Crude Oil Fly Ash Waste for Road Pavement Application

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Abstract. This paper investigates the use of crude oil waste fly ash generated from electrical and desalination power plants in Saudi Arabia to improve the performance of asphalt flexible pavement. Several asphalt pavement materials were prepared to contain fly ash by-product waste of desalination and electrical power plants in Saudi Arabia. In addition, the paper proposed a new simple surface capacitance sensor for the assessment of asphalt pavement material. The proposed device is a low cost, simple fast and portable which makes it easy to adapt for field investigation. The results obtained from testing several asphalt pavement materials indicate the usefulness of this sensor in evaluating several critical parameters to control pavement quality conditions. These parameters include asphalt moisture condition, the effect of waste fly ash filler additives, pavement thickness, and detection of pavement cracks. The electromagnetic properties of asphalt pavement were measured using the proposed sensor in the frequency range between 100 kHz to 1000 kHz at various moisture conditions. The results show the applicability of the sensor to determine moisture and waste content in the pavement material. In addition, the sensor could be a useful tool to detect cracks of pavement and the thickness and crack orientation in asphalt pavement. The results also indicate that the waste fly ash could improve pavement properties and contribute to solve a major environmental problem in Saudi Arabia.

1. Introduction

Crude and heavy oil industry currently have been an important role in Saudi’s economy. However, it also produces a large amount of waste such as crude oil fly ash (COFA). Fly ash in general, shows good potential to be used as filler in asphalt pavement mixture [1]. Saudi Arabia used a vast amount of heavy crude oil in electrical power generation and desalination plants. These plants produce HFOA waste. To date, these wastes were dumped in sanitary landfill which may lead to groundwater contamination and several environmental pollutions. KSA has a mix of power and water desalination capacity, with more than 80.5 GW of power generation. KSA has the most significant installed capacity (including desalination) among Arab countries, and the total consumption of electric power in KSA during 2016 approximately was 300 terawatt hours. KSA has more than 70 power plants which consumed more than 22 million metric tons of crude and heavy oil. These power plant produced a vast amount of fly ash waste. The total amount of fly ash waste in 2008 was about 0.25 million cubic meters, and it is expected to increase to half million cubic meters by 2016. Example of electrical power plants which produces crude oil fly ash waste and the location of this waste in Saudi Arabia map is shown in Figures 1 and 2.

Premature deterioration of road pavement material is a major problem in road construction in Saudi Arabia and many countries around the world. This problem absorbs a huge amount of money for repair and rehabilitation of these material. Several problems could cause asphalt and road materials to deteriorate deterioration. The major defects occur in asphalt pavement is asphalt cracking results from improper design of roads and pavement mixtures. Environment also cause several problems to asphalt
pavement like high temperature, freeze and thaw problem. In addition, moisture content in asphalt pavement may cause several problems to pavement mixture. Intensive research was conducted to improve the performance of asphalt pavement material. Part of these research try to enhance pavement performance by additive of various filler materials. These fillers could be lime, cement, crumb rubber, polymers, and fly ash waste from different resources. Fly ash waste by products is the most material used as a filler in asphalt pavement [2-6]. Therefore, development invasive and nondestructive method to evaluate asphalt pavement material such as determination of filler content and effect on asphalt performance will be a valuable method to help the construction industry. Also, determination of moisture content of asphalt pavement will be of great interest to industry to assess the potential deterioration of asphalt pavement.

Figure 1. Saudi Arabia map and location fly ash waste from electrical power plant.

Figure 2. Electrical power plant in Jazan which produce crude oil fly ash waste.

Invasive method to evaluate asphalt pavement receive attention from many researchers around the globe. In the last two decades, several electromagnetic nondestructive testing method have been conducted for evaluation of asphalt pavement material. These methods measured the dielectric properties of road and asphalt pavement material such as asphalt, soil, and concrete [7-10]. Several techniques were used to measure the dielectric properties of road construction materials including ground penetration radar [7-8], free space method [9-10], coaxial transmission line [11], waveguide method [12], time domain reflectometer [13-14], parallel plate method [15-19], resonant cavity method [20], and capacitance electrode method [21]. Among these electromagnetic methods, capacitance electrode method possesses several advantages such as low cost, lightweight, simple method, safe, fast, and various setup of electrode could be used to suite the testing condition. Therefore, this method was adopted to develop a surface capacitive sensor for evaluation asphalt pavement material.

