. The plane of the image is parallel to the scan pattern of the transducer. C-scan presentations are produced with an automated data acquisition system, such as a computer-controlled immersion scanning system. Typically, a data collection gate is established on the A-scan and the amplitude or the time-of-flight of the signal is recorded at regular intervals as the transducer is scanned over the test piece. The relative signal amplitude or the time-of-flight is displayed as a shade of gray or a color for each of the positions where data was recorded. The C-scan presentation as shown in Figures 8 and 9 provides an image of the features that reflect and scatter the sound within and on the surfaces of the test piece.

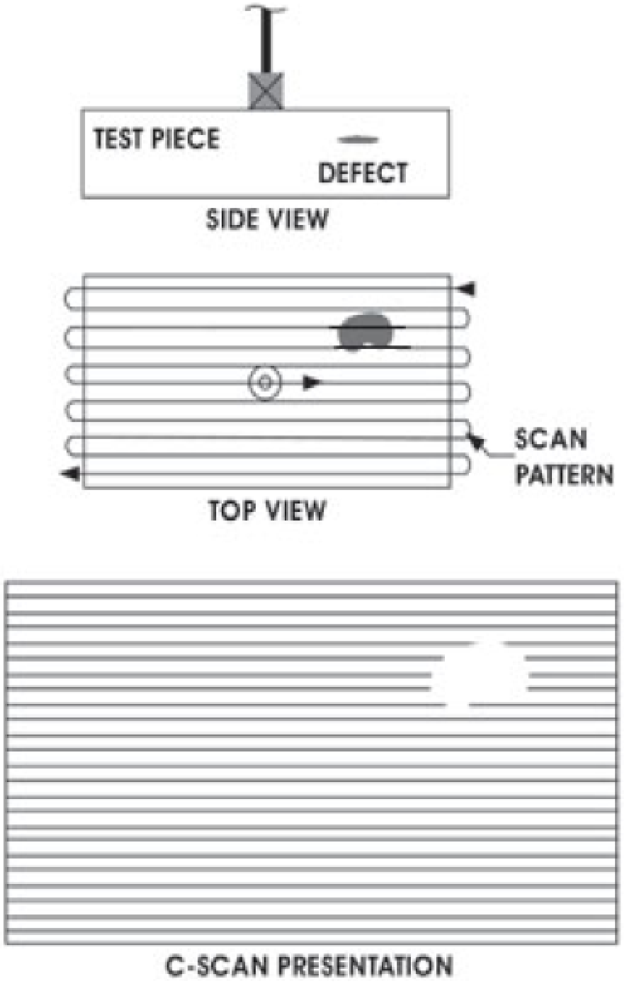


Figure 7. C-scan presentation.

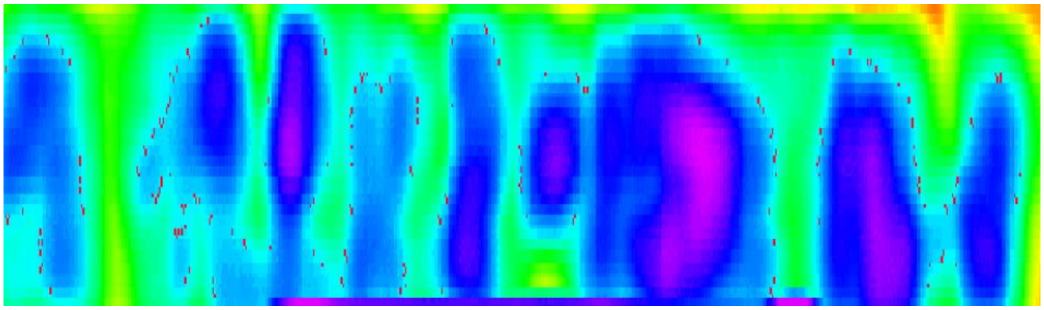


Figure 8. C-scan of the reference sample.

