

Characterising the ageing behavior of bitumen modified with textile pyrolysis oil

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ABSTRACT

Several research studies have been conducted on bitumen modification using solid waste materials. However, since textile waste contributes significantly to the formation of solid waste, more research is required on bitumen modification using textile waste. This study tried to modify bitumen using Textile Pyrolysis Oil (TXPO) and test its ageing properties. Pyrolysis oil was made by pyrolysing textile waste at 500°C. Textile Pyrolysis Oil Modified Bitumen (TXPOMB) was made by adding 1, 2 and 3% TXPO by weight of the Viscosity Grade 30 (VG30) bitumen and mixing in a high shear mixer. The binders are subjected to short-term ageing using a rolling thin film oven and long-term ageing using a pressure ageing vessel test in the laboratory. The effect of adding TXPO to a base binder and their oxidation process were investigated using Fourier Transform Infrared (FTIR) Spectroscopy. Chemical indices such as aromatic, aliphatic, carbonyl, and sulfoxide indices are calculated from FTIR spectroscopy to evaluate the effect of ageing. It was seen that 2% TXPO modification enhances the base binder's ageing resistance in both short and long-term ageing conditions. This modification not only addresses environmental concerns but also improves the performance and longevity of the bituminous materials.

Keywords: Fourier transform infrared spectroscopy; Textile pyrolysis oil; Textile pyro-oil modified bitumen; Short-term ageing; Long-term ageing etc.

1. INTRODUCTION

Bitumen is a black, sticky material that binds aggregate in asphalt [1]. The mechanical and structural characteristics of bitumen, including its strength, stiffness, and colloidal structure, are determined by its chemical makeup [2]. Characterising the mechanical properties of bitumen and bituminous mixture requires understanding the chemical components found in bitumen. For the mechanistic study, bituminous binder is categorised as a viscoelastic substance because of its high temperature, time, and rate-dependent physical characteristics, particularly its reaction to applied stress or strain [3].

The bituminous binder undergoes two ageing processes. At first, it is exposed to short-term ageing corresponding to mixing, transportation and compaction process; this ageing is simulated in the laboratory using a Rolling Thin Film Oven (RTFO) test. After the paving process, binder is subjected to a service period in which it is affected by environmental exposure and traffic loading throughout the in-service life of the pavement. The ageing that occurs in this period is called long-term ageing, and it is simulated in the laboratory using a Pressure Ageing Vessel (PAV) test. Bituminous binder is an organic compound that ages primarily through oxidation. With ageing, a material's viscoelastic behaviour shifts over time, becoming more brittle and stiffer. Recently, Fourier transform infrared spectroscopy (FTIR) has been utilised more and more to study how bitumen's chemical structure is affected by oxidative ageing. Different sources of bitumen always produce the same sorts of oxidation products, mostly sulfoxides and ketones [4]. For this reason, the ageing of bitumen has long been determined by analysing the carbonyl and sulfoxide functional groups identified by infrared spectroscopy [5]. Typical FTIR spectra peaks and areas, such as sulfoxide, carbonyl, aliphatic, and aromatic, are typically identified to assess the chemical variations in bitumen samples at various ageing stages [3]. Among these, the bitumen's physical and rheological characteristics are associated with the carbonyl and sulfoxide peaks appearing at 1700 cm⁻¹ and 1030 cm⁻¹, respectively, which have been effectively used to characterise the impact of ageing [6]. The chemical process of synthesising ketones is described by a shift from 1655 cm⁻¹ and carboxylic acids at 1730 cm⁻¹ towards ketones at 1700 cm⁻¹ [7]. It is difficult to detect changes in functional groups during the ageing process because of the area shift caused by increased polarity and the overlap of spectral bands denoting distinct functional groups [7, 8]. FTIR spectroscopy analysis validates the shifts in peak positions and different chemical

compositions for a base and modified binders [9]. The benzyl carbon's oxidation in side chains connected to a highly concentrated aromatic ring structure forms the ketone functional group, making up most of the carbonyl absorption zone in FTIR. Oxidation of sulfides results in sulfoxides. Usually, the light components of bitumen contain aliphatic structures. As the binder ages, lighter components, volatiles, and aliphatic chains are converted into aromatic rings [10]. The aromaticity index can assess the bitumen aromatisation. This process involves aromatising alkyl-substituted naphthenic and perhydro-aromatic rings [11, 12]. As these changes also happen prominently during the ageing of bituminous binders, aromatic and aliphatic indices are considered to evaluate the ageing of the binder.

