Laboratory simulation and mechanical performance of asphalt materials under the action of saline

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Highlights

- Four contents of teak fibre was selected to characterise the rheological properties.
- Thermal conductivity of bitumen increased with Teak fibre addition.
- Teak fibre slightly improve the toughness of bitumen at service life temperature under action of salt.
- Teak fibre increased complex modulus norm at service life temperature under action of salt.
- Optimum addition of teak fibre considering rheological improvements is 2%.

Abstract

Conventional asphalt mixture performs well in most asphalt pavement applications. However, blistering, which is a common phenomenon in semi-arid areas, is one distress mechanism caused by various detrimental salts resulting in the loss of adhesion at the interface of aggregates and bitumen. When moisture reaches this delaminated interface, it can lead to blistering under the action of heat and thermal expansion. There is heightened interest in the semi-arid areas to modify bitumen and enhance the mechanical properties of asphalt mixtures to address durability and cost-effectiveness issues. One of the approaches being investigated includes using renewable additives to promote a more environmentally friendly production of asphalt mixtures. In this study, two bitumens of penetration grades 40/60 and 50/70 were modified with various percentages of Teak (TK) fibre contents to prolong the service life of asphalt pavements in the semi-arid areas. The properties, including rheological information of base and TK fibre-modified bitumens, were obtained through rutting, penetration, thermal conductivity, and multiple stress creep recovery (MSCR) tests. Base and TK fibre-modified bitumens were soaked in different sodium hydrogen carbonate ($NaHCO_3$) solution concentrations for varying durations. The MSCR test was used to investigate the mechanical performance of the bitumen and binder mastics under salt action. TK fibre modified bitumens demonstrated better rutting resistance, reduced penetration and lower thermal conductivity. The test results indicated that all binder mastics with TK fibres had reduced shear strain, higher recovery, and higher non-recoverable creep compliance than the base bitumen. The TK fibre-modified binders showed better resistance to the action of salt than the base bitumen but exhibited an increase in shear strain, reduction in recovery and increase in non-recoverable creep compliance for soaked samples with increasing salt content. Both base bitumens exhibited excessive softening and showed negative recovery at stress levels from 0.5 kPa with increased soaking duration and salt content. These results show that the optimum level of TK fibres was 2% by weight of bitumen. The results from this study are encouraging for the potential use of TK fibres to improve the performance of asphalt mixtures in semi-arid field conditions where the presence of salt, and specifically $NaHCO_3$, is expected.

Keywords: Blistering; Loss of adhesion; Percentage recovery; Non-recoverable creep compliance; Shear strain

1. Introduction

Asphalt mixture is commonly used to construct road and airport pavements due to its excellent performance and workability. General knowledge suggests that, in arid areas, a build-up of either volatile gases or moisture vapour from the underlying layers of the asphalt pavement that accompanies an increase in surface temperature cause blisters in asphalt pavements. As illustrated in Fig. 1a, salt-containing moisture evaporates through the pores of the subgrade up to the upper asphalt layers resulting in asphalt blisters during high temperatures; the example is shown in Fig. 1b. In these areas, a combination of dry climates with saline materials and saline groundwater or surface water induces salt damage. Several investigations have suggested that blistering and deformation of asphalt pavement are due to concentrated salts in moisture from underlying layers of the asphalt pavement [1]–[3]. Blistering could also be due to interaction between the salts and the mineralogy from aggregates source in the asphalt materials. This means certain mineral phases might be particularly detrimental and result in blistering [2], [4], [5].

In a country like Botswana, more than two-thirds of the total land area contains sodium chloride (NaCl) and $NaHCO_3$ in the soil [6]. Reported locations damaged by action of salts in Botswana include Sua Pan airstrip, Nata-Maun Road (km 0–45), Sebina Nata, Phikwe runway and Sekoma-Kang road (Trans- Kgalagadi road) [6]. It is important, therefore, to develop a detailed understanding of the effect of the action of salt on the performance of asphalt mixtures, especially in semi-arid regions.

McAloney et al. [7] performed a test to verify that nano-modified asphalt can remove cryoprotectants (antifreeze compounds and antifreeze proteins) that degrade asphalt mixtures. In their study, the indirect tensile test was performed on unmodified and nano-modified asphalt mixture specimens treated with NaCl solution, and one of the findings was that chloride salts reduced the strength of the asphalt mixture. Similarly, Cooley et al. [8] found that antifreeze agents, especially those containing chloride salts, had adverse effects on the aggregate and the asphalt mixture. They discovered that various antifreeze solutions degrade asphalt mixtures through freezing and thawing more than pure water. Yu et al. [9] analysed the master curves of complex modulus and phase angle as well as the ultimate fatigue temperature of a long-term aged unmodified and polymer-modified bitumen after soaking in various salt solutions. The study concluded that salt reduces the low-temperature and fatigue resistance properties of asphalt mixtures. The study also found that salt enhances the high-temperature properties of the aged bitumen, which portrays poor sensitivity to salt effects on complex modulus and phase angles at low frequencies for both unmodified and Polymer

Modified Binder (PMB) bitumens. Özgan et al. [10] highlighted specimens soaked with a de-icing solution exhibited low Marshall Stability and flow values.

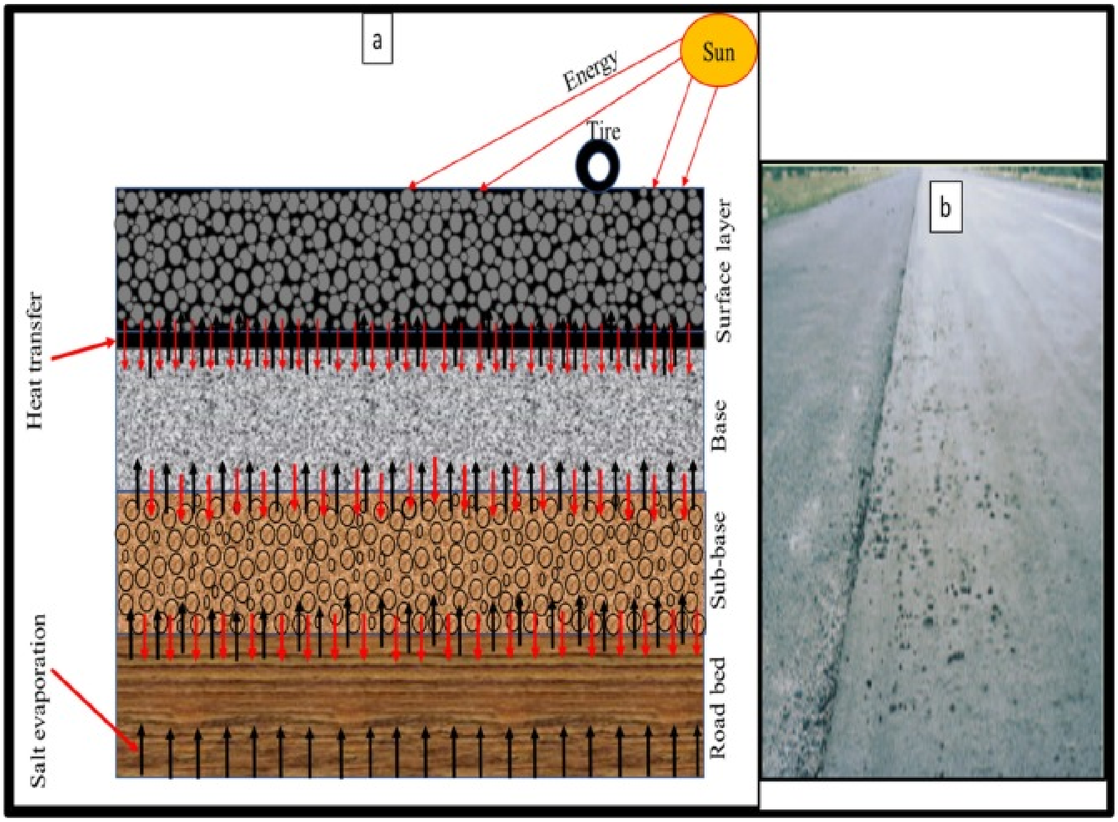

Fig. 1. a: Illustration of heat transfer coupled with salt transport, Fig. 1. b: example of blistering on the asphalt layer.

Teak (TK) is a lignocellulosic hardwood commonly found in Botswana. It has various names: in Botswana is called *Mukwa*, in South Africa is known as *Morhotso* and it is mainly used for furniture, building construction, and medicine [11], [12], [13]. Its main constituents are lignin, hemicellulose and cellulose [14]. Amongst those, cellulose's chemical and physical properties are associated with the arrangement of the cellulose molecules and have various proportions of crystallinity and amorphous structures [15]. Hemicellulose is a common polysaccharide that consists of assorted sets of pentose and hexose sugars [16]. Lignin is a common amorphous heteropolymer composed of various phenylpropane units assembled with various linkage types [17]. Generation of lignocellulosic wood waste from saw-mills/woodworks and other production has become a major cause for concern as the waste is preordained for landfills that in turn becomes a fire hazard to the society and the environment in Botswana [18]–[20]. Currently, small amounts of lignocellulosic waste are used and recycled as useful bioproducts. Lignocellulosic materials have shown great potential as reinforcing fillers in the manufacturing of wood-plastic composites [20], [21]. It is readily available, low cost and renewable. Watkins et al. [22] highlighted the existing chemical likenesses between cellulose, lignin and bitumen since they are hydrocarbon materials made primarily of carbon, hydrogen and oxygen. In this regard, lignocellulosic biomass is a potential modifier to enhance the performance of road construction materials. Also, applying lignocellulosic products as a modifier and partial substitute can reduce the concern of shortages of petroleum bitumen production [18].

