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EXPERIMENTAL STUDY OF PHYSICAL AND MECHANICAL PROPERTIES OF NATURAL AND SYNTHETIC WAXES USING UNIAXIAL COMPRESSIVE STRENGTH TEST

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ABSTRACT

Microstructural weakening begins when a load whether compressive or tensile is applied to any material. To simulate the rock behavior under such load, natural and synthetic waxes were tested in laboratory for waterjet drilling. The main objective of this study is to investigate the physical and mechanical properties of wax materials using uniaxial compressive strength test. This study explores the potential of diametral stress-strain behavior of natural beeswax and synthetic paraffin wax samples by the uniaxial compressive test to measure their strength. Experimental results show that the compressive strengths of beeswax and paraffin wax samples are 526.7 and 658.4 kPa respectively whereas the moduli of elasticity of beeswax and paraffin wax samples are 39.0 and 55.7 MPa, respectively. The stress-strain curves show that beeswax is analogous to rock and paraffin wax is similar to steel material. Moreover, empirical correlations show that natural beeswax can be a good substitute for reservoir rocks to study the waterjet drilling in the laboratory experiments.

Keywords: Beeswax; paraffin wax; physical properties; uniaxial compressive strength test; stress-strain

1. INTRODUCTION

The natural waxy materials have been used for various purposes from ancient times. Their 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 [1, 2]. Synthetic waxes have also served many purposes after the beginning of the industrial revolution throughout the world. Paraffin wax is a synthetic waxy material coming from petroleum refinery.

Hard rock drilling and the use of excavation machines have been increasing in recent years in the mining, oil and gas, and civil engineering fields. Therefore, it is important to improve the existing technology or look forward to 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 [3]. 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, forces acting on a cutting tool, chipping, and brittle nature of rock govern the drilling process 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 shortcomings 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 the field and the wax samples in the laboratory. The uses of soft waxy materials as a substitute of rock in the laboratory are very limited in the available literature. So far, the related research work accomplished has not solved this problem. There are very few references that deal with the physical and mechanical properties of the beeswax and paraffin wax. The corresponding literature review follows.

Craig et al. [4] studied the paraffin, beeswax, and carnauba waxes. They determined the modulus of elasticity, compressive strength, and proportional limit for those waxes. Mancktelow [5] 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 [6] 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 [7]. 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 the flow of 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 [6]. Morgan et al. [8] studied the mechanical properties of beeswax and measured these properties as a function of temperature. They used a variety of techniques and compared them with each other. In their 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 Amontons' laws and behaves instead as a classic soft, elastic polymer.

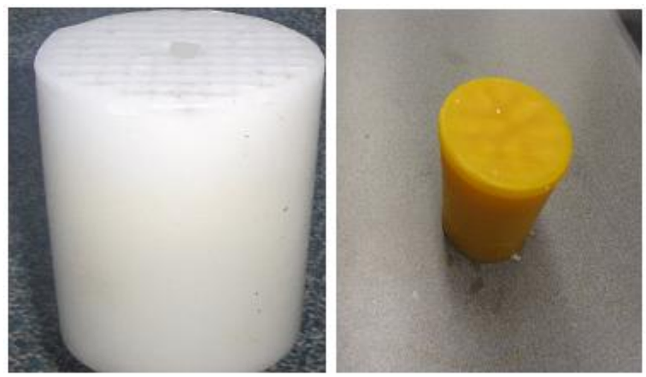
To analyze the effectiveness and sustainability of waterjet as a drilling technique, a series of laboratory tests were conducted and justified the results using natural and synthetic waxes in laboratory [1, 2, 9, 10]. A detailed procedure and experimental analysis of waterjet drilling are shown in those papers. They proposed empirical models for rate of penetration and depth of penetration 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 [11, 12]. In literature, there exists the structural and chemical analysis of beeswax and paraffin wax. A detailed overview of its analysis and usages are well explained by Hossain et al. [11, 12]. 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 tests. The scale-up models from laboratory to field scale are also established by Hossain et al. [9]. In continuation of these research studies, the present work has been conducted. Then, the physical and mechanical properties of beeswax and paraffin wax samples have been measured based on the uniaxial compressive strength test. This research presents the comparison of stress-strain relationship between beeswax and paraffin wax to simulate the behavior of reservoir rock in the field.