This study is conducted to investigate the useful of the proposed surface capacitance sensor to evaluate asphalt pavement material. The sensor is used to measure the dielectric properties of asphalt pavement material. The dielectric properties of asphalt pavement material could be linked and determine the factors causing deterioration. The most important factor causing pavement deterioration will be studied including moisture content in asphalt pavement, filler content and pavement crack.

2. Surface capacitance sensor
The proposed surface capacitance sensor is used to measure the electromagnetic properties of asphalt pavement material called dielectric properties and relate the dielectric properties of asphalt pavement to pavement conditions such as moisture condition. The sensor excites the asphalt material with alternative current (AC) in low frequency range from 1 kHz to 30 MHz. The interaction of the AC and material under testing such as asphalt depends on the electromagnetic properties of asphalt called complex permittivity \( (\varepsilon^*) \). The complex permittivity of material like asphalt composed of two distinguished properties. These properties are the real component of complex permittivity known as dielectric constant and the imaginary component called loss factor. Dielectric constant \( (\varepsilon') \) represents
the amount of energy the asphalt absorbed from the AC current. This amount of absorbed energy depends on the ionic, electronic, and interfacial polarization of the material from the AC current. Loss factor ($\varepsilon''$) represents the energy loss of asphalt from AC current as current pass through the asphalt material. The dielectric constant and loss factor of Complex permittivity is given in equation (1).

$$\text{Complex Permittivity} = \varepsilon^* = \varepsilon' + \varepsilon''$$  \hspace{1cm} (1)

2.1. Surface capacitance design

The schematic diagram of surface capacitance sensor (SCS) design and setup is presented in Figure 3. The SCS is composed of LCR or impedance meter used as source of AC signal and is used to measure the impedance of the electrical circuit including asphalt material which forms part of this circuit. The LCR meter connected to two co-planner brass electrodes supported on rectangular Teflon plates. The LCR meter is connected to personal computer for data acquisition and computing. The two brass electrodes are pressed to the surface of asphalt pavement material and AC signal will penetrate the asphalt and changing the measured impedance of the circuit based on the asphalt pavement conditions and properties. The electric field in the asphalt material is presented in Figure 4.

![Figure 3. Schematic diagram of SCS.](image)

![Figure 4. Electric field inside asphalt material.](image)

The complex impedance ($Z=Z'+iZ''$) of asphalt pavement material measured by the LCR meter at each frequency is used to calculate the dielectric constant and loss factor of asphalt pavement using equation 2 through equation 5. The admittance of asphalt could be calculated from the measured impedance using equation 2.

$$Y_{\text{asphalt}} = \frac{1}{Z} = Y_{\text{asphalt}}' + iY_{\text{asphalt}}'' = G_{\text{asphalt}} + iB_{\text{asphalt}}$$  \hspace{1cm} (2)

The dielectric constant and loss factors of asphalt pavement could be determined using equation 3 and equation 4, respectively.

$$\text{Dielectric Constant} = \varepsilon_{\text{asphalt}}' = \left(\frac{B_{\text{asphalt}}}{\omega C_o} - \frac{C_b}{C_o}\right)$$  \hspace{1cm} (3)

$$\text{Loss Factor} = \varepsilon_{\text{asphalt}}'' = \left(\frac{G_{\text{asphalt}}}{\omega C_o}\right)$$  \hspace{1cm} (4)

Where $\omega$ is the angular operation frequency which is calculated by $\omega = (2 \pi f)$. Where f is the frequency in Hz. It is clear from equations 3 and 4 that dielectric properties of asphalt pavement could be calculated if two parameters $C_o$ and $C_b$ of the surface sensor were determined. These two parameters are constants for the probe at each frequency. These two parameters could be determined by conducting two measurements on two materials with known dielectric properties and form two linear equations using equation 5. Solving the two linear equations the probe parameters $C_o$ and $C_b$ could be found at each frequency.