Some studies towards bitumen modification by lignocellulosic materials have shown promising results. Arafat et al. [19] used various lignin fibres to modify the asphalt mixture and observed improved rutting resistance without losing resistance to moisture-induced damage. McCready and Williams indicated that lignin fibres enhanced the temperature sensitivity of bitumen [23]. A study by Pan discovered that the addition of lignin fibre reduces the rate of ageing of bitumen [24]. In a study by Batista et al. [25] the addition of lignin to the bitumen showed better performance in rutting and cracking resistance. The inclusion of lignin also led to better thermal stability. Other reports on the application of cellulose to modify bitumen have shown the enhancement of the mechanical performance of mixtures, such as rutting and fatigue cracking resistance [26].

Yang et al. [27] pointed out that a small amount of nanoclay called polysiloxane-modified montmorillonite improved the stripping resistance, reduced moisture susceptibility, and minimised the damage of asphalt mixtures to de-icers without chloride. The results from a study by Wei et al. [28] suggested that asphalt mixture modified with nanoclay and carbon microfibres improved the moisture susceptibility and performance after the de-icing solution's corrosion. The material was produced using fine fibres basalt extracted from plagioclase and pyroxene and was tested using the bending test. Olivine improved the low-temperature properties of the low-temperature properties. Shi et al. [29] investigated the impact of nanoclay in reducing the deterioration of asphalt mixture to non-chloride deicers. Results indicated that when soaked in the 31% calcium chloride ($CaCl_2$)-based deicer, the fracture energy of unmodified hot mix asphalt (HMA) averaged at 34.3 J/m^2, while a fracture energy up to 42.4 J/m^2 (a 24% increase), was achieved by adding 2% nanoclay and 0.7% carbon microfiber modified bitumen. Xiong et al. [30] investigated the effect of a freeze–thaw cycle, including salt concentration, on asphalt-aggregate interfacial bonds. The results showed that the asphalt-aggregate mixture slowly lost adhesion due to increased freeze–thaw cycles and salt concentrations.

In the original Superpave binder specifications, the parameter rutting factor ($G^*/\sin(\delta)$) measured at 10 rad/s is used to predict pavement rutting. This test is conducted at the high-performance graded (PG) temperature and after short-term ageing by the standard rolling thin film oven (RTFO) test [31]. For pavement that is exposed to either high traffic volumes or low-speed traffic, bump grading can be included to help improve bitumen performance. High grading temperatures are adopted for rutting tests, which are possibly higher than the actual temperature occurring in the pavement. However, related literature pointed out that grade bumping is unsuitable for modified bitumens [32], [33]. Delgadillo et al. [33] showed that cyclic reversible loading does not separate energy dissipated in the permanent deformation and energy dissipated in the delayed elasticity. The study [16] indicated that the parameter $G^*/\sin(\delta)$ is appropriate and positively correlates with wheel-tracking tests. However, particularly for modified bitumen, this correlation is achieved if the repeated test of the parameter $G^*/\sin(\delta)$ is reduced significantly and is adjusted to the average loading times experienced in wheel-trafficking tests. An advanced testing method called MSCR can be used to anticipate the performance of both modified and unmodified bitumens. Applying a range of stress levels can identify bitumens that are excessively stress-sensitive in the non-linear domain.

1.1. Problem statement

The exact mechanism of salt-induced blistering is still not fully understood. In drylands, the various salt types that can contribute to pavement damage include but are not limited to NaCl, sodium sulphate (Na_2SO_4), $NaHCO_3$ and magnesium sulphate ($MgSO_4$) [6]. Several studies have evaluated the performance of asphalt mixtures under the action of NaCl, Na_2SO_4 and $MgSO_4$ [9], [34], [35], [36] but not the $NaHCO_3$. The focus of this study was to evaluate the performance of the asphalt mixture under the action of $NaHCO_3$ only.

1.2. Objectives and scope

I. The first objective of this study was to assess the effect of TK fibres on the rheological properties of the bituminous binders. The scope of the assessment includes tests on rutting factors, penetration, as well as the multiple stress creep recovery (MSCR) on the base and TK fibre-modified bitumens; and

II. The second objective was to investigate the stress sensitivity of bitumens to assess adhesion loss due to the action of salt i.e. $NaHCO_3$ solution. The scope of this assessment includes the MSCR test on the base and modified bitumens.

2. Experimental programme

2.1. Materials and preparation

TK fibre was collected from a local company, Terry Cooney, that manufactures furniture. TK fibre was divided into two lengths (13 mm and 6 mm), all with a diameter of 12 μm before drying in an oven at 60 °C for 24 h to reduce the amount of moisture. This study designated 13 mm long TK fibres as TK 1 and 6 mm long as TK 2. Then 0.50 kg specimens of 40/60 pen and 50/70 pen bitumen were placed in an oven for 1hr at 160 °C. These grades were selected because they are the most commonly used in Botswanan pavements based on the climatic conditions in the country. The TK fibres at 0.5%, 1.0%, 1.5% and 2.0% by weight of the bitumen were added and mixed to form the TK fibre-modified bitumens. These TK contents were selected as they are realistic because a high amount of fibre can cause high absorption of bitumen [37]. Also, some studies have shown brittleness of the bitumen caused by a high amount of fibre [38], [39]. All fibre contents were mixed with bitumen using a paddle mixer, a Ross LDM-130 12,852 at a low speed (140 ± 5 rpm). The study followed a procedure used by Sobolev et al.[40]. Mixing was carried out for 90 s, and then the mixtures were reheated for 10 min at 160 °C. The procedure was repeated four times to complete 6 min of mixing for each sample. Each mixture was then mixed for an additional 90 s after four repetitions, reheated for 10 min at 160 °C, and remixed for an additional 30 s. All the materials were mixed again for 8 min. The TK fibre's basic properties are presented in Table 1, and Table 2 summarises the experimental programme.

Table 1. Properties of TK fibres.

TK Fibre	Specific density (g/cm3)	Length (cm)	Width (μm)	Colour
TK 1	2.557	13	12	Cream white
TK 2	2.557	6	12	Cream white

Table 2. Experimental programme.

Materials	Variables	Methods
Bitumen	Fibre content 0.5%, 1%, 1.5%, 2%	Penetration test
Pen 40/60		Rutting factor
Pen 50/70		Thermal conductivity
Fibre	Fibre names TK 1, TK 2	Multiple stress creep recovery test

The penetration test was performed to assess TK fibre's influence on the rutting resistance properties of the modified bitumen. The penetration test was conducted to evaluate the stiffening of the bitumen. The procedure was carried out with a Stanhope-Seta penetrometer [41]. The dried samples were aged using RTFO at temperature 163 °C for 85 mins to simulate the short-term ageing. Then to simulate the long-term, the dried samples were aged by using a pressure ageing vessel (PAV) at 90 °C and 2.1 MPa for 20 h

A Bohlin Gemini 200 Dynamic Shear Rheometer (DSR), with a torque range between 0.5 (μN·m) and 200 (mN·m) and a sensor on the shaft to detect the movement of the plates, was used to evaluate the rheological properties of bitumens. The following parameters were used in the rheological testing [42]:

I. Frequencies ranging from 0.1 to 10.0 (Hz), 1% strain control and,
II. Temperatures between 30 and 70 °C (at 5 °C increments).

To measure the thermal conductivity, bitumen samples were prepared to a size of 60 mm thickness by 300 × 300 mm. A Hilton Heat Transfer Unit H112N was used to measure the thermal conductivity, and the procedure given in ISO 8301 [43] was followed.

In semi-arid areas, asphalt pavements roads are exposed to heat from the radiation of the sun. This heat is conducted through to the lower layers to the underlying moisture that contains salts. As a result, salt-containing moisture evaporates through the pores of the lower layers of the pavement to the asphalt layer. All specimens were soaked in various salt concentrations for different duration periods to simulate all possible conditions in semi-arid areas. Trona was selected as the salt to simulate semi-arid conditions. Botswana has one of the largest salt pans in the world, the Makgadikgadi Pan system. These pans extend through the Kalahari Desert southeast of the Okavango Delta in the northern part and are one of the largest producers of Trona in the world [44], [45], [46]. The concentrations applied were 0.3%, 1%, 3%, and 5% and the exposure durations were, 7 days (d7) and 28 days (d28). All the specimens were placed above salt solutions at 25 °C. Several case studies in Botswana on damaged roads have recorded between 0.1 and 3% on the surface of damaged roads[6], [47], [48]. Other studies have shown between 0.1 and 5% in the subgrade material and on the near surrounding [6], [47], [48].

2.2. Multiples stress creep recovery

The MSCR test was conducted to determine the creep and recovery behaviour of the base and TK modified bitumens. The 1.0 s creep loading and 9.0 s recovery period were applied in this test at eight stress levels, ranging from 0.1 kPa to 3.2 kPa for 10 cycles each, as provided in Table 3. The temperature of 65 °C, which was used, represented the peak temperature of the pavement surface during the summer season in Botswana. The percentage recovery (%) and non-recoverable creep compliance (J_{nr}) are given in Eqs. (1), (2), respectively, were calculated using the data obtained from the MSCR test.

$$R\,(\%) = \frac{(\varepsilon_1 - \varepsilon_{10})}{\varepsilon_1} X100 \tag{1}$$

Table 3. Stress levels for the MSCR test.

Stress level	**0.1**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.2**
No of cycles	10	10	10	10	10	10	10	10

where

$R(\%)$	refers to the percentage recovery
ε_1	refers to the strain value at the end of the creep portion
ε_{10}	refers to the strain value at the end of the recovery portion

$$J_{nr} = \frac{Non-recoverablestrain}{Stress} \tag{2}$$

3. Results and discussion

3.1. Characterisation

TK fibres contain a high amount of cellulose and hemicellulose [21]. Several studies have shown cellulose fibre to be compatible with bitumen and that it can improve its properties such as penetration point, softening point and viscosity. Therefore, they can enhance the deformation resistance of asphalt mixtures [37], [49]. Table 1 shows that TK fibres were placed at 160 °C for 1 h30 to test decomposition and reduce water content. TK fibres managed to resist decomposition at high temperatures. Similarly, Setswalo et al. [21] performed a decomposition test of TK fibres at high temperatures and results showed that TK fibres started decomposing at temperatures between 290 and 300 °C. The results are also consistent with a study by Motoc et al. [20], who conducted degradation of cellulose and lignin and found that their degradation temperatures were 300 and 400 °C, respectively. This implies that they will be able to withstand bitumen or asphalt mixing temperatures. Mohammad et al. [37] reinforced bitumen with cellulose fibre and found a significant reduction in the phase angle at all ranges of frequencies. The reduction of phase angle indicates improved bitumen elasticity. Similarly, Chen et al. [50] evaluated the effects of rock, wool, cellulose, and polyester fibre on the mechanical properties of the asphalt mixture. The results showed that all fibres had a good adhesion with bitumen and enhanced the strength of the bitumen-fibre mastics. Luo et al. [51] showed that lignin fibre significantly enhanced the low-temperature properties of the asphalt mixture. Lignin fibre can entangle itself between the aggregates, increasing the thickness of bitumen film [52].

