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*Research Article*

# Displacement Investigation of KNN-Bitumen-Based Piezoceramics in Asphalt Concrete

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Piezoelectric material has excellent characteristics of electromechanical coupling so that it could be widely applied in structural health monitoring field. Nondestructive testing of piezoelectric technique becomes a research focus on piezoelectric field. Asphalt concrete produces cumulative damage under the multiple repeated vehicle load and natural situation, so it is suited material and structure for nondestructive application. In this study, a test system was established by driving power of piezoceramic, laser displacement sensor, computer, and piezo-embedded asphalt concrete. Displacement, hysteresis, creeps, and dynamic behavior of KNN piezoceramic element embedded in asphalt concrete were tested. The results indicate that displacement output attained 0.4 $\mu$m to 0.7 $\mu$m when the loads were from 0 N to 150 N. The hysteresis was not obvious when the load was from 0 N to 100 N, aside from higher loads. The creep phenomenon can be divided into two parts: uptrend and balance. The more serious the asphalt binder ageing is, the larger the displacement is, when piezo-asphalt concrete has already been in serious ageing.

## 1. Introduction

Piezoelectric material is a kind of intelligent material which can translate between mechanical energy and electrical energy. At present, the yearly sales amount of piezoceramics is over 10 billion, and the application filed is from consumer electronics to aerospace, naval sonar, and high-speed train [1]. Hundreds of years, lead zirconate titanate piezoceramic (PZT) still reign supreme due to excellent performance, but PZT has lead harm for body or environment, so that its application is gradually limited in the Europe, Japan, United States, and China. Dealing with this problem, researchers intend to discover a new piezoceramic to replace PZT which uses "lead-free" components [2]. Hence, many researchers have invested heavily in research and development of high performance lead-free piezoelectric materials. The study focused on the piezoceramics of potassium-sodium niobate (KNN), sodium bismuth titanate (BNT), and barium titanate (BT) which can improve piezoceramic property and temperature stability like PZT [3–8]. However, compared with PZT, the performance of almost all of lead-free piezoceramics is poor so that cannot replace it.

At present, major type of pavement in road engineering is asphalt concrete. As a result of heavy traffic, climate, and environment in a long period, the strain and kinetic energy were accumulated in the asphalt concrete [9–11]. Furthermore, those strain and kinetic energy are absorbed by asphalt and changed to thermal energy of pavement so that it increases the risk of crack and track in pavement [12, 13]. In fact, structural health monitoring and damage detection using piezoceramics are important research topics due to the advantages of piezoceramics, such as quick response, broadband frequency, and low price [14–16]. Although researchers have obtained some achievements of piezoceramic application in engineering, some problems need to be further studied, like the displacement properties of piezoceramics embedded in the structure.

In the present study, the properties of KNN-bitumen-based lead-free piezoceramics (KNN) were focused after embedding in asphalt mixtures. The KNN was a stacked-type piezoelectric material that was prepared by a $KN_bO_3$–$N_aN_bO_3$

ceramic doped with Li and bitumen as a binder. Encapsulated piezoelectric elements were embedded into asphalt mixture. The experimental results and analyses include the following aspects: displacement, hysteresis, creep properties, and displacement changes of piezoceramics after ageing.

## 2. Materials and Methods

*2.1. Materials.* Potassium carbonate ($K_2CO_3$), sodium carbonate ($Na_2CO_3$), lithium carbonate ($Li_2CO_3$), and niobium oxide ($Nb_2O_5$) were produced by China Sinopharm Chemical Reagent Co., Ltd, which are raw materials used in the preparation of KNN. They are all powders and analytically pure.

In order to stack pieces of KNN each other, electrode layer was designed. The Young modulus, Poisson ratio, and electric conductivity of electrode materials have to be considered. To cost effectiveness, brass is a better one compared to others. The thickness of brass is 0.1 mm as thin as possible because the brass only serves as an electrode.