2. EXPERIMENTAL STUDIES

Experimental investigation of any research in any branch of petroleum engineering has a meaningful credence. However, there are some areas of research, for which the representation of the process and its behavior is very difficult to investigate experimentally. Sometimes, it seems impossible to figure out the true event experimentally, only it might be presumed. In such a situation, numerical simulation and scale-up approach are the best tools to approximate the process in advancement toward the reality. This study has taken the approaches of experimental and scale-up methods to fulfill its objectives.

2.1 Uniaxial Compressive Strength Test

Uniaxial compression tests were performed on beeswax and paraffin wax samples, which had a diameter of 2" (50.8mm) and a length of 5" (127mm) (see Figure 1). The length-to-diameter ratio is 2.5. The stress rate was applied within the limits of 0.5-1.0 MPa/s.



a) Paraffin wax b) Beeswax

Figure 1. *Paraffin wax (a) and beeswax (b) samples [1].*

Figure 2 shows the paraffin wax and beeswax samples in a compressive strength test machine along with a strain meter (linear traveling dial machine). It illustrates the setup before starting the experiment. Figure 3 displays the paraffin wax and beeswax samples 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 and Beeswax sample for compressive strength test [1].*

a) Paraffin wax b) Beeswax

Figure 3. *Paraffin wax sample and Beeswax sample after compressive strength test [1].*

3. RESULTS AND DISCUSSION

Figure 4 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. The 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 1 shows the average density, compressive strength and modulus of elasticity of paraffin wax [1, 2]. 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.

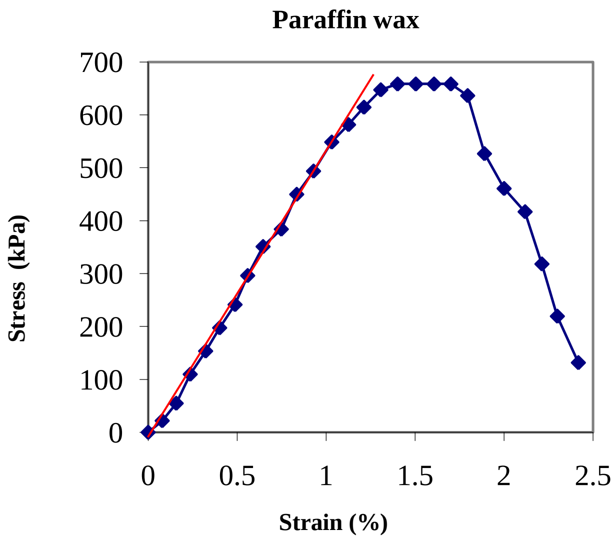


Figure 4. *Stress variation with strain for paraffin wax*

Figure 5 represents the stress-strain curve of paraffin wax up to the first maximum stress values that are reported in Figure 4. The curve trend of the synthetic wax that was 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 5. This is a straight line representing the linear behavior of the material. The empirical stress-strain relationship has been derived by best fit regression analysis. The equation can be presented by Eq. (1).

$$\sigma_p = 509.8\,\varepsilon_p - 2.812 \tag{1}$$

Table 1. 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

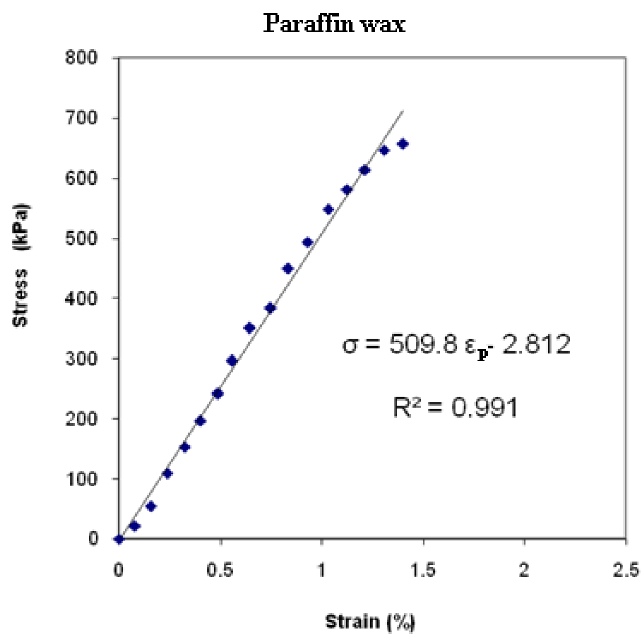


Figure 5. *Stress variation with strain for empirical relation based on paraffin wax*

Figure 6 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 slight increase of strain, 0.047 (0.06 mm of elongation). The increasing trend of stress-strain curve is a nonlinear 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 1 shows the average density, compressive strength and modulus of elasticity of beeswax.