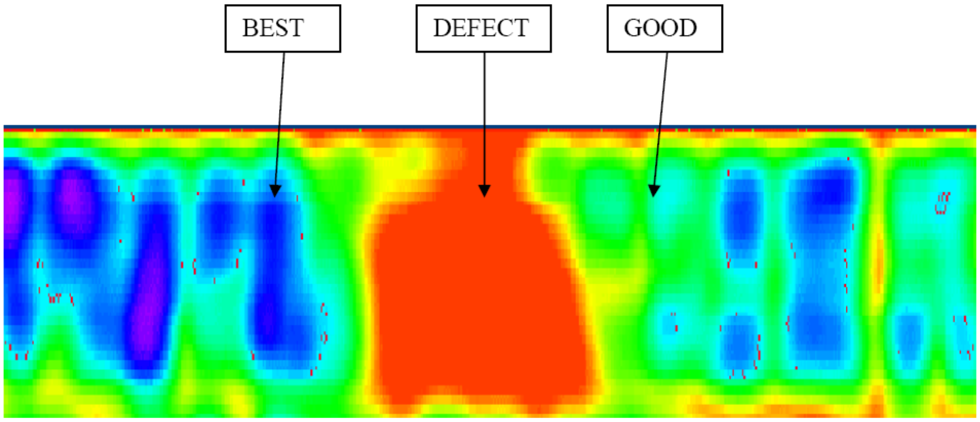


Figure 9. C-scan of defective sample.

4.4. Tools Used for Development of System

The multi axes ultrasonic testing systems used to obtain our C-scan images are MATEC water coupled system and QMI–SONDA air scan system. Figure 10 represents laboratory setup for the ultrasonic NDT.

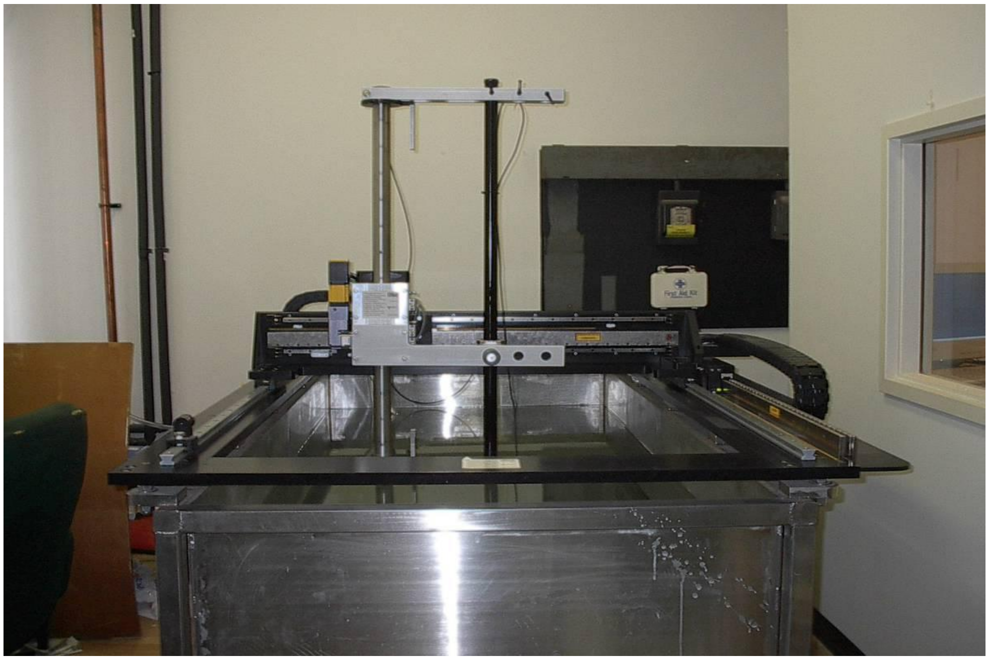


Figure 10. Ultrasonic water immersion C-scan imaging system.

5. RESULTS AND DISCUSSIONS

5.1. Uniaxial Compressive Strength Test

Figure 11 shows the stress-strain curve for paraffin wax in room temperature. Initially, with the increase of stress, strain increases linearly. This simply means that strain rate increases with the increase of load on the test machine. This continuation of this trend is up to 295 lbs at 10.5 minutes. However, when the strain rate is in the range of 1.4 to 1.7, there is no change of stress which is 658.4 kPa at a load of 300 lbs. In this range, the linear elongation starts from 2.34 mm to 2.72 mm. At the time of 12.5 minutes, elongation of 2.72 mm and at the load of 300 lbs, the failure of the paraffin wax sample occurs which is the yield strength point of the sample at room temperature. Table 2 shows the average density, compressive strength and modulus of elasticity of paraffin wax. The shape and nature of curve and failure pattern of paraffin wax indicates the similar nature of steel material. Therefore the synthetic wax represents the processed materials of natural resources. Figure 12 represents the stress-strain curve of paraffin wax up to the first maximum stress values that are reported in Figure 11. The curve trend of the synthetic wax that has ostensibly linear can be mathematically explained by an empirical relation. The trend line for stress (σ_p) with strain (ε_p) is presented in Figure 12. This is a straight line representing the linear behavior of the material. The empirical relationship between stress-strain has been derived by best fit regression analysis. The equation can be presented by Eq. (1).