The metal panel improves the mechanical properties of the piezoelectric materials. From the choice of metal panel materials, the duralumin was chosen. It has a few good features such as corrosion resistance, good electrical and thermal conductivity, positive alloy strength, heat-resistant properties, and so on. The thickness of duralumin is 1.6 mm.

A base bitumen was procured from China with a penetration of 78 (0.1 mm at 25°C, 100 g, and 5 s), ductility of 49.4 cm (at 15°C), and softening point of 45.7°C. Basalt with particle size less than 19 mm was supplied from China. Limestone powder was used as the mineral filler from China, too.

### 2.2. Methods

*2.2.1. Preparation of KNN.* $KNbO_3$–$NaNbO_3$–0.035Li (KNN) obtained by the traditional solid-phase reaction method. In order to remove the adsorbed water from the powder, the raw materials of $K_2CO_3$, $Na_2CO_3$, $Li_2CO_3$, and $Nb_2O_5$ were applied by air-drying in the oven at 105°C for 24 hours. Following this, the dried materials were weighed according to the stoichiometric ratio of the formula and milled by the planetary ball mill for 12 hours. According to the content of Li, the dry materials were mixed with $Li_2CO_3$, and the presintering temperature is 920°C in 4 hours. Afterwards, the calcined powder was milled by the planetary ball mill for 12 hours once again and compressed into the ring. The diameter of the KNN piece was 18 mm, and thickness was 2 mm. Finally, the KNN piece was sintered at 1135°C for 2 hours. The performance of KNN was as follows: piezoelectric constant $d_{33}$ was 163 pc/N and $d_{33}{}^*$ was 212 pm/V, electromechanical coupling factor $k_p$ was 0.384, and dielectric loss $\tan\delta$ was 0.12%.

*2.2.2. Preparation of KNN Stacked Element.* The stacked piezoelectric specimen was composed of KNN pieces, bitumen and electrodes. The KNN piezoceramics were connected tandem. The brass sheets were pasted on two sides of each piece as electrodes by epoxy and bitumen. Duralumin sheets were pasted on two sides of the stacked piezoelectric specimen. At last, bitumen was heated to encapsulate the piezoceramics and wires in a mold as shown in Figure 1. Encapsulation size of the stacked piezoceramic is 20 mm × 20 mm × 30 mm like an aggregate of asphalt mixture, which contains 12 pieces of the KNN piezoceramic.


Figure 1: Sample of the KNN-bitumen stacked piezoceramic.

*2.2.3. Preparation of Asphalt Concrete.* According to the experimental method of T0703-2011 (JTG E20-2011, China), a slab of asphalt mixture was prepared. Afterwards, the slab was drilled in the center by the drill of 150 mm. Finally, new hot asphalt mixture and stacked piezoceramic filled the space in the center of the slab. The upper surface of the stacked piezoceramic kept same flat with the surface of asphalt slab. After compaction and cooling, the specimen can be applied to experiments as follows. The mix proportion of AC-13 and the best bitumen-aggregate ratio of asphalt mixture were taken in this research as shown in Table 1. The void content was controlled at 4% [14].

*2.2.4. Experimental Method.*

*(i) Test System.* Figure 2 shows the diagram of the test system of piezoceramic asphalt. Driving power of piezoceramic was employed using the equipment HVA-200 produced by the Xinmingtian Company of China. The displacement of the stacked piezoceramic was tested by a noncontact laser displacement sensor named M72L/0.5 produced by Melsensor in Germany. The testing precision is 0.1 $\mu$m. The displacement of the stacked piezoceramic was generated after driving voltage was applied; afterwards, the data of displacement output were transferred from the displacement sensor to the destination computer.