3.2. Penetration

The simplest way to measure the stiffness of bitumen is by the penetration test. The mean of three penetration readings was calculated. Fig. 2 shows a significant decrease in value with the addition of TK 1 and less so with the addition of TK 2 for both 40/60 pen and 50/70 pen bitumens. The degree of the reduction in penetration is due to TK content, with fibre length also having a slight effect and the small variation between TK l and TK 2. TK 2 are shorter than TK 1 and may be less able to generate stiff networks within the bitumens.

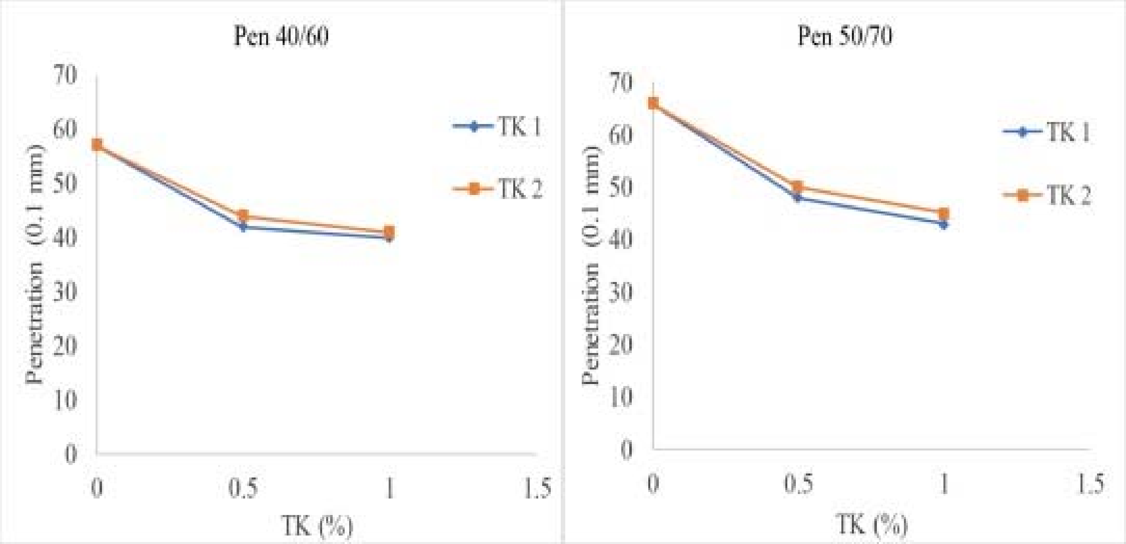

Fig. 2. Penetration of base and modified bitumens.

3.3. Rutting factor

Fig. 3 illustrates how frequency and temperature govern the rutting parameter (G*/sinδ). The rutting parameter (G*/sinδ) is a high-temperature specification parameter and rutting performance indicator of the unmodified and fibre modified bitumens. As seen by the upward shift, the addition of TK content enhanced the stiffness of the bituminous binder at high temperatures. The analysis showed that the values of G*/sinδ of TK 1 concentrations for both bitumens were higher than TK 2 for all concentrations, with the lowest value being exhibited by the base bitumens. The rutting parameter was highest with the highest TK concentration and decreased with increasing test temperature. Therefore, information about the behaviour of the fibre mastics of the bituminous binder is based on the sensitivity at a reference temperature. The results indicate that fibres can increase the permanent deformation resistance of asphalt mixtures at high temperatures.

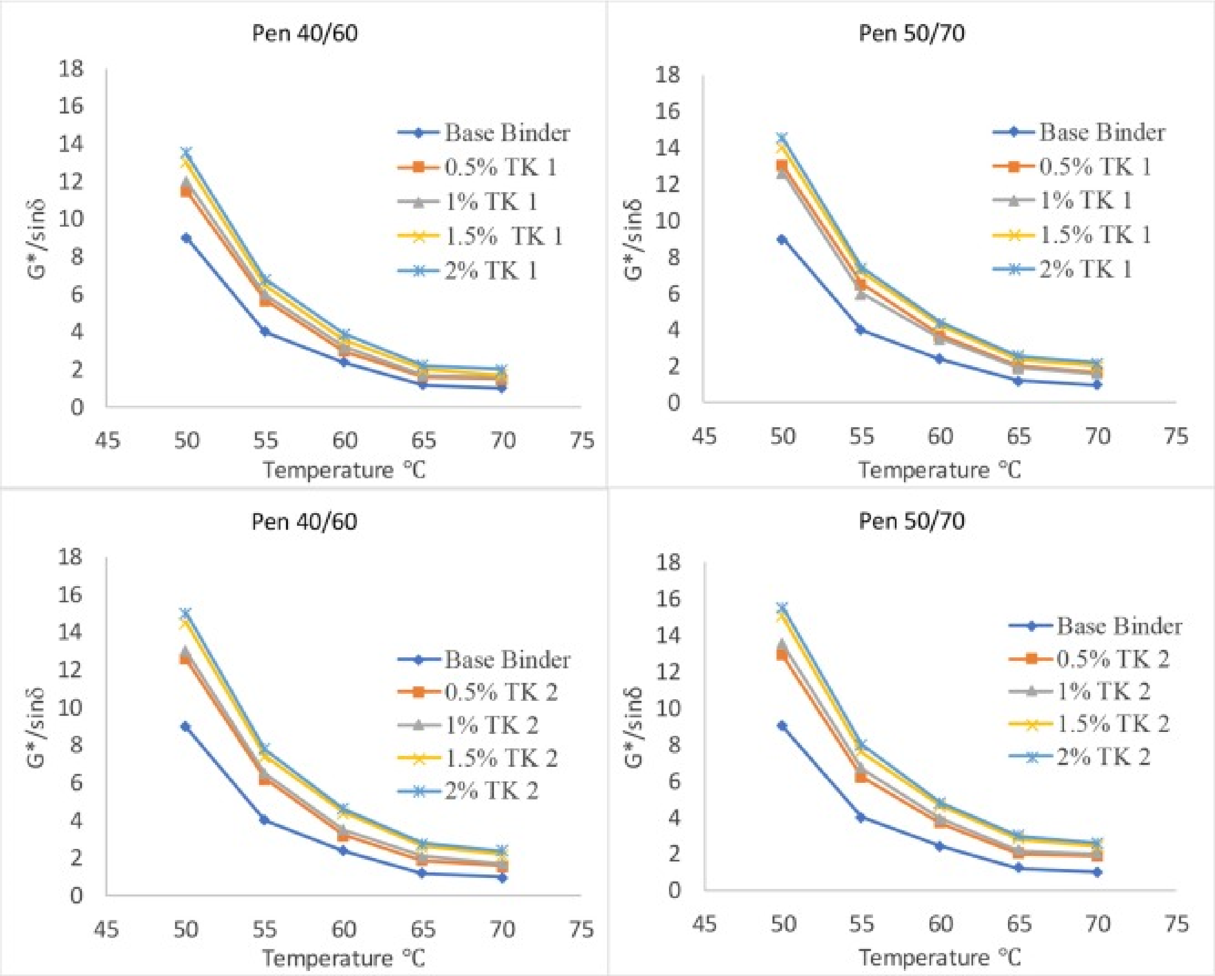

Fig. 3. Rutting factor of base and modified bitumens.

3.4. Thermal conductivity

Semi-arid areas are known for high temperatures. Asphalt layers are dark in colour, which absorbs higher heat levels from the sun and transfers (thermal conductivity) to the lower layers. Applying some treatments or additives to reduce high thermal conductivity is essential to reduce salt transportation in moisture from the underlying layers. Fig. 4 illustrates that thermal conductivity reduced with increasing TK content because of its low coefficient of thermal conductivity. It was also observed that TK 1 was more effective than TK 2 in this regard. Thermal conductivity measurements are an indication that the TK1 provided a better insulation layer. Rahman and Mohajerani [53] conducted a thermal conductivity assessment of cigarette butts (made from cellulose acetate) modified bitumen. The test results have demonstrated a significant thermal conductivity reduction due to incorporating cigarette butts in asphalt. Also, the results suggested that the thermal conductivity of stone mix asphalt (SMA) was reduced by 5%, 7%, and 8% compared to the unmodified SMA when it was modified with the concatenations of 1%, 2%, and 3% cigarette butts [53]. Low thermal conductivity in material slows down the heat transfer rate, will potentially last longer in high temperature exposure. One of the main applications of cellulose is thermal insulation [54] because their characteristic low thermal conductivities (i.e. high thermal insulation capacities [55].