$$\sigma_p = 509.8\, \varepsilon_p - 2.812 \qquad (1)$$

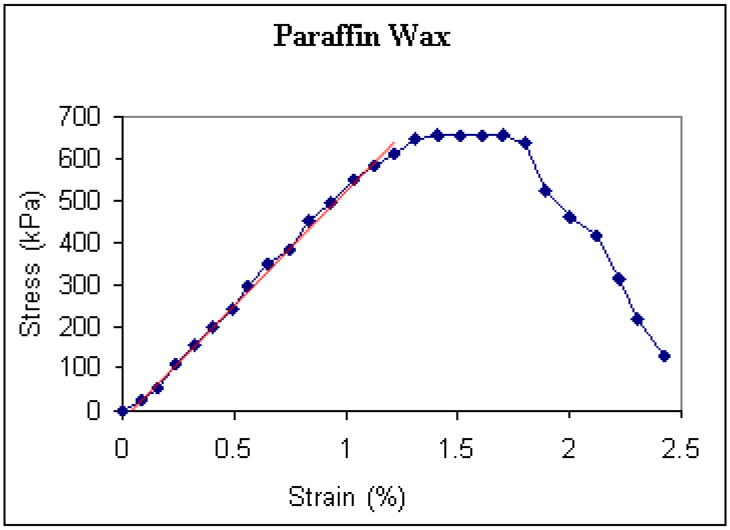


Figure 11. Stress variation with strain for paraffin wax.

Table 2. Wax mechanical properties

Wax type	Density (g/cc)	Compressive strength (kPa)	Modulus of elasticity (MPa)
Paraffin wax	0.7855	658.4	55.7
Beeswax	0.854961	526.7	39.0

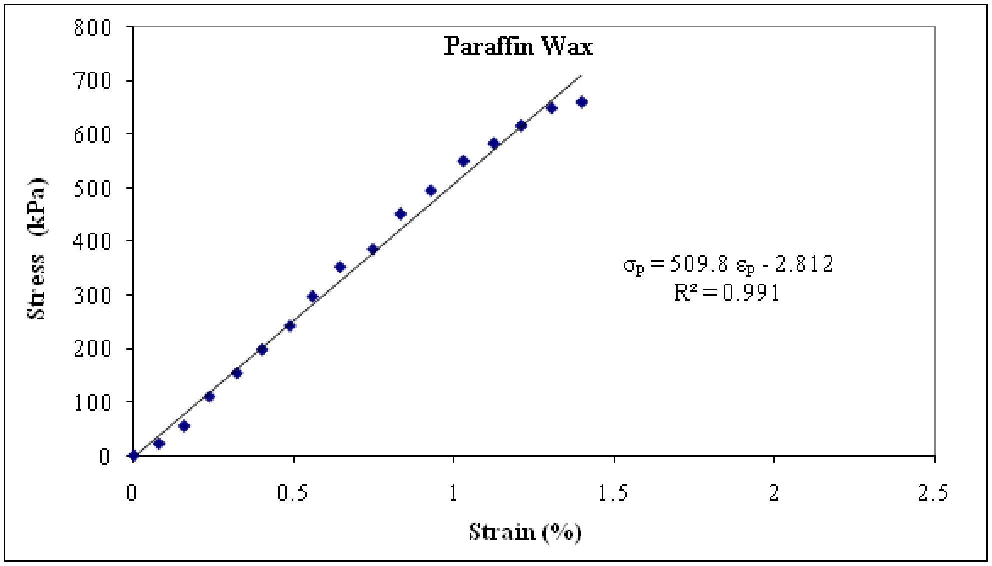


Figure 12. Stress variation with strain for empirical relation based on paraffin wax.