*(ii) Displacement and Hysteresis under Different Loads.* The input voltage increased from 0 V to 150 V by 10 V each step and then decreased to 0 V. The input voltage and displacement data were collected and recorded by the

Table 1: Mixture gradations.

| Mesh (mm) | 16 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | 0.15 | 0.075 | Bitumen-aggregate ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AC-13 | 100.0 | 86.1 | 75.3 | 56.7 | 37.3 | 24.3 | 15.9 | 111 | 8.7 | 6.8 | 4.8% |

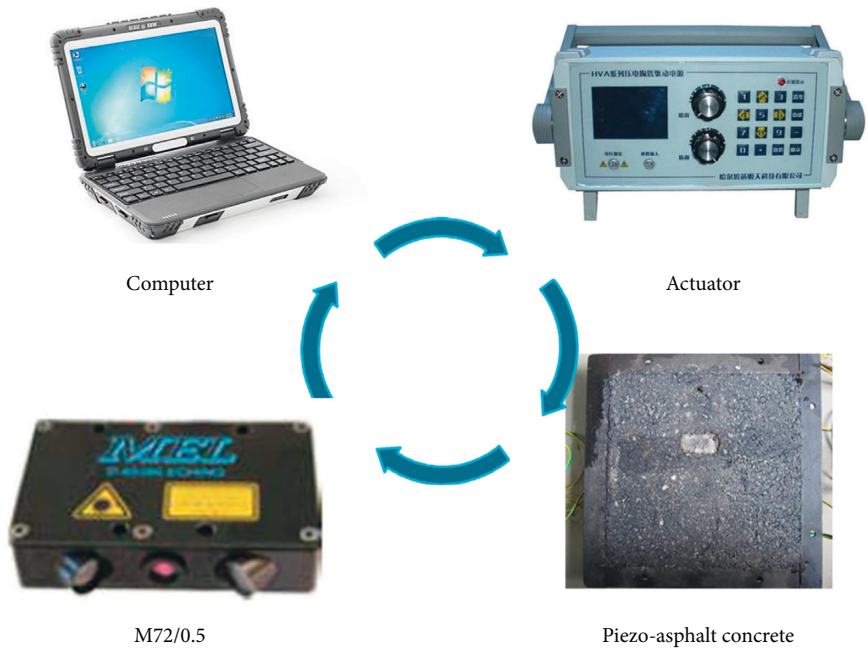


Figure 2: Diagram of the test system.

abovementioned test system. The stress of vehicles and the surface area of KNN element have to be considered. Therefore, the load was 0 N, 50 N, 100 N, and 150 N.

*(iii) Creep*. The input voltage was 50 V, 100 V, and 150 V. The displacement data were collected per 30 seconds for 20 times.

*(iv) Dynamic Behavior*. The input voltage was 150 V, and the bias voltage was 75 V. According to the vibrational frequency of pavement, a sinusoidal voltage signal was input with different frequencies of 5 Hz, 10 Hz, and 20 Hz.

*(v) Ageing of Piezoelectric-Asphalt Concrete*. The SHRP plan provides several methods for ageing, such as oven ageing, delayed mixing, microwave heating, pressurized oxidation, and ultraviolet ageing. Oven ageing is considered to be the most effective method for ageing of asphalt mixes in the laboratory. Hence, short-term oven ageing (STOA) and long-term oven ageing (LTOA) were conducted. For STOA, the piezoelectric-asphalt concrete was placed in a forced ventilated oven at 135°C for 4 hours. For LTOA, the piezoelectric-asphalt concrete was aged through STOA first, afterwards was placed in a forced ventilated oven, and underwent a long-term ageing of 5 days at a temperature of 85°C. After ageing, the asphalt concrete which filled in the space center of slab was picked up, and ageing bitumen was reclaimed. The extraction procedure of bitumen followed the Abson method (T0726-2011, JTG E20-2011, China). The solution used for extraction was trichloroethylene. Finally, the softening point, penetration, and ductility should be tested.

## 3. Results and Discussion

*3.1. Displacement under Different Loads.* One of important parameters is the displacement output of KNN element under different loads. In order to analyze displacement properties close to the real pavement, the loading test was carried out under slow loading speed at ambient temperature. As shown in Figure 3, compared with no load, the KNN element had a greater displacement output under different loads. Displacement output attained 0.4 $\mu$m to 0.7 $\mu$m when the load was from 0 N to 150 N. In the experimental range, sensitivity of displacement has nonlinear relationship with the excitation voltage. With the excitation voltage increasing and decreasing, the phenomenon of hysteresis is becoming more and more serious. Ideally, according to converse piezoelectric effect, the relationship between displacement output of KNN element and excitation voltage should be linear. In reality, there is no superposition between the rising curve and the decline curve like the curve shown in the Figure 3. This nonlinear relationship between displacement and excitation voltage was named hysteretic loops.