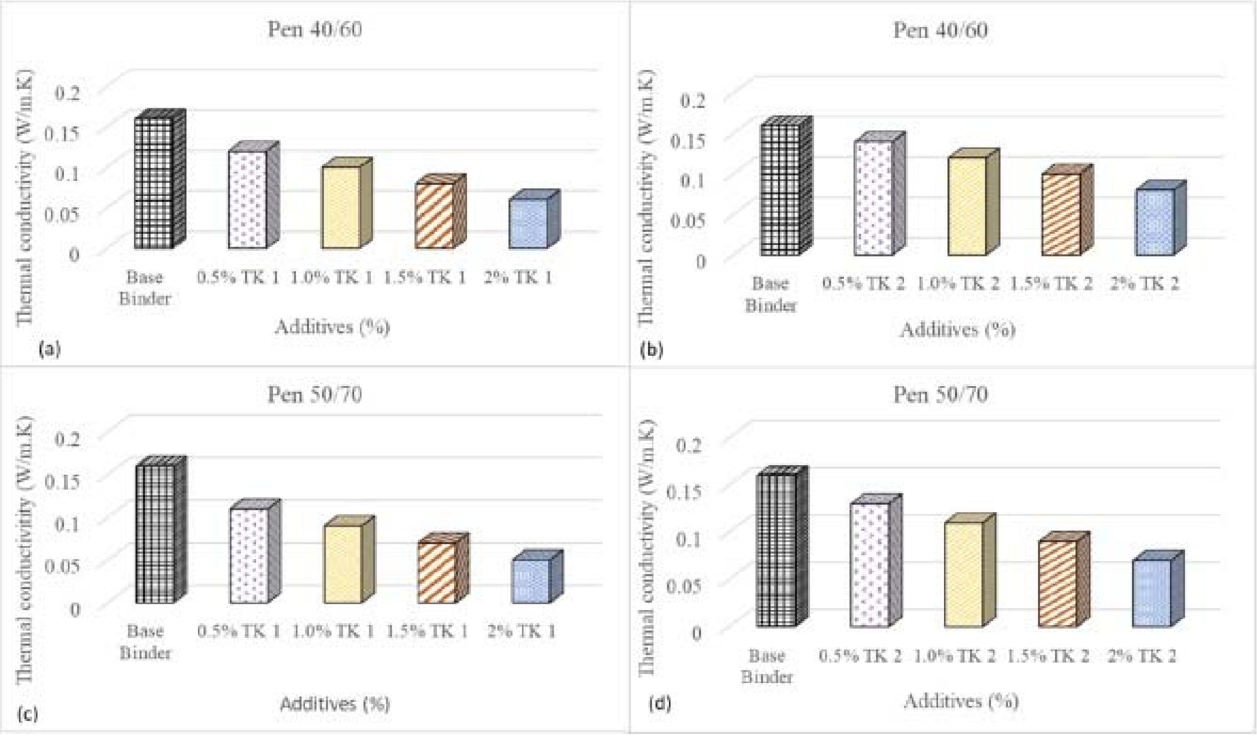

Fig. 4. Thermal conductivity of base and modified bitumens.

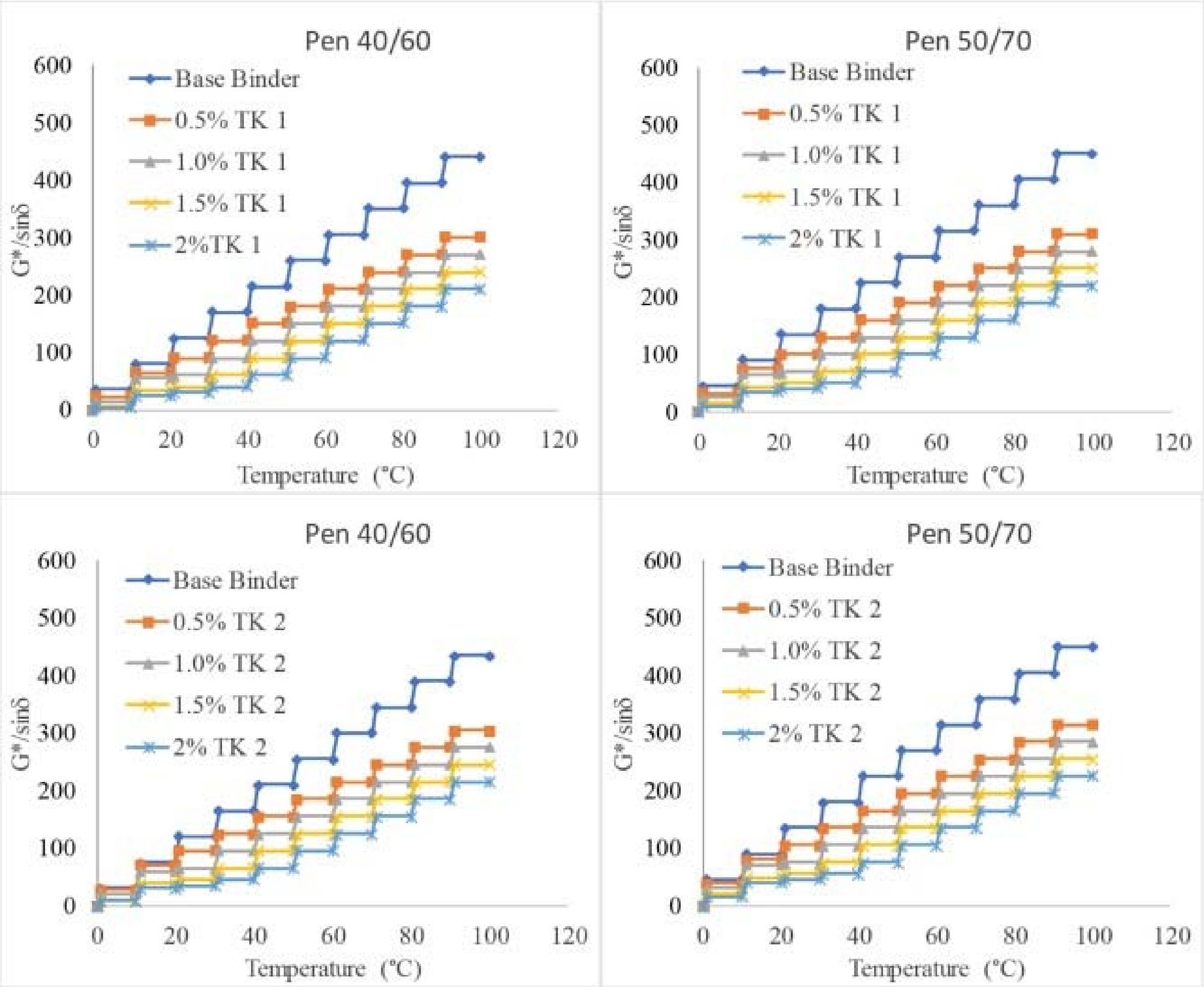

Fig. 5. Creep-recovery curves of base and modified bitumens.

3.5. Multiple stress creep recovery test (MSCR)

The MSCR test is an accurate and simple gauge of the permanent deformation behaviour of a bituminous binder or mastic used to make an asphalt mixture. Percentage recovery (%) was used to illustrate the effect of a range of stress levels along with the non-recoverable creep compliance (Jnr). These demonstrate the creep-recovery behaviour of base bitumen and TK fibre modified bitumens. Fig. 6 shows the curve that illustrates the creep-recovery behaviour curves for base and TK modified bitumens at 0.1 kPa. It was observed that in both scenarios, the addition of TK fibres resulted in less shear strain relative to the base bitumens. A content of 1.5 to 2% TK 1 in bitumen had a minimal percentage of shear strain, whilst 1% and 0.5 % contents exhibit a slightly higher shear strain, and the base bitumen demonstrated the highest shear strain. Fig. 7 and Fig. 8 show the percentage recovery and non-recoverable creep compliance obtained at various stress levels. There was a significant increase for TK 2 bitumens and an even higher percentage recovery for TK 1 at all contents. The base bitumens had the lowest percentage recovery.

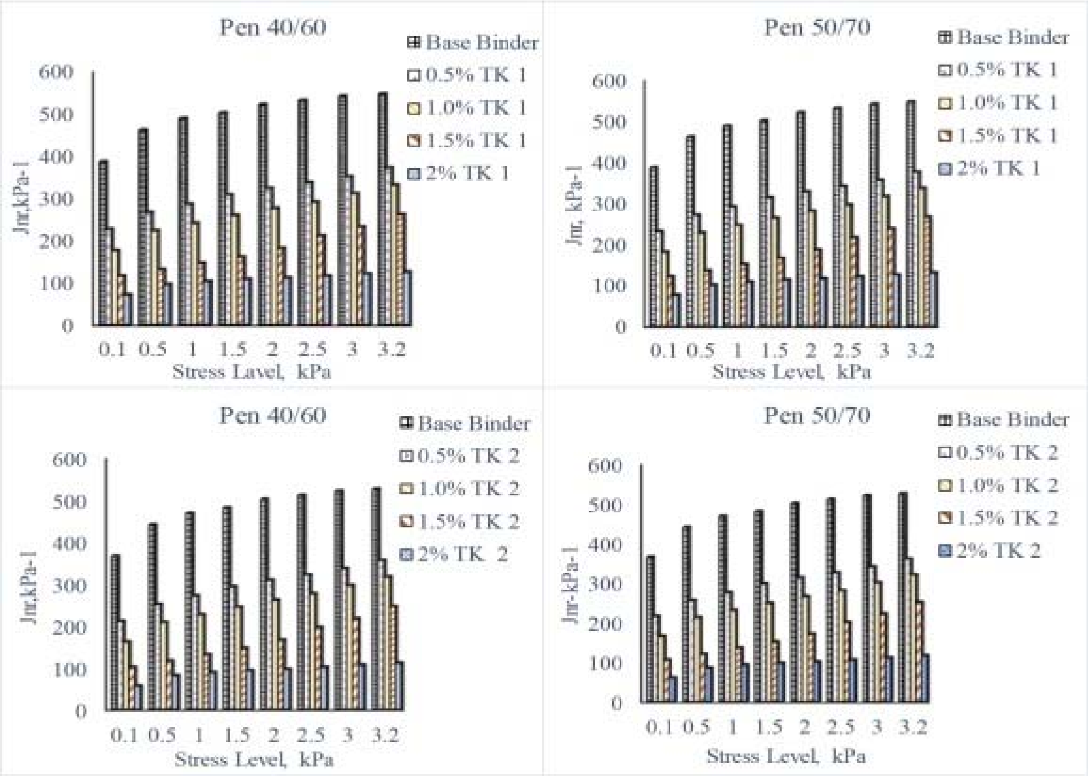

Fig. 6. Percent recovery at all stress levels.