Figure 13 presents the stress-strain curve for beeswax in room temperature. Initially, when elongation starts, beeswax took more load than paraffin wax (60 lbs whereas paraffin wax took 10 lbs for same elongation). Therefore, there is a jump of stress value of 131.68 kPa for a slide increase of strain, 0.047 (0.06 mm of elongation). The increasing trend of stress-strain curve is a non-linear type which is quite fluctuating at its closer range of maximum strength (yield strength value). For the strain range of 1.68 to 2.18 there is no change of stress value which is 526.72 kPa. At this range of strain values, the linear elongation is continued from 2.89 mm to 3.54 mm and the load is 240 lbs. After that point of strain value (2.18), with the increase of stress value up to 537.69 kPa (245 lbs), strain is decreased to 1.48. After this strain, for the same stress value, strain starts to increase up to 1.78. At this point, the failure of the beeswax sample occurs. The normal decreasing trend of the curve continued up to the strain of 2.65 where the stress is 471.85 kPa (215 lbs). After this strain point, there is a certain decrease of strain up to 1.16 and then increase again for the same stress value. Table 2 shows the average density, compressive strength and modulus of elasticity of beeswax.

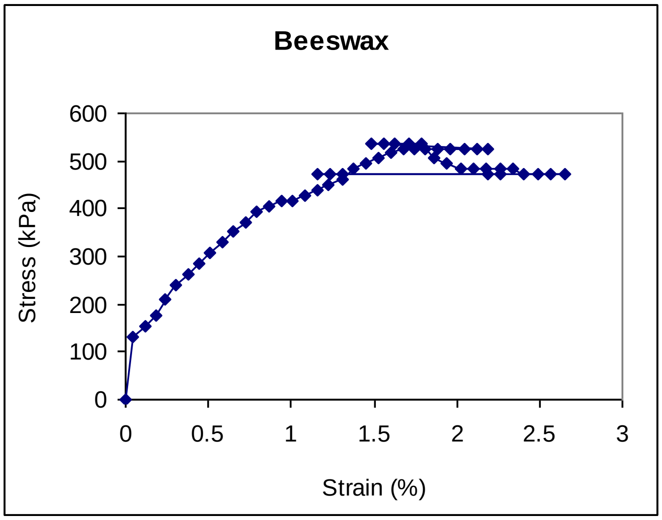


Figure 13. Stress variation with strain for beeswax indicating true load.

Figure 14 represents the stress-stain curve of beeswax up to the first maximum stress values, as reported in Figure 13. Here, the non-linear pattern of the cure is more visible and self explanatory. Therefore, the extremely non-linear and chaotic behavior of the stress-strain relationship of beeswax is quite unpredictable. This has no regular shape and pattern of the conventional stress-strain curve. The behavior of the curve is similar to natural materials, which can be used as a rock sample in laboratory to simulate rock in field scale.