Oxidative ageing changes the chemical and physical properties of bitumen. The rheological and physical properties of bitumen are greatly influenced by the chemical changes that occur as it ages. Bitumen stiffens with less molecular flow as it ages, as evidenced by increased viscosity, complex modulus, and decreased phase angle [13, 14]. Bituminous pavement performance deteriorates due to the stiffening effect, which increases the pavement's resistance to permanent deformation but decreases its ability to relax under environmental and traffic loads. Characteristic FTIR spectra peaks and areas, such as carbonyl, sulfoxide, aliphatic, and aromatic, are typically identified to assess the chemical changes in bitumen samples at various ageing stages [3].

It is a well-known practice to use modifiers in pavement construction to improve bitumen performance [15]. Modifiers can enhance bitumen's mechanical and physical qualities, like durability, flexibility, ageing, and cracking resistance. Pyrolysis oil produced from waste materials is one such modifier that has shown potential in bitumen modification [16-19]. The process of heating organic compounds without oxygen to disintegrate them into smaller molecules is known as pyrolysis. KULKARNI and RANADIVE [20] examined the effect of low-density polyethylene (LDPE) pyrolysis oil on Viscosity Grade 10 (VG10) bitumen. They concluded that modification of LDPE pyrolysis oil improves VG10 performance as a tack coat in bituminous pavement construction. Similar research was done using High-Density Polyethylene (HDPE) pyrolysis oil as a modifier in VG30 bitumen, and the moisture damage resistance of modified bitumen was evaluated. HDPE pyrolysis oil enhances the effect of short-term ageing by improving the adhesion of modified binders compared to base binders [19]. BHAGAT *et al.* [17] evaluated the chemical characteristics of HDPE pyrolysis oil-modified bitumen using FTIR spectroscopy, where HDPE pyrolysis oil-modified binder increases the resistance to short-term ageing of the binder. Bitumen can be strengthened by adding rubber, which absorbs the elastic qualities of rubber and improves pavement quality [21].

Several research studies have been conducted on bitumen modification using solid waste materials, such as plastics and rubber pyrolysis oil, as modifiers. According to a 2023 report by IDH, India produces around 7,793 kilotons of textile waste annually, which is 8.5% of the world's total [22]. Since textile waste contributes significantly to the formation of solid waste, more research is required on reusing this textile waste into bitumen modification. Reusing this textile waste for bitumen modification might lessen the environmental effects of textile waste and the pavement sector. Also, the chemical composition of pyrolysis oil obtained from different materials is different, which may affect the behaviour of their modified bitumen differently. This study examines how the chemistry of textile pyrolysis oil-modified bitumen is affected by laboratory short- and long-term ageing. Chemical functional groups in the preparation of modified bitumen were characterised using FTIR, which also analysed the changes that occurred during short-term and long-term ageing.

2. MATERIALS AND METHODS

2.1. Materials

VG30 bitumen is used as base bitumen as it is widely used in India for road construction and maintenance, primarily because of its excellent performance in the country's hot and humid climatic conditions. Textile pyrolysis oil is used as a modifier to prepare modified bitumen. Textile waste was collected from a local dumping yard in the vicinity of Pune, Maharashtra, India; after cleaning and shredding, it was subjected to pyrolysis at a temperature of 500°C [16, 23] using a pilot pyrolysis plant available at the transportation laboratory, Civil Engineering Department, COEP Technological University, Pune, Maharashtra, India.

2.2. Laboratory testing

2.2.1. Preparation of modified binder

Textile Pyrolysis Oil (TXPO) was blended with a VG30 binder in doses of 1%, 2%, and 3% by weight of the binder to investigate the impact of TXPO addition in a base binder. The selected percentage of TXPO was decided based on the previous studies [16, 17, 19]. Textile pyrolysis oil-modified bitumen (TXPOMB) is

prepared using an IKA- T25 homogeniser at about 3000 rpm for 15 min; after that, the speed was increased to 5000 rpm for 5 min at a temperature of about 150°C [16, 19, 24, 25]. The terms 1TXPOMB, 2TXPOMB, and 3TXPOMB correspond to 1%, 2%, and 3% TXPO modifications.

2.2.2. Ageing of bituminous binder

The VG 30 and Textile pyrolysis oil-modified bitumen (TXPOMB) had been exposed to short—and long-term ageing. An RTFO test was adopted for short-term ageing. It evaluates how susceptible binders are to ageing and toughening over time when exposed to air and elevated temperatures. The ASTM D2872 was used to carry out RTFO ageing [26]. Binders are short-term aged in RTFO at 163°C for 85 minutes.