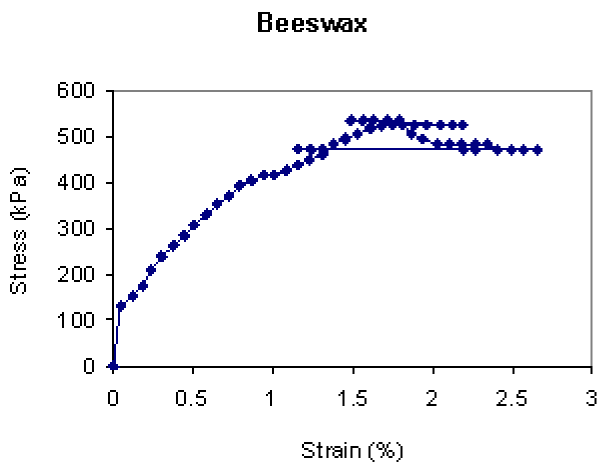


Figure 6. *Stress variation with strain for beeswax indicating true load*

Figure 7 represents the stress-strain curve of beeswax up to the first maximum stress values. Here, the nonlinear pattern of the curve is more visible and self-explanatory. Therefore, the extremely nonlinear 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. The nonlinear 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. [9], Figure 8 is generated for field application. The semi-log plotting shows the curve for both laboratory findings and the scaled-up field application.

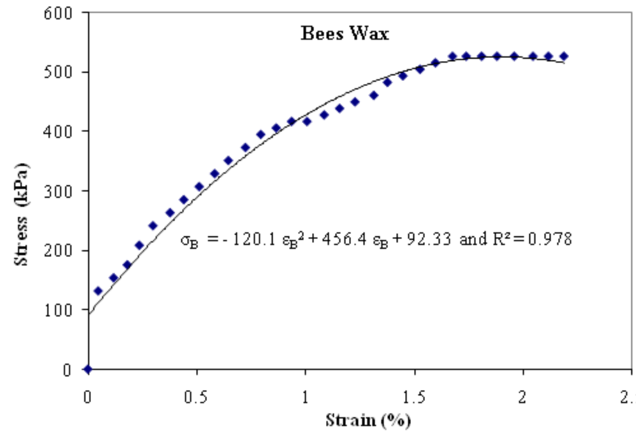


Figure 7. *Stress variation with strain for empirical relation based on beeswax*

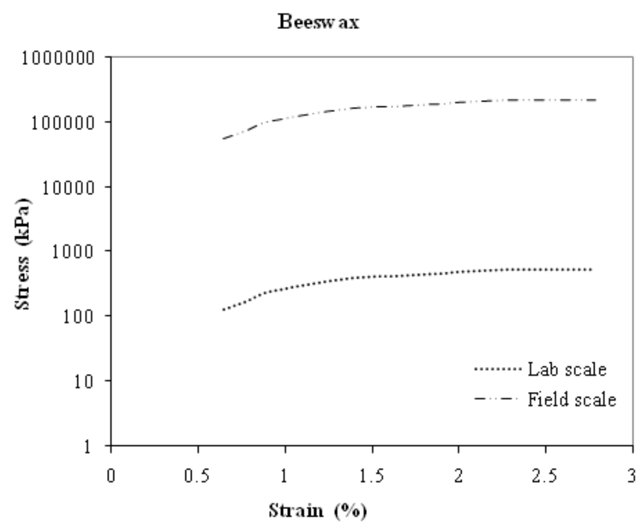


Figure 8. *Scaled up stress-strain variation for beeswax in field use*

4. CONCLUSIONS

This paper investigates the physical and mechanical properties of beeswax and paraffin wax. Empirical stress-strain relationships have been developed to simulate the reservoir rock using the laboratory samples consisting of waxy material. 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 to simulate waterjet drilling into rock for oil and gas applications. The physical and mechanical properties determined in this study include the density and uniaxial compressive strength for beeswax and paraffin wax samples.

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