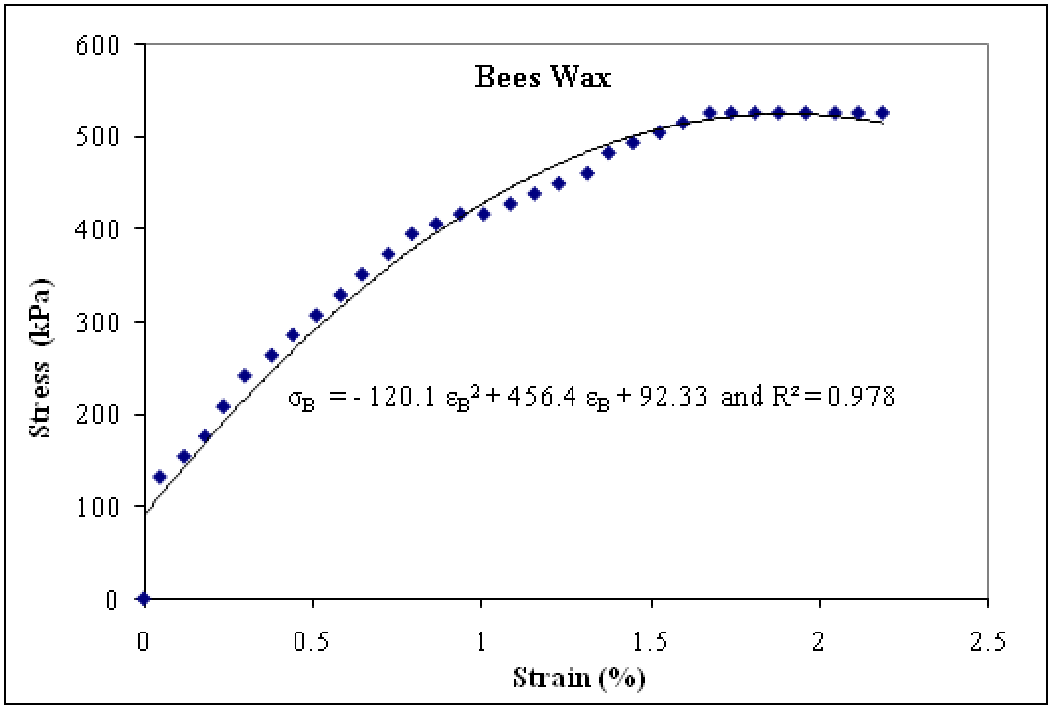


Figure 14. Stress variation with strain for empirical relation based on beeswax.

The non-linear trend of the natural wax that has complex features can be mathematically explained by an empirical relationship. The trend line for stress (σ_B) with strain (ε_B) is shown in Figure 14. The empirical relationship between these two parameters has been derived by best fit regression analysis, which is shown in Eq. (2).

$$\sigma_B = -120.1\,\varepsilon_B^2 + 456.4\,\varepsilon_B + 92.33 \qquad (2)$$

The above discussion indicates that natural wax (beeswax) represents the complex nonlinear behavior, which is a true representation of reservoir rock sample. Therefore, using the scaling criterion and scaling groups presented by Hossain et al. (2007a), Figure 15 is generated for field application. The semi-log plotting shows the curve for both laboratory findings and the scaled up field application.

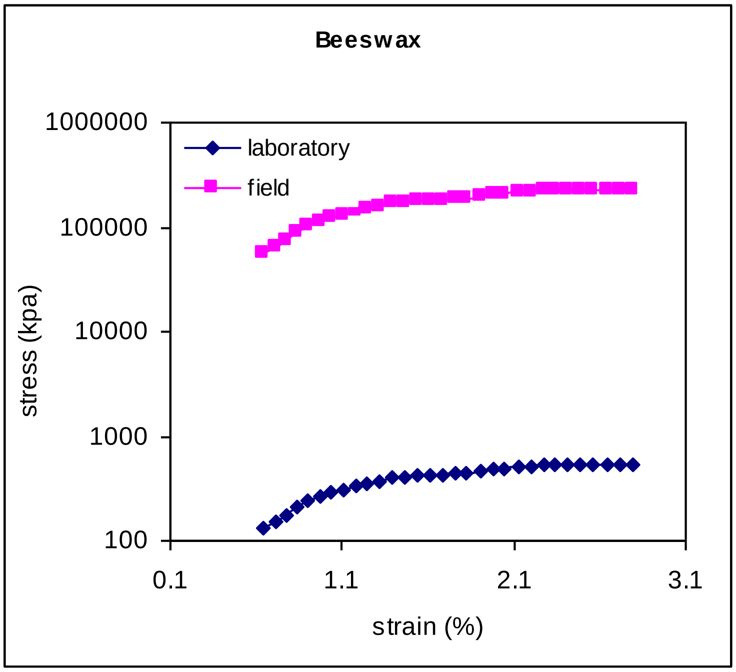


Figure 15. Scaled up stress-strain variation for beeswax in field use.

5.2. Ultrasound Test

Figures 16 to 20 display the waterjet-wax interaction. They illustrate the hole drilled by the waterjet. They also show the effect of the waterjet at various levels of the wax layers. As the waterjet goes deeper, it becomes more difficult to drill, which explains the lower effect on the deeper wax layers.