*3.2. Hysteresis.* Figure 4 shows the hysteresis curve under different loads. Changes of hysteresis from 0 N to 100 N were

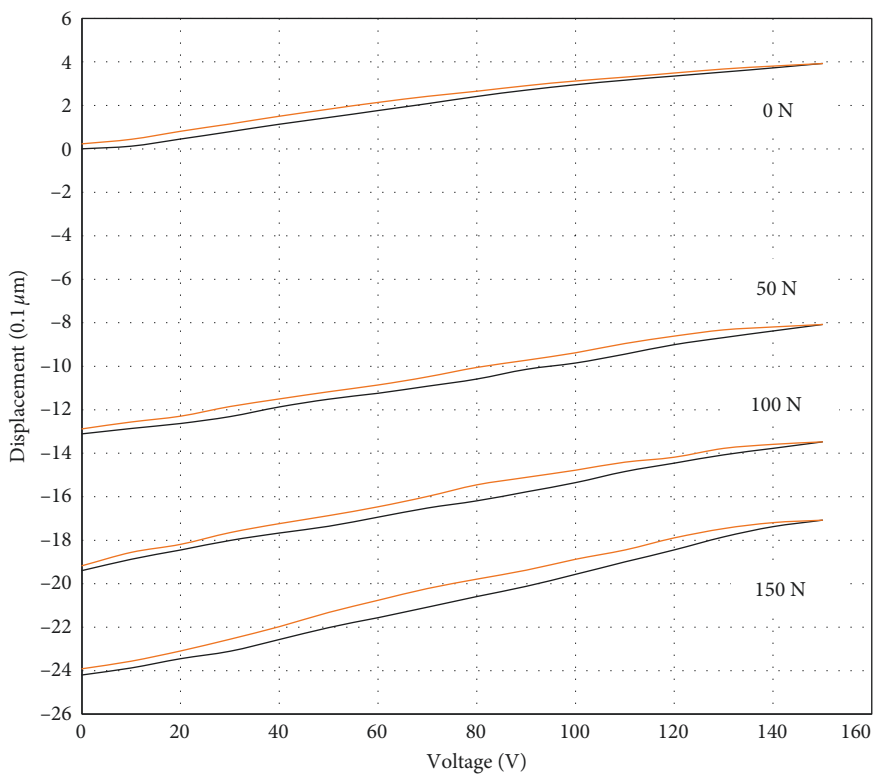


Figure 3: Displacement of KNN element in the asphalt concrete under different loads.

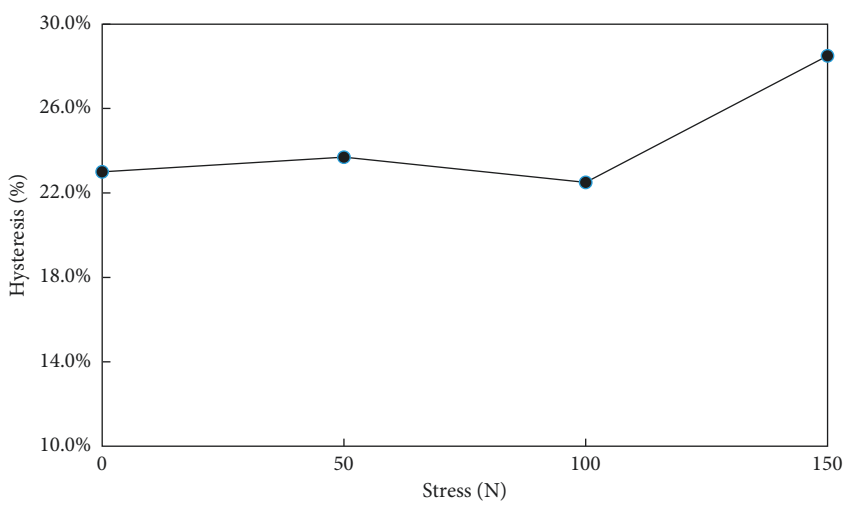


Figure 4: Hysteresis of KNN element in the asphalt concrete under different loads.