$$B_{\text{material}} = \omega (\varepsilon_{\text{material}}' C_o + C_b)$$  \hspace{1cm} (5)

PVC and nylon materials having known dielectric properties were used to determine the probe parameters (front capacitance= $C_o$ and back capacitance = $C_b$). An open/short calibration standard method build in the LCR meter and developed by HP were used to calibrate the surface sensor [22].
Another method is used for calibration. This method, called the standard material calibration, uses Teflon material as a standard to calibrate the surface sensor. The dielectric properties of Teflon (2.063) are in good agreement with the values reported (2.1) in literature [23]. The difference between the measured dielectric of Teflon using the proposed sensor and actual value is very small (less than 2% at all frequency from 100 kHz to 1 MHz). Methyl alcohol is used to validate the SCS. The complex permittivity of methyl alcohol is measured using the surface capacitance sensor. The complex permittivity of methyl alcohol at 25°C was 9.0 - i7.0 [23]. The measured value using the proposed SCS was 8.79 – i6.71. The error was about 2%.

2.2. Final SCS design
The final design of the SCS is presented in Figure 5. The surface probe using two co-planner electrodes. These electrodes could be used with various surface area, various separation distances and operating at different frequencies. This variation in design could sense the asphalt pavement to various depths. Increasing the area of the electrode, increasing the distance between electrodes, and reducing frequency will increase the depth of testing asphalt material because the depth of penetration of AC signal will be increased and vice versa. Several surface probes were manufactured using different plate shapes and area, different separation distances. Figure 6 presents sample of these surface probes.

3. Materials and methods
After design and validate the SCS for accurate measurement of dielectric constant and loss factor of material, The SCS was used to measure the dielectric properties of asphalt pavement road construction material in the frequency range of 100 kHz to 1000 kHz. Several asphalt pavement materials were used and tested to evaluate the effect of asphalt moisture content, asphalt fly ash waste content, and crack of asphalt on dielectric properties of asphalt pavement. The following sections presents the asphalt material used and the condition of asphalt prepared for evaluation.

3.1. Raw materials
In this study, bitumen asphalt was used. This asphalt pavement binder was AC 60/70. The properties of this asphalt pavement are given in Table 1. The waste fly ash from electrical power generation plant was used. The classification of this waste ash was class F fly ash. The XRF and SEM of this waste ash were conducted. The results of these tests are presented in Figures 7 and 8. The chemical composition of this ash is given in Table 2.
Table 1. Properties of Asphalt pavement AC60/70.

| Properties                   | Standard test | Asphalt AC60/70 |
|------------------------------|---------------|-----------------|
| Density                      | ASTM D7       | 1.01-1.06       |
| Penetration @25°C, 10/mm     | ASTM D5       | 60-70           |
| Softening Point (°C)         | ASTM D36      | 49-56           |
| Ductility at 25°C (cm)       | ASTM D113     | Min 100         |
| Flash Point (°C)             | ASTM D92      | Min 250         |
| Solubility in Disulfide % wt | ASTM D4       | Min 99.5        |
| Strain Test                  | AASHTO 102    | Negative        |
| Weight Loss by Heating % wt  | ASTM D6       | Max 0.2         |
| Penetration Loss by Heating %| ASTM D5       | Max 20          |

Figure 7. SEM of crude oil fly ash waste.

Figure 8. TXRF of crude oil fly ash waste.

Table 2. Chemical composition of crude oil waste fly ash.

| Composition in fly ash | SiO₂ | Fe₂O₃ | Al₂O₃ | CaO | K₂O | Na₂O | SO₃ | MgO | LOI |
|------------------------|------|-------|-------|-----|-----|------|-----|-----|-----|
| Percentage (%)         | 55.17| 11.27 | 24.82 | 1.42| 1.70| 1.48 | 0.14| 0.29| 5.13|

3.2. Asphalt pavement mixtures

The asphalt pavement was prepare using Marshal mix procedures. Granite aggregate was used with filler fine particles 5% and 5% asphalt AC60/70. The aggregate properties meet the grading limits of the Transportation Ministry in Saudi Arabia. The grading of the aggregate sing sieve analysis is presented in Figure 9. The result show that the fine particles of aggregate less than 0.075 mm is 5%.