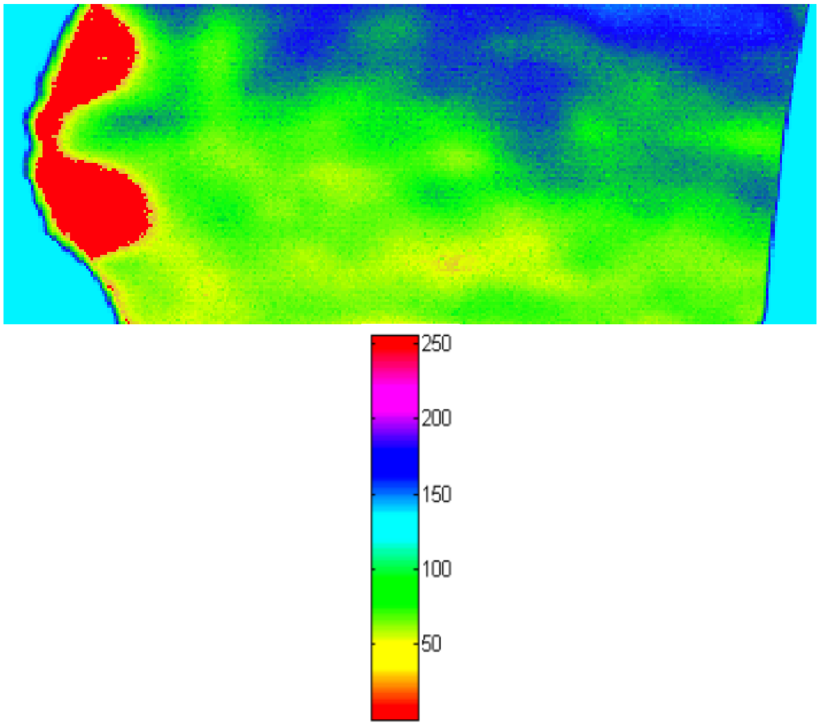


Figure 16. Ultrasonic C-scan of paraffin wax sample.

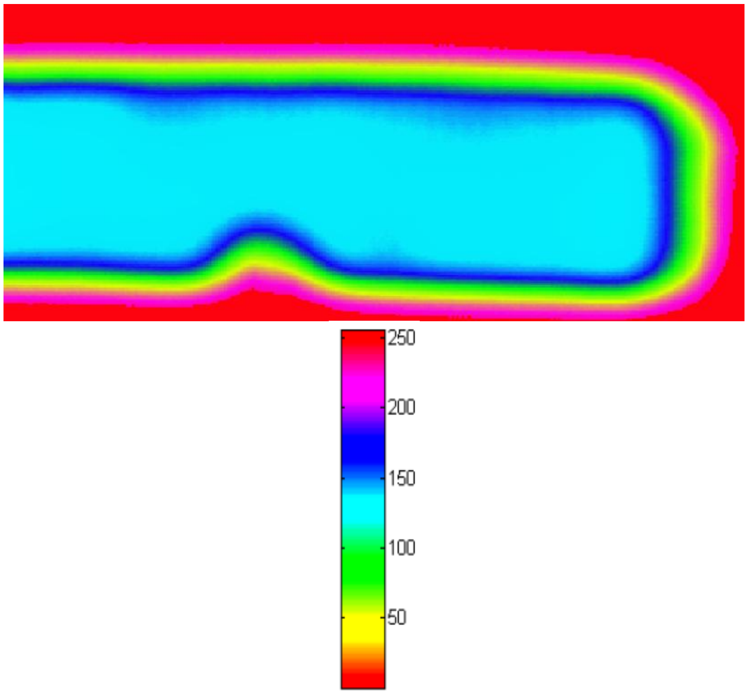


Figure 17. Ultrasonic C-scan depth view of paraffin wax sample 1 for predicting waterjet drilling depth.

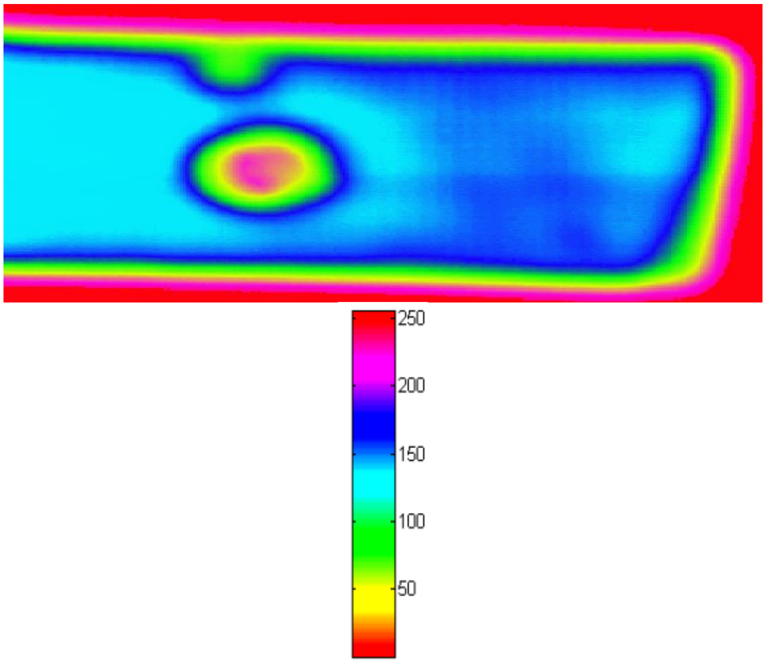


Figure 18. Ultrasonic C-scan top view of paraffin wax sample 1 for predicting waterjet drilling hole diameter.