not obvious, but hysteresis was 28.3% when the load was 150 N. On the micro level, according to the polarization of the piezoceramic, the cause of the hysteresis phenomenon of KNN element is the viscosity among the electric dipoles in the dielectric medium based on the analysis of electric domain formation of piezoceramics. The shape of the hysteresis curve is influenced by the value and frequency of excitation voltage and own properties of piezoceramics. On the macro level, the cause of the hysteresis phenomenon of KNN element is electrostriction effect, ferroelectric effect, and damping effect of bitumen. Bitumen has plasticity and viscoelasticity and blocks the motion of KNN element in the asphalt concrete.

*3.3. Creep.* Creep phenomenon was occurred when excitation voltage is applied to the KNN element. This is because displacement output is more volatile immediately. The displacement always increases to a certain value at the beginning and then grows slowly to the final value in a short time. The final displacement cannot be completed immediately when KNN element exposed to an electric field,

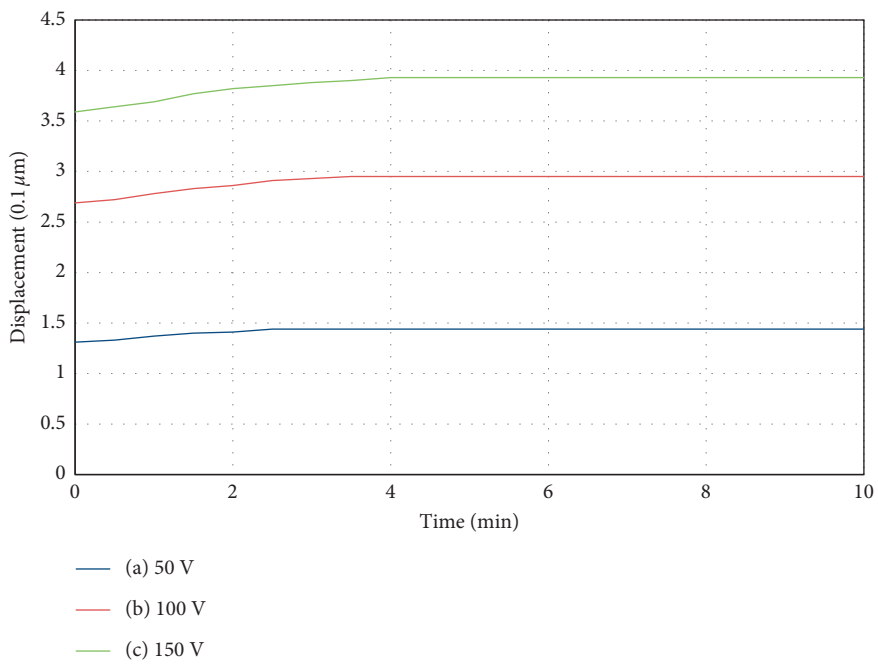


Figure 5: Creep of KNN element in the asphalt concrete under different voltages.

because of friction among internal lattices of the piezoceramic. Hence, the piezoceramic has to fully meet the final deformation in a short time and shows the hysteresis of displacement output from a macroscopic view.

The creep test of KNN element embedded in the asphalt concrete was carried out under voltages of 50 V, 100 V, and 150 V respectively. Figure 5 reveals the creep of KNN element. In Figure 5, the creep phenomenon can be divided into two parts. First, the displacement output was close to the maximum value within a few milliseconds. Afterwards, the displacement output attains the maximum value in a matter of minutes. In addition, the creep rate related to the input voltage, and the creep time increases with the input voltage.