These RTFO-aged samples are subjected to long-term ageing during the in-service life of bituminous pavement in the field. A PAV test was adopted to assess the long-term ageing of a binder. This test used the ASTM D6521 protocol [27], where binders are subjected to long-term ageing in PAV for 20 hours at 100°C at a pressure of 2.1 MPa. PAV test is followed by the vacuum degassing oven (VDO) method, which includes heating and vacuuming aged bitumen samples. This procedure eliminates any volatile substances that may have been collected during the PAV test, accurately imitating the ageing of asphalt in the actual world. PAV-aged binders are placed in the VDO for 30 mins at 170°C at an absolute pressure of 15 kPa.

2.2.3. Fourier transform infrared spectroscopy

FTIR technique detects chemical bonds in a molecule by producing an infrared absorption spectrum. It allows the identification of chemical changes in samples during modification based on specific absorption peaks in the FTIR spectra. During oxidation, bitumen molecular groups form bonds with oxygen in the atmosphere, and the bitumen's chemical makeup can change. Carbonyl, sulfoxide, aromatic, and aliphatic compounds are often created during the chemical changes due to oxidative ageing [28]. Hence, peak areas below the corresponding band were recorded from valley to valley at set wavenumbers of the resulting spectra to assess the changes of particular functional groups affected by ageing [10].

Different bond indices are used to analyse the impact of short and long-term oxidative ageing on the base and modified binders. Following equations (1), (2), (3), and (4) were used to determine the bond indices:

$$\text{Carbonyl Index: } I_{c=O} = \frac{A_{1700 (1665-1721)}}{\sum A} \quad (1)$$

$$\text{Sulfoxide Index: } I_{S=O} = \frac{A_{1028 (980-1050)}}{\sum A} \quad (2)$$

$$\text{Aromatic Index: } I_{Ar} = \frac{A_{1600 (1540-1640)}}{\sum A} \quad (3)$$

$$\text{Aliphatic Index: } I_{Al} = \frac{A_{1375} + A_{1456}}{\sum A} \quad (4)$$

Where,

A_{1028} –band area around 1028 cm⁻¹ (i.e. From 980 cm⁻¹ to 1050 cm⁻¹);

A_{1600} –band area around 1600 cm⁻¹ (i.e. From 1525 cm⁻¹ to 1620 cm⁻¹);

$A_{1375} + A_{1456}$ –band area around the peak at 1375 and 1456 cm⁻¹;

A_{1700} –band area around 1700 cm⁻¹ (i.e. From 1665 to 1721 cm⁻¹);

$\sum A$ – sum of the total considered peak areas

All these considered peaks and their corresponding wavenumbers range are material dependent.

3. RESULTS AND DISCUSSION

3.1. Assessment of physical properties

Table 1 shows the physical properties of the VG30 and TXPOMB in unaged conditions. Three tests were conducted on each sample for each test, and their average and corresponding standard deviation are tabulated in Table 1.

Table 1: Physical properties of VG30 and TXPOMB.

TEST	VG 30	1TXPOMB	2TXPOMB	3TXPOMB	REFERENCE	SPECIFIED LIMITS (IS 73: 2013)
Penetration at 25°C (1/10 th of mm)	50	53	56	60	IS 1203/ ASTM D5	Min 45
Standard Deviation	0.452	0.514	0.673	0.694		
Kinematic Viscosity at 135°C (cSt)	500	425	375	350	IS 1206 (3)	Min 350
Standard Deviation	0.511	0.456	0.568	0.681		
Absolute viscosity at 60°C (Poises)	2550	2625	2675	2750	IS 1206 (2)	Min 2400
Standard Deviation	0.347	0.376	0.423	0.459		
Softening point (°C)	50	49	47.5	46	IS 1205/ ASTM D36	Min 47
Standard Deviation	0.392	0.423	0.516	0.578		
RTFO Aged sample						
Mass Change (%)	0	-0.361	-0.435	-0.572	AASHTO M 320	Max. 1
Ductility at 25°C (mm)	75	81	88	90	IS 1208/ ASTM D113	Min 40
Standard Deviation	0.404	0.457	0.515	0.596		

Adding TXPO increases penetration and ductility while decreasing the viscosity and softening point of base binder VG30. It results in reduced stiffness and increased binder workability with aggregates while mixing. Also, the physical properties of unaged and aged binders are explained in detail by CHAUDHARI *et al.* [16].