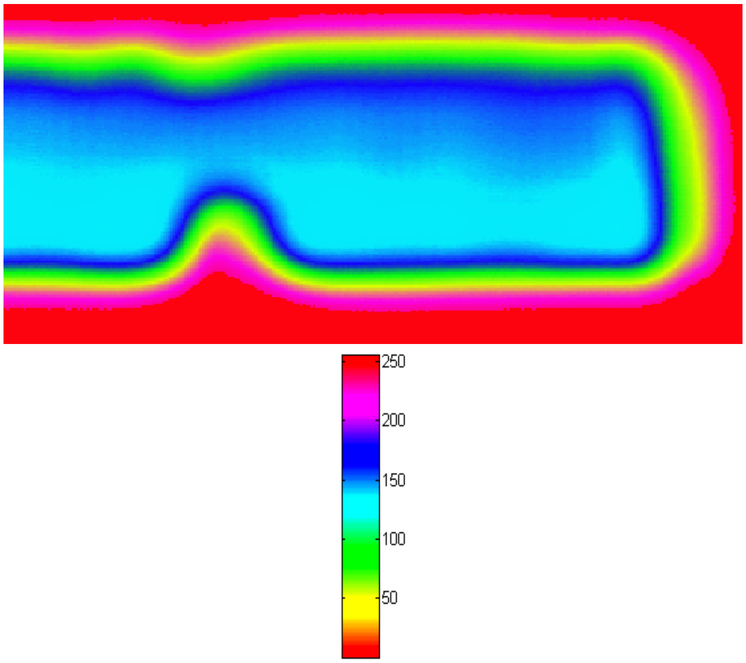


Figure 19. Ultrasonic C-scan depth view of paraffin wax sample 2 for predicting waterjet drilling depth.

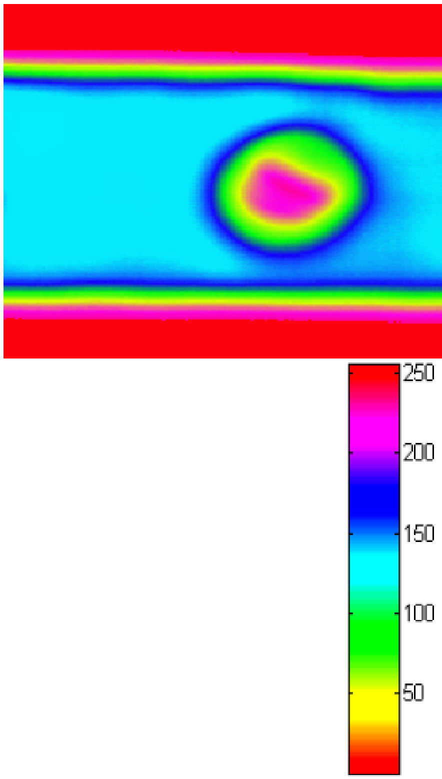


Figure 20. Ultrasonic C-scan top view of paraffin wax sample 2 for predicting waterjet drilling hole diameter.

CONCLUSIONS

This paper investigates the physical and mechanical properties of beeswax and paraffin wax. Empirical stress-strain relationships have been presented to simulate the reservoir rock using the waxy material as laboratory samples. Results show that synthetic wax has a linear relationship whereas natural wax has a complex nonlinear relationship. Therefore, empirical correlation based on beeswax sample can be used later to simulate waterjet drilling into rock for oil and gas applications. Physical and mechanical properties include wax density and uniaxial compressive strength. Then, the density is measured for beeswax and paraffin wax. The results show that the beeswax is heavier with an average density equal to 0.854961 g/cc compared to paraffin wax with an average density of 0.7855 g/cc. In addition, ultrasound nondestructive testing of wax was performed to study the waterjet-wax interaction showing the resulting hole in the wax under the waterjet pressure.

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