*3.4. Dynamic Behavior.* The vibration frequency of the pavement structural layer is from 1 Hz to 20 Hz when a vehicle travels forwards with different speeds. In common, the frequency of 10 Hz always be used in the test of asphalt mixture, or approximately a vehicle moves on the pavement with a speed of 60–65 km/h. The dynamic behavior was characterized by amplitude. Figure 6 shows the displacement amplitude of the piezoceramic which was drove by single-phase sinusoidal alternating voltage. In Figure 6, compared with the peak and trough of the sinusoid, the waveform of displacement amplitude was distorted a little. The displacement amplitude of the piezoceramic was the same and around 0.4 $\mu$m under voltage of 150 V without any load. This indicates that the displacement was not related to the frequency.

*3.5. Displacement after Ageing.* The ageing of bitumen is a complex physical change and chemical change. The rheological properties also have a large change after ageing, eventually leading to cracking and damage of pavement, seriously affecting the durability of the road. Table 2 shows the properties of bitumen and asphalt samples with different ageing. The results indicated that the penetration became smaller, the softening point increased, and the ductility was greatly reduced. Furthermore, the conventional performance of the asphalt concrete sample was tested, and the Marshall stability decreased.

In order to study the relationship between bitumen ageing and displacement of KNN element, the displacement was measured without any load. Then, the voltage was applied from 0 to 150 V by 10 V each step. The input voltage and displacement data were collected and recorded by the test system, and the voltage-displacement curve was drawn, as shown in Figure 7. It reveals that the displacement increases with the aggravated ageing process. In addition, the displacement curve of the sample was not smooth after STOA and LTOA. Three curves were close to each other at the beginning stage; afterwards, the curves were separated due to different ageing. The more serious the asphalt binder ageing, the larger the displacement output.

This phenomenon can be explained in two ways. One is the effect of bitumen ageing. Bitumen is composed of saturates, aromatics, resins, and asphaltenes. For ageing, acceleration movement of bitumen molecules causes the evaporation of internal light-weight components so that a series of physical and chemical changes occurred and the content of asphaltenes increases. Hence, the bitumen becomes hard and brittle, and the viscosity decreases. In a word, the capability of impeding relative movement decreases. The other one is adhesion between bitumen and KNN element. Saturates and aromatics are Low-molecular weight and nonpolar compounds and play the role of providing lubrication and flexibility. These two compositions mainly adhere

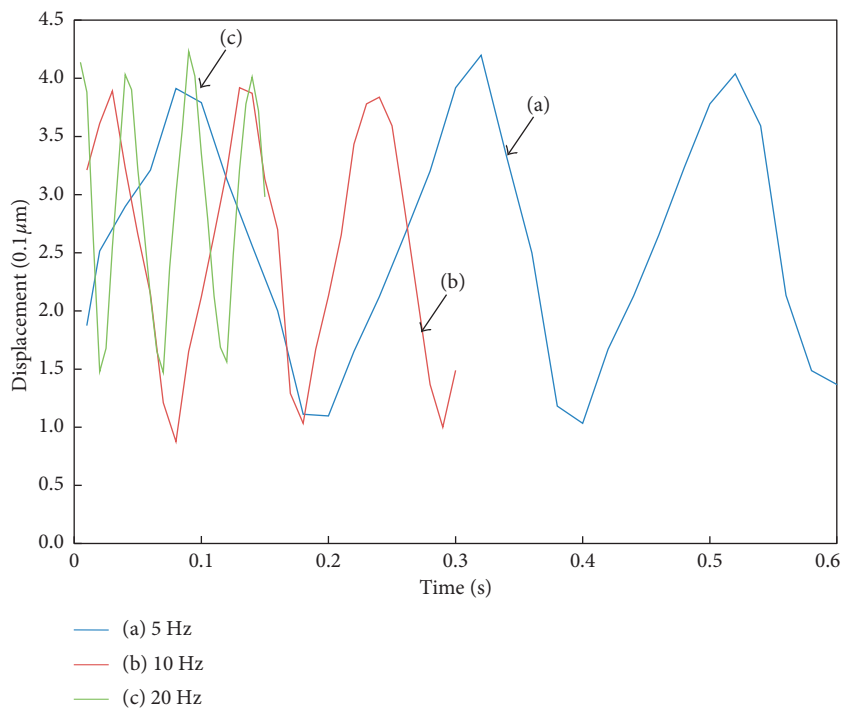


Figure 6: Dynamic behavior of KNN element in the asphalt concrete under different frequencies.