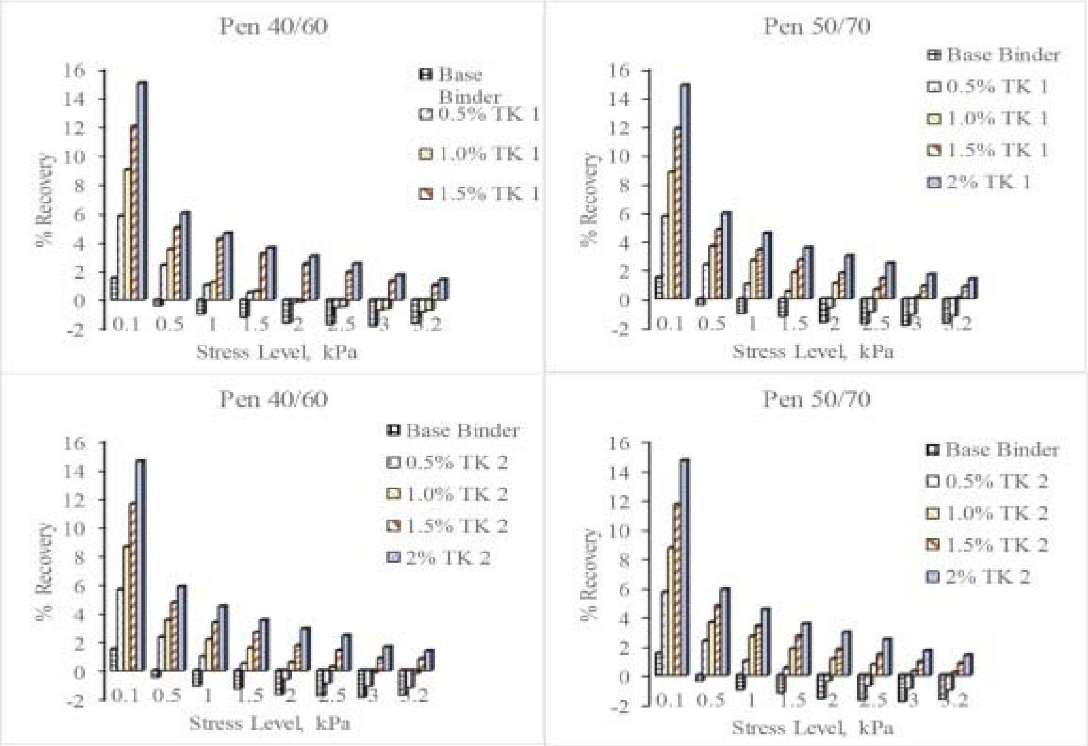

Fig. 7. Non-recoverable creep compliance at all stress levels.

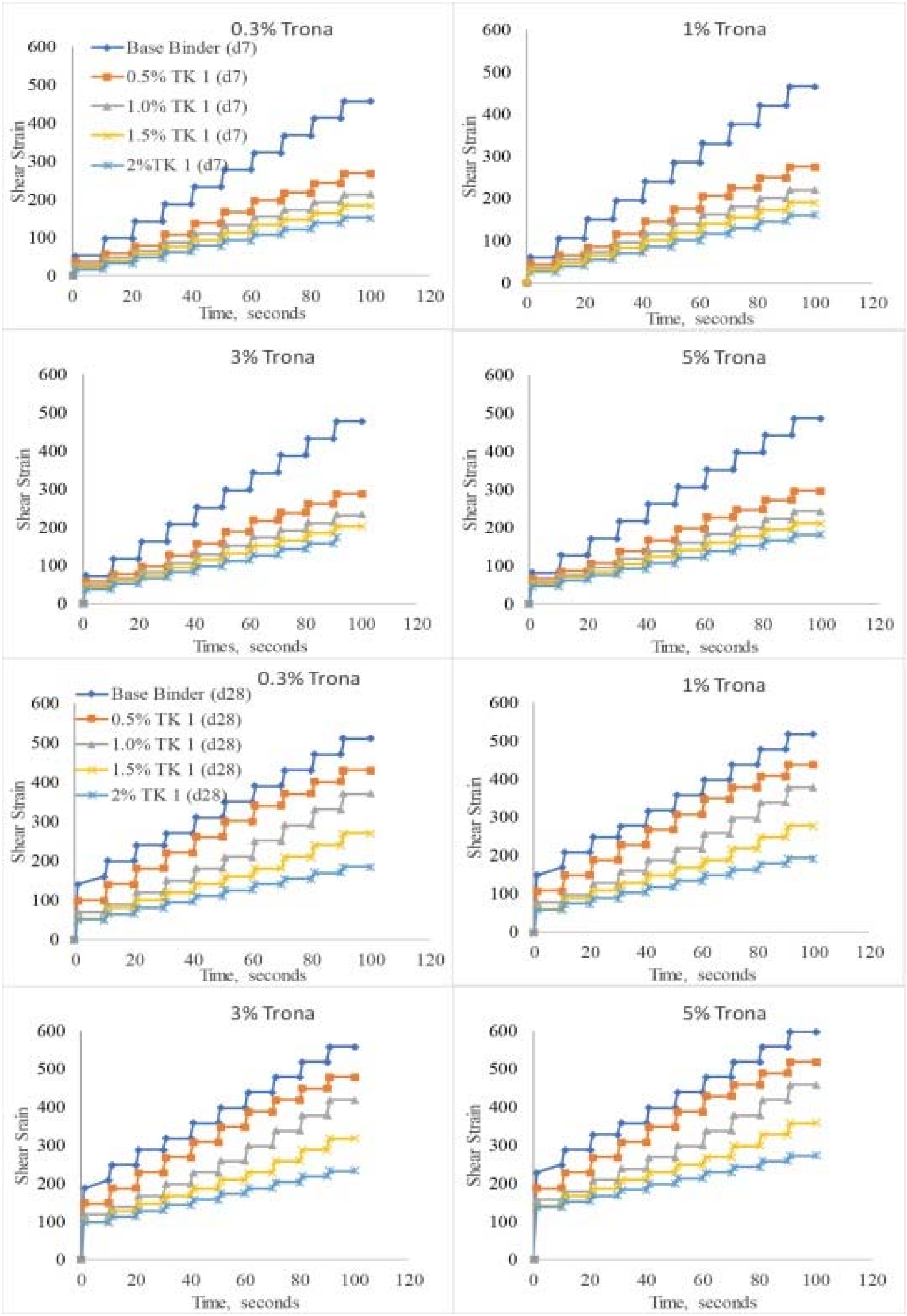

Fig. 8. Creep-recovery curves of base (Pen 40/60) and TK 1 bitumen at all salt contents and ageing times.

An ANOVA test called the Kruskal-Wallis test was performed for better accuracy and to substantiate recoverable and non-recoverable creep compliances. This method uses a non-parametric test, and it provides accurate results for TK compatibility at any stress level. The comparisons were at the 95% confidence level. Table 4 presents p-values of percentage recovery and Jnr values with TK fibre content and stress level. From the observation, the base bitumen presented recovery values below zero with the increase in stress level, which could have been due to extreme softening at high temperatures (65 °C). This demonstrates strain accumulation with the rest period phase in the absence of a creep load. As shown in Table 5, the p-values suggest that the addition of TK at different contents and sizes significantly affects percentage recovery. Another statistical tool called "pair-wise comparison" was used to validate the results. Pair-wise comparison analysis helps to weigh up the overall significance of various choices. The tool gives a structure for comparing every alternative against all others and demonstrates the distinction in significance between factors. Table 5 and Table 6 show that TK's addition gave a significant difference between base bitumens and modified bitumens when considering the values of recovery and Jnr. The addition of 2% TK fibres exhibited the highest recovery values, reasonably higher than 1.5% TK. These levels of fibre modification are recommended for improving the performance of asphalt mixture in semi-arid areas.

Table 4. Kruskal-Wallis test.

Factor 1: TK Fibres Content				
Bitumen type	**Recovery Percentage**	**Non-recoverable creep compliance**	**Recovery Percentage**	**Non-recoverable creep compliance**
	Chi-Square degree of freedom		p-value	
Pen 40/60	712.17	1066.22	<0.05	<0.05
Pen 50/70	680.39	1097.21	<0.05	<0.05
Factor 2: Stress level				
Bitumen type	Recovery Percentage	Non-recoverable creep compliance	Recovery Percentage	Non-recoverable creep compliance
	Chi-Square degree of freedom		p-value	
Pen 40/60	74.12	79.19	<0.05	<0.05
Pen 50/70	71.11	76.44	<0.05	<0.05

Table 5. Pair-wise comparison of recovery for TK fibres (%).

Pen 50/70			Pen 40/60		
Recovery					
Pairs	**Test value**	**p-value**	**Pairs**	**Test value**	**p-value**
Base bitumen − 0.5% TK 1	−212.32	0.0001	Base bitumen − 0.5% TK 1	−202.32	0.0001
Base bitumen − 1% TK 1	−378.68	0.0001	Base bitumen − 1% TK 1	−371.68	0.0001
Base bitumen − 1.5% TK 1	−653.23	0.0001	Base bitumen − 1.5% TK 1	−645.23	0.0001
Base bitumen − 2% TK 1	−660.07	0.0001	Base bitumen − 2% TK 1	−651.07	0.0001
0.5% TK 1–1% TK 1	−166.36	0.0001	0.5% TK 1–1% TK 1	−169.36	0.0001
0.5% TK 1–1.5% TK 1	−440.91	0.0001	0.5% TK 1–1.5% TK 1	−442.91	0.0001
0.5% TK 1–2% TK 1	−447.75	0.0001	0.5% TK 1–2% TK 1	−448.75	0.0001
1% TK 1–1.5% TK 1	274.55	0.0001	1% TK 1–1.5% TK 1	273.55	0.0001
1% TK 1–2% TK 1	281.39	0.001	1% TK 1–2% TK 1	279.39	0.001
2% TK 1–1.5% TK 1	−6.84	0.796	2% TK 1–1.5% TK 1	−5.84	0.736
Jnr					
Pairs	**Test value**	**p-value**	**Pairs**	**Test value**	**p-value**
Base bitumen − 0.5% TK 1	223.45	0.0001	Base bitumen − 0.5% TK 1	218.45	0.0001
Base bitumen − 1% TK 1	209.43	0.0001	Base bitumen − 1% TK 1	201.43	0.0001
Base bitumen − 1.5% TK 1	327.89	0.0001	Base bitumen − 1.5% TK 1	316.89	0.0001
Base bitumen − 2% TK1	420.23	0.0001	Base bitumen − 2% TK1	412.23	0.0001
0.5% TK 1–1% TK 1	104.44	0.0001	0.5% TK 1–1% TK 1	98.44	0.0001
0.5% TK 1–1.5% TK 1	196.78	0.0001	0.5% TK 1–1.5% TK 1	193.78	0.0001
0.5% TK 1–2% TK 1	−14.02	0.0001	0.5% TK 1–2% TK 1	−17.02	0.0001
1% TK 1–1.5% TK 1	−92.34	0.0001	1% TK 1–1.5% TK 1	−95.34	0.0001
1% TK 1–2% TK 1	118.46	0.0001	1% TK 1–2% TK 1	115.46	0.001
2% TK 1–1.5% TK 1	92.34	0.084	2% TK 1–1.5% TK 1	95.34	0.092

Table 6. Pair-wise comparison of Jnr for Recovery TK Content.