Figure 9. Aggregate grading curve using sieve analysis.
Asphalt pavement mixture prepared using this aggregate and asphalt AC60/70. This pavement material was used as control mixture. The fine particles of aggregate less than 0.075 mm were replaced using waste fly ash at five percentage level. Fly ash was used as filler at 0, 25, 50, 75 and 100 percent replacement of fine particles in aggregate. The performance of asphalt pavement mixtures at five level fly ash were determined by measuring the stability of asphalt and tensile strength. The effect of fly ash in enhancement of asphalt pavement mixture was also measured using Rutting factor. Rutting factor resistance was determined using equation 6. The results of tensile strength, stability of asphalt pavement mixture and rutting factors are presented in Table 3.

\[ Rutting\ factor = \frac{\sigma}{\tan(\delta)} \]  

Table 3. Properties of Asphalt pavement AC60/70.

| Asphalt pavement mixture code | Fly ash replacement (%) | Unit weight (kN/m³) | Tensile strength (kPa) | Stability (kN) | Rutting factor |
|-----------------------------|------------------------|---------------------|-----------------------|----------------|---------------|
| APM1                        | 0.00                   | 25.6                | 824.5                 | 13.88          | 1.32          |
| APM2                        | 25.0                   | 25.4                | 750.2                 | 13.72          | 1.40          |
| APM3                        | 50.0                   | 25.3                | 710.3                 | 13.61          | 1.49          |
| APM4                        | 75.0                   | 25.2                | 654.2                 | 13.45          | 1.54          |
| APM5                        | 100.0                  | 25.1                | 618.4                 | 13.35          | 1.68          |

3.3. Dielectric testing and condition

The proposed SCS was used to measure the dielectric constant and loss factors of all asphalt pavement mixture at all fly ash waste content. All measurements were performed at 25°C and in the frequency range between 100 kHz to 1000 kHz with increment 100 kHz. Samples of asphalt pavement were saturated in water for 24 hours the left in air. Dielectric properties performed at several moisture condition of asphalt pavement during drying in air. Moisture condition were measured by drying the sample in oven at 105°C until reach constant weight. The difference in wet and dry sample divided by the dry sample is taken as moisture condition. In addition, asphalt pavement mixture containing artificial cracks with width 2, 4 and 6 mm were prepared. Dielectric properties of pavement mixture were measured at different angles between crack direction and electric field.

4. Results and discussion

The results of pavement mixture indicate that pavement performance such as rutting factor increase with increasing fly ash waste in pavement mixture. The result also shows that stability and tensile strength of pavement mixture slightly reduced with the increase of fly ash. The unit weight of asphalt mixture also reduced with increasing fly ash content in the mix. This is due to replacement of relatively heavy fine granite particles (specific gravity equal 2.7) by lighter fly ash filler (specific gravity (2.1). The effect of frequency, ash content, moisture content and crack on dielectric of asphalt pavement are presented in the following subsections.

4.1. Effect of frequency and fly ash content

The dielectric constant and loss factor of asphalt pavement at various fly ash content over frequency range from 100 kHz to 1000 kHz are presented in Figure 10 and 11, respectively. Both dielectric constant and loss factor decrease with increasing frequency. Polarization of a dielectric material such as asphalt pavement used in this research is contributed by ionic, electronic, interfacial, and dipole polarization. The electronic and dipole polarization of asphalt samples occurs in longer interval of time than the time required for alternative current (AC) to change its direction at high frequency. The dipole molecules of asphalt cannot reorient themselves within a short time available at the high frequency. This will not allow the asphalt material to store more energy from the applied AC where the AC direction changed very fast. This phenomenon is responsible to decrease both the dielectric
constant and loss factor at high frequency for asphalt sample at all fly ash content. To better visualize the effect of fly ash content, dielectric properties of asphalt pavement at various fly ash content were compare at frequency 600 kHz. The results in Figures 12 and 13 indicate that dielectric constant increases with increasing ash content while the loss factor decreases with increasing ash content. The increase in dielectric constant may attribute to double layer polarization of fly ash particles. The reduce in loss factor due to more connected particles because fine fly ash particles could bridge the void of the asphalt material as a filler. This will allow the energy to be loss as an AC current bass through asphalt material.