Table 2: Properties of bitumen and asphalt samples with different ageing.

| Index | Softening point (°C) | Penetration (dmm, 25°C) | Ductility (cm, 15°C) | Marshall stability (kN) |
|---|---|---|---|---|
| No-ageing | 45.7 | 78 | 59.4 | 9.34 |
| STOA | 48.5 | 72 | 41.7 | 8.17 |
| LTOA | 51.4 | 63 | 33.8 | 6.45 |

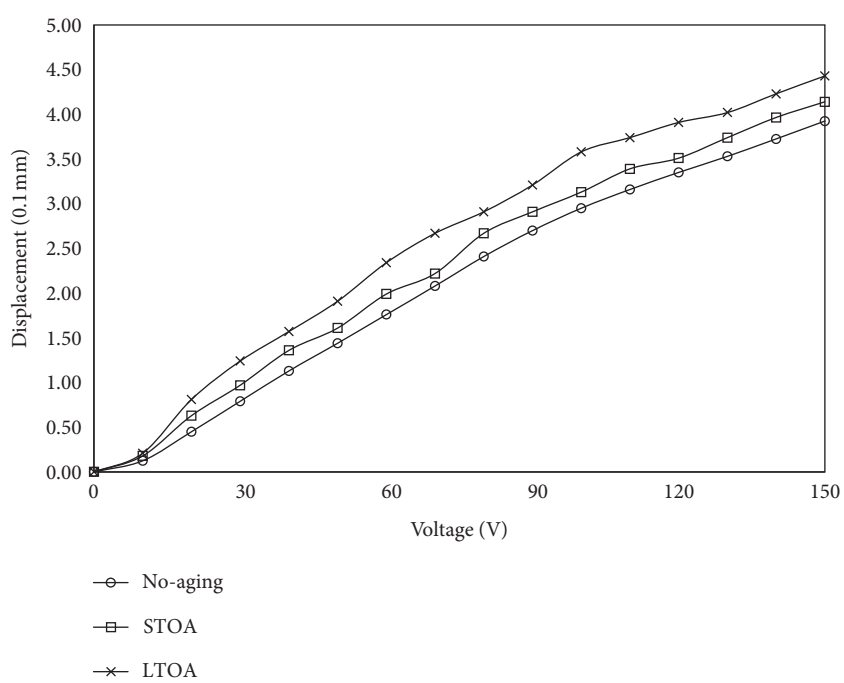


Figure 7: Displacement-voltage curve of KNN element in asphalt concrete after ageing.

to KNN element by the Van der Waals force. Resins and asphaltenes are polar and surfactivity compounds and contain asphaltic acid and anhydrides. These two compositions mainly adhere to KNN element through chemisorption. On the whole, the content of saturates and aromatics decreased due to bitumen ageing so that adhesion became worse and ultimately led to displacement changes.

## 4. Conclusions

The theoretical analysis and experimental verification are combined to conduct the research, and conclusions are as follows:

(a) Displacement output of KNN element embedded in the asphalt concrete attained 0.4 $\mu$m to 0.7 $\mu$m when the loads were from 0 N to 150 N. Changes of hysteresis from 0 N to 100 N were not obvious, but hysteresis attained 28.3% when the load was 150 N.

(b) The creep phenomenon of displacement of KNN element embedded in the asphalt concrete can be divided into two parts. First, the displacement output was close to the maximum value within a few milliseconds. Second, displacement output attains the maximum value in a matter of minutes.

(c) Displacement output of KNN embedded in the asphalt concrete increases with the aggravated ageing process. The more serious the asphalt binder ageing, the larger the displacement.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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