Pairs	Test value	p-value	Pairs	Test value	p-value
Base bitumen − 0.5% TK 2	−217.32	0.0001	Base bitumen − 0.5% TK 2	−208.32	0.0001
Base bitumen − 1% TK 2	−385.0.68	0.0001	Base bitumen − 1% TK 2	−375.68	0.0001
Base bitumen − 1.5% TK 2	−659.0.46	0.0001	Base bitumen − 1.5% TK 2	−650.26	0.0001
Base bitumen − 2% TK 2	−666.0.07	0.0001	Base bitumen − 2% TK 2	−658.07	0.0001
0.5% TK 1–1% TK 2	−168.0.36	0.0001	0.5% TK 1–1% TK 2	−167.36	0.0001
0.5% TK 1–1.5% TK 2	−442.0.14	0.0001	0.5% TK 1–1.5% TK 2	−441.94	0.0001
0.5% TK 1–2% TK 2	−448.0.75	0.0001	0.5% TK 1–2% TK 2	−449.75	0.0001
1% TK1 − 1.5% TK 2	273.0.78	0.0001	1% TK 1–1.5% TK 2	274.58	0.0001
1% TK 1–2% TK 2	280.0.39	0.001	1% TK 1–2% TK 2	282.39	0.001
2% TK 1–1.5% TK 2	−6.0.61	0.696	2% TK 1–1.5% TK 2	−7.81	0.816
Jnr					
Pairs	**Test value**	**p-value**	**Pairs**	**Test value**	**p-value**
Base bitumen − 0.5% TK 2	229.45	0.0001	Base bitumen − 0.5% TK 2	223.45	0.0001
Base bitumen − 1% TK 2	202.43	0.0001	Base bitumen − 1% TK 2	209.43	0.0001
Base bitumen − 1.5% TK 2	319.89	0.0001	Base bitumen − 1.5% TK 2	327.89	0.0001
Base bitumen − 2% TK 2	411.23	0.0001	Base bitumen − 2% TK 2	420.23	0.0001
0.5% TK 1–1% TK 2	90.44	0.0001	0.5% TK 1–1% TK 2	104.44	0.0001
0.5% TK 1–1.5% TK 2	181.78	0.0001	0.5% TK 1–1.5% TK 2	196.78	0.0001
0.5% TK 1–2% TK 2	−27.02	0.0001	0.5% TK 1–2% TK 2	−14.02	0.0001
1% TK 1–1.5% TK 2	−91.34	0.0001	1% TK 1–1.5% TK 2	−92.34	0.0001
1% TK 1–2% TK 2	117.46	0.001	1% TK 1–2% TK 2	118.46	0.001
2% TK 1–1.5% TK 2	91.34	0.096	2% TK 1–1.5% TK 2	92.34	0.796

Specimens were soaked in the salt (Trona) solution for 7 (d7) and 28 (d28) days. It was observed from Fig. 9 and Fig. 10 that from d7, especially at d28, the shear strain increased for both the base and modified bitumens compared to Fig. 5. Bitumens with 2% TK fibres exhibited the lowest shear strain values while 1.5% concentration was slightly lower than 1% and 0.5%, respectively. The base bitumens showed the highest shear strain. It was also observed that all base and modified bitumens showed increased shear strain when the salt content was increased. Specimens soaked at 5% salt solutions presented the highest shear strain followed by 3%, 1% and 0.3% salt solutions, respectively. This suggests that asphalt pavements modified with TK fibres have better permanent deformation resistance under salt action. This agrees with the results shown in Fig. 11 and Fig. 12 and at d7 for various stress levels, where specimens presented increased non-recoverable creep compliance compared to that shown in Fig. 5. It is clear the values for 2% TK fibres were the lowest for all the ageing levels, while the base bitumens had the highest values of non-recoverable creep compliance followed by TK fibre contents of 0.5%, 1% and 1.5%, respectively.

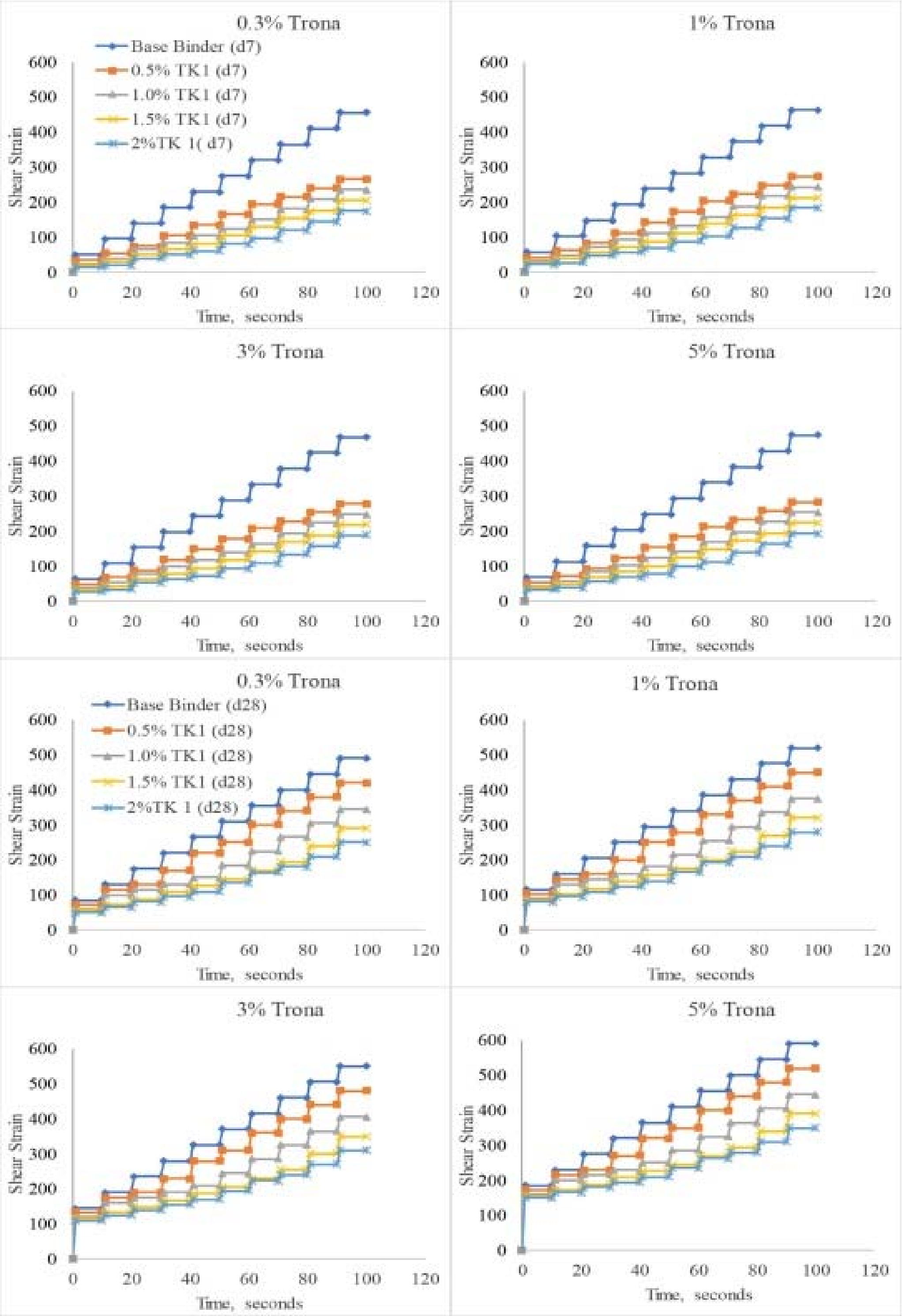

Fig. 9. Creep-recovery curves of Base (Pen 50/70) and TK 1 bitumens at all salt contents and ageing times.