These results could also be used to estimate the stability, tensile strength and rutting factors of asphalt pavement materials because all the properties is function of ash content as indicated in previous section in Table 3. The dielectric properties could be used as indirect method to predict unit weight, tensile strength, stability and rutting factor by estimating ash content in asphalt.

4.2. Effect of moisture content

The effect of moisture content of asphalt pavement on asphalt dielectric constant and loss factors are presented in figures 14 and 15, respectively. The moisture condition was 0% for dry asphalt pavement mixture and 7.1% moisture content at wet condition and surface dry. The results also evaluated at moisture content 2.1%, 4.3% and 5.6%. The results indicate that both dielectric constant and loss factor increase with increasing moisture content of asphalt pavement. This is due to the high dielectric constant and loss factor of water compare to the asphalt pavement. Small inclusion of polar water molecules will increase the polarization of asphalt. Also increase water in the pore structure of asphalt could enhance the conductivity of asphalt and increase the AC current to pass through the asphalt which lead to high loss factor.
4.3. Effect of crack
The surface capacitance sensor was aligned to make the electric field in asphalt pavement sample parallel to the crack length. The dielectric properties were measured at 0 degree then the sensor rotate 22.5 degree and the dielectric were measured again. This procedure was continuing, and the measurements were evaluated from 0 degree to 180 degree. The results of dielectric constant and loss factor at various angles are presented in Figures 16 and 17. In 90 degree the electric field was perpendicular to the crack direction. The results show that both dielectric constant and loss factor were maximum at parallel condition and minimum when the crack perpendicular to crack direction. The results also indicate that increasing crack width from 0, 2, 4 and 6 mm both dielectric constant and loss factor were decreased. The reductions of dielectric constant were 1.2, 2.8 and 4.2 form non cracked asphalt for 2, 4, and 6 mm crack width respectively. Similarly, the reductions in loss factor were 0.65, 1.4, and 2.1 for 2, 4, and 6 mm crack width respectively. These results indicate that the SCS could be used to determine crack direction and quantify crack width.

5. Conclusion
The results in this study indicate that the use of crude oil waste fly ash produced in the electrical power plant and desalination could be used to enhance the performance of asphalt flexible pavement. This could also provide a sustainable dispose of this toxic waste in road construction which may lead to solve a large environmental problem in Saudi Arabia because this waste currently dumps in sanitary land fill. In addition, the rutting factor of asphalt pavement incorporated crude oil waste fly ash was improved which save a large amount of money in repair the roads in Saudi Arabia. Surface capacitive sensor was also developed to measure asphalt pavement material. The sensor was calibrated using open/short calibration standard and validated was achieved for accurate measurement of dielectric properties of material with error less than 2%. The dielectric properties of asphalt pavement decrease
with increasing frequency due to reduction of current conductance at high frequency. The dielectric constant increases with increasing fly ash content while the loss factor decreases with increasing ash content. This may use to quantify the fly ash as filler content in asphalt pavement mixture which could help in estimating asphalt performance such as tensile strength, stability, and rutting factors. The results also indicate that both dielectric constant and loss factor increase with increasing moisture content in asphalt pavement mixture. This could estimate the potential of deterioration of asphalt material. The measured dielectric properties of asphalt show its potential to detect cracks and crack orientation in asphalt pavement. Further testing is necessary to evaluate the sensor material. The measured dielectric properties of asphalt show its potential to detect cracks and crack orientation in asphalt pavement. Further testing is necessary to evaluate the sensor material.

The future need is to include other factor such as temperature and various type of asphalt not used in this study.

6. References

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