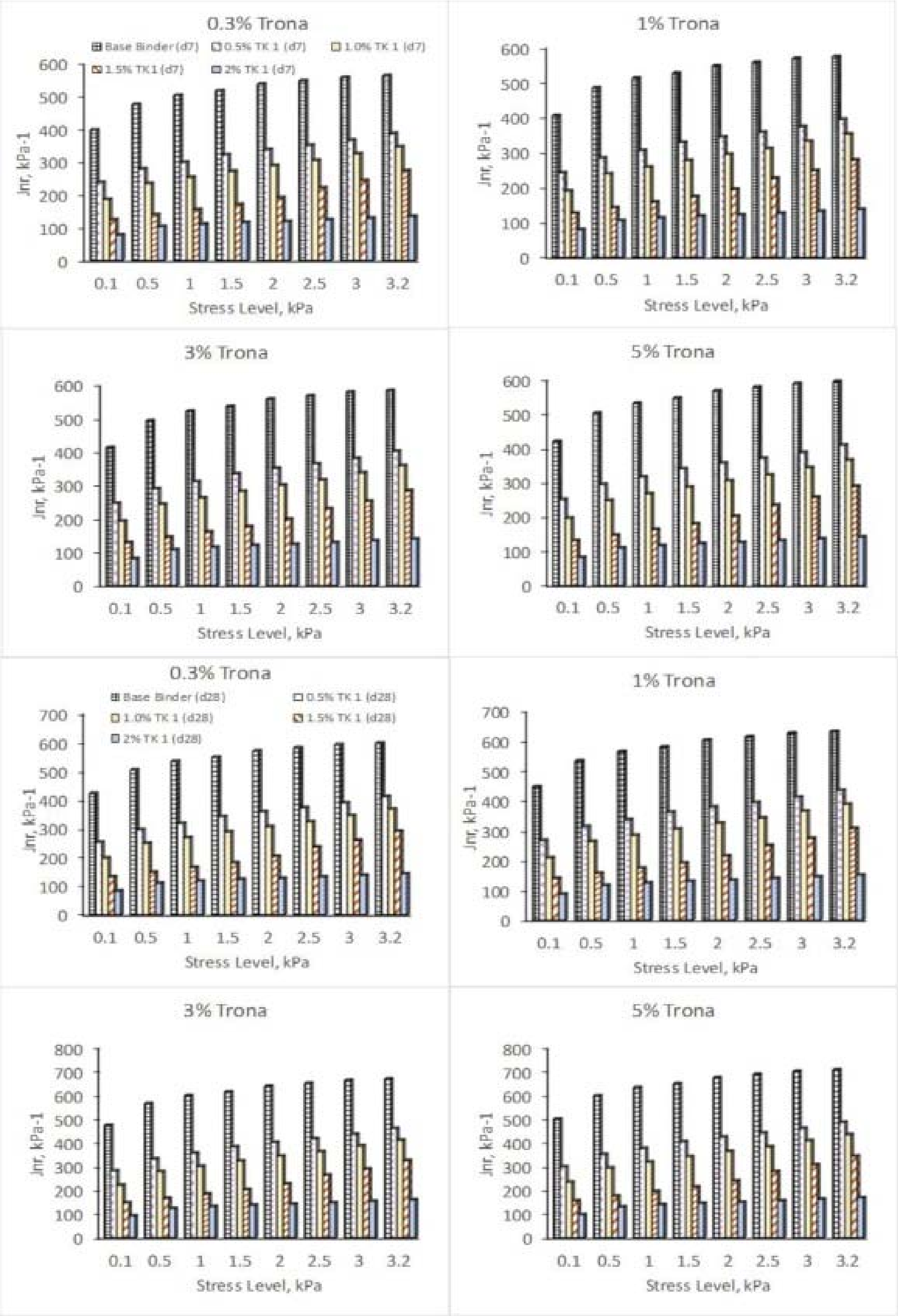

Fig. 10. Percentage recovery of base (Pen 40/60) and TK 1 bitumens at all salt contents and different ageing times.

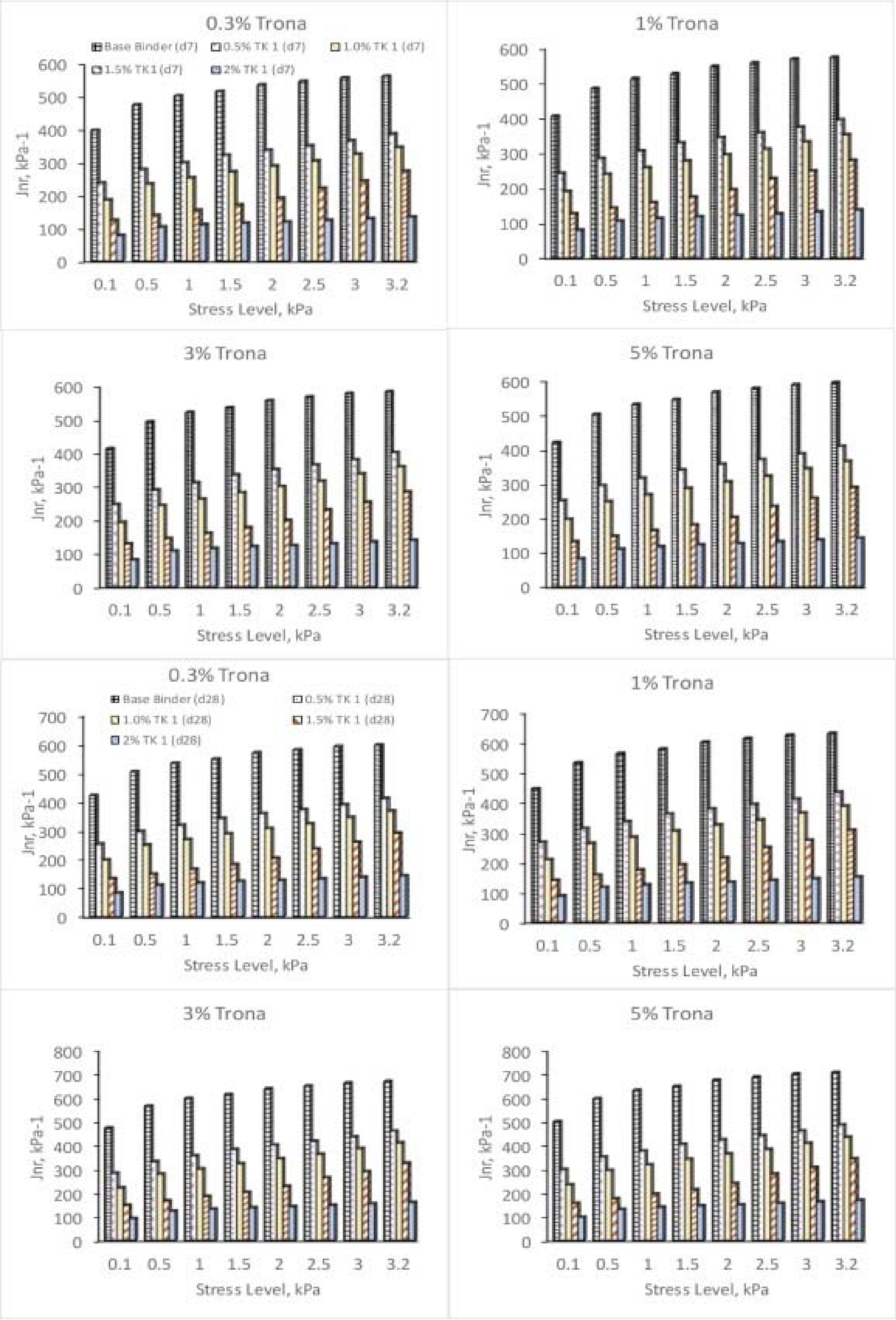

Fig. 11. Percentage recovery of base (Pen 60/70) and TK 1 bitumens at all salt contents and ageing times.

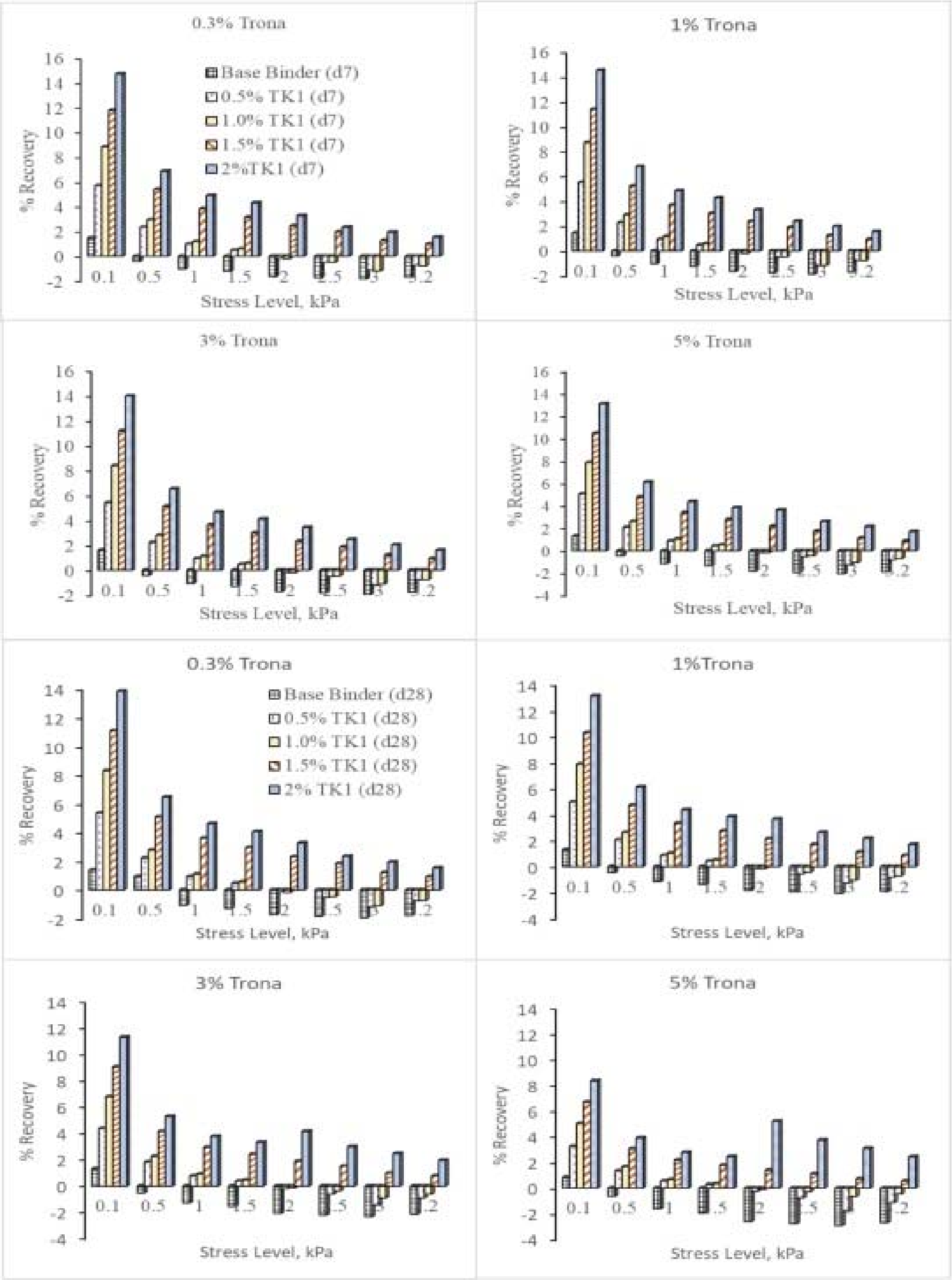

Fig. 12. Non-recoverable creep compliance of base (Pen 40/60) and TK 1 bitumens at all stress levels, salt concentrations and ageing times.

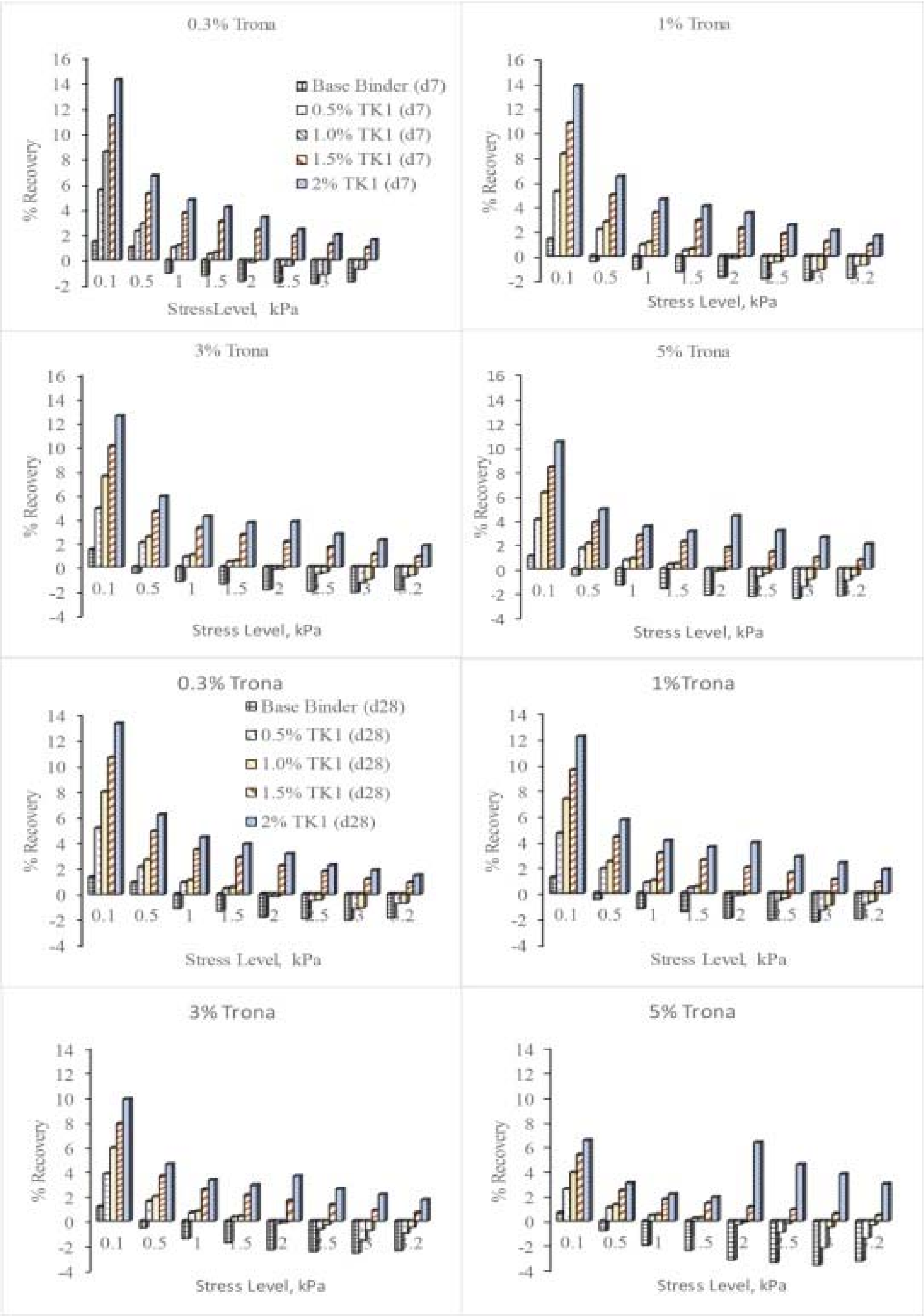

Fig. 13. Non-recoverable creep compliance of base (Pen 50/70) and TK 1 bitumens at all stress levels, salt concentrations and ageing times.

Furthermore, the values for non-recoverable creep compliance decreased with an increase in salt concentration. At 5% salt concentration, the values were the lowest at both ages d7 and d28. The next lowest values were exhibited by 1.5%, 1%, 0.5%, and base bitumens. Lower non-recoverable creep compliance indicates a better resistance to repeated loads under the influence of salt conditions. Similarly, the results depicted in Fig. 13 and Fig. 14 show that the addition of 2% and 1.5% TK fibres had better resistance to deformation across all stress levels. However, the resistance decreased with increased salt contents at age d7 and more so at age d28. It was observed that at 0.5 kPa all base bitumens had negative recovery percentages at all salt contents and ageing steps. The addition of 0.5% and 1% TK fibres showed a negative value at a stress level of 2 kPa for all salt contents and all ageing steps. An increase in non-recoverable creep compliance could suggest ascribed to excessive softening after temperature 65 °C indicating that strain increasing even in the rest period phase, where the creep load was absent. At night, at low temperatures, bitumen will transition from the viscous phase to a glassy state. This can lead to a loss of adhesion between aggregates and the bitumen. There is a suggestion that the material will become more brittle by changing from viscous to a glassy state [1]. Chowdhury et al. [56] indicated that laboratory test results showed gradually increased value of the penetration and specific gravity and flash point, fire point. They then gradually decreased softening point due to the increasing salts content in the bituminous mixture. Cui et al. [57] highlighted that salt solution concentration mostly affects the elastic parameters and also that a 4 % salt concentration had the least significant influence on the elasticity of asphalt mortar. The Botswana road department (BRD) observed salt damage in the form of blistering, doming, and powdering. This occurred in the second seal of the carriageway along sections of the first 12 km of the Sekoma - Kang road [6]. This could indicate that under the action of traffic loading on a materials section in its glassy phase, it is susceptible to breaking down by powdering. Also, some studies pointed out that the deterioration of asphalt mixture due to de-icing salt solution immersion performance led to the stripping, cracking, and permanent deformation of asphalt pavement [28], [58]. Accordingly, the deterioration mechanism of de-icing salts on asphalt mixture primarily reduces adhesion between bitumen and aggregates. Note that all results suggested that the addition of TK 1 had better results than TK 2 at all stress levels, salt concentrations and ageing steps. This may be due to the longer size of TK 1 fibres, meaning they could form longitudinal networks within the bitumen and exhibit better tensile capacity. The results show that TK fibres can enhance the deformation resistance of asphalt mixtures. The MSCR test successfully demonstrated the likely behaviour of asphalt mixtures under the action of salt.

4. Conclusions

The first objective of this study was to assess the effect of TK fibres on the rheological properties of the bituminous binders. The scope of the assessment includes tests on rutting factors, penetration, and multiple stress creep recovery (MSCR) on the base and TK fibre-modified bitumens. The second objective was to investigate the stress sensitivity of bitumens to assess adhesion loss due to the action of salt i.e. $NaHCO_3$ solution. The scope of this assessment includes the MSCR test on the base and modified bitumens. The below conclusions are drawn from this study:

1. TK fibres can significantly improve bitumen mastic penetration point. TK 1 showed the greatest decrease in penetration and thermal conductivity. This indicates improved bitumen stiffness, mainly at high temperatures, which is beneficial to mastic strength. Decrease penetration point could lead to reduced drain down and permanent deformation of asphalt mixture.
2. The rutting parameters increased significantly with the increase in fibre content at moderate and high temperatures. This indicates that the addition of fibres may lead to improved rutting resistance of asphalt mixtures.

3. At all stress levels, salt concentrations, and soaking duration, specimens modified with TK fibres exhibited lower shear strain values than the base bitumens. The addition of 2% TK fibres gave the best results, followed by 1.5%, whilst 0.5% and 1% improved slightly compared to the base bitumens.
4. A similar trend was observed when the specimens were soaked in salt solutions. The bitumens modified with TK fibres had better performance under the action of salt as compared to the base bitumens but showed an increase in shear strain, reduction in percent recovery and increase in non-recoverable creep compliance after ageing for 7 days (d7) and significantly more so after 28 days ageing (d28) and with increasing salt content.
5. Results showed that under the action of salt and at the stress level 0.5 kPa, the value of non-recoverable creep compliance of base bitumen was negative. The negative value increased with increasing salt content significantly so after 28 days of ageing (d28). This suggests the transition from the viscous phase to the glassy state. The glassy state can lead to loss of adhesion between aggregates and bitumens.
6. The addition of 1.5 and 2% TK fibres had a positive value of non-recoverable creep compliance throughout the testing showing that they can be used to improve the performance of asphalt mixtures under the action of salt.
7. TK1 showed the best results throughout the study, meaning the 13 mm length of TK fibre is more suitable for reinforcing bituminous binder and would be recommended for use in semi-arid areas at an optimum content of 2% TK.

In this study, the MSCR test was found to be suitable for investigating the performance of fibre modified bitumen mastics under the influence of salt solutions. The performance of these bitumens could indicate how they would perform in asphalt mixtures to help prevent blistering caused by salt in moisture from underlying layers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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