3.2. Impact of TXPO modification on FTIR spectra

Figures 1 and 2 show the peaks corresponding to functional groups in FTIR spectra of VG 30 binder and textile pyrolysis oil (TXPO), respectively. It has been observed that the spectra of TXPO and VG30 binder differ, which may be mainly due to the diverse chemical compositions of both materials. According to Figures 1 and 2, the primary peaks for VG30 binder were found at 2920 to 2850 cm⁻¹ (CH₂), 1665 to 1721 cm⁻¹ (C = O), 1600 cm⁻¹ (C = C), 1456 cm⁻¹ (CH₂ bend), 1373 cm⁻¹ (CH₃ bend), 1028 cm⁻¹ (S = O) and 652 to 895 cm⁻¹ (C-H bend). Additional peaks were observed in the TXPO spectra at 3030 and 3065 cm⁻¹ (O-H) and 1267 and 1152 cm⁻¹ (C-O).

The peaks at 1153 and 1267 cm⁻¹ indicate ethers and esters in textile pyrolysis oil, and alcohol functionalities are represented by the peaks at 3030 and 3065 cm⁻¹. For comparative purposes, the FTIR spectra of VG30 and TXPOMB are shown in Figure 3. 1TXPOMB is considered for comparison, and TXPOMB exhibited similar spectra variation as a base binder. Figure 3 shows that no new peaks were seen upon adding TXPO to the VG 30, signifying that new functional groups were not formed due to modification.

However, when comparing the spectra of 1TXPOMB and VG30, few shifts in the peaks are detected. For instance, as shown in Figure 3, the 1916 and 2117 cm⁻¹ peaks are detected to be moved right to 1912 and 2132 cm⁻¹, respectively, upon modification with TXPO. This results from a chemical reaction between the VG30 base binder and TXPO molecules.

The TXPOMB spectra's peak shifts from 1600 cm⁻¹ to 1597 cm⁻¹, which refers to aromatic functional groups having C = C bonds stretching, and from 1300 cm⁻¹ to 1028 cm⁻¹, which relates to carbonyl function group having C = O bond, shown in Figure 4. An evolution in absorbance value is detected along with the shift in peak, signifying that the modified binder contains more aromatic compounds. There is a similar decrease in aliphatic compound absorbance at wave numbers 1375 cm⁻¹ and 1456 cm⁻¹ (CH₂ stretch). This indicates that upon TXPO modification, aliphatic molecules are changed into aromatic ones. At the same time, a decrease in the absorbance value of sulfoxide (S = O) and carbonyl (C = O) functional groups is observed. It shows a chemical interaction between the TXPO and base binder molecules, as shown in Figure 4.

The FTIR spectrum of VG 30 binder in unaged, RTFO, and PAV-aged conditions are shown in Figure 5. The absorbance of all functional groups in a base binder increases after RTFO ageing, and this observation is similar after PAV ageing. Figure 5 shows that after RTFO ageing, the carbonyl is visible. It can be seen in PAV spectra, indicating that PAV ageing causes a high increase in carbonyl compounds in base bitumen.

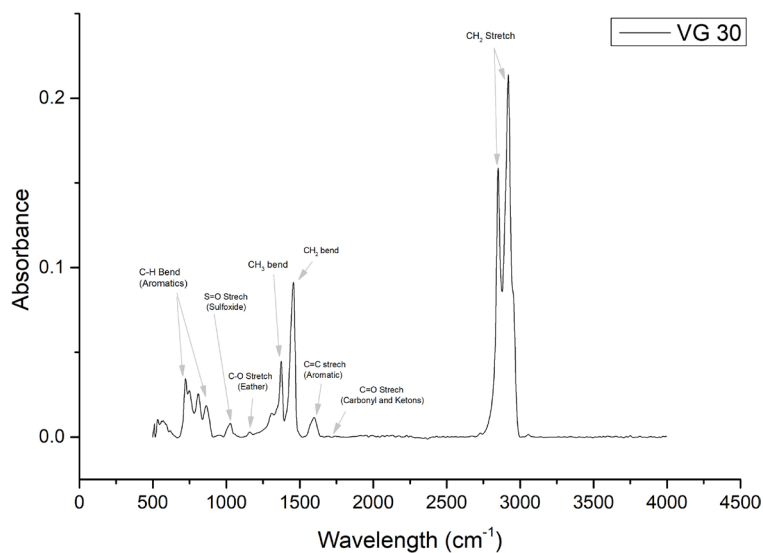


Figure 1: FTIR Spectrum of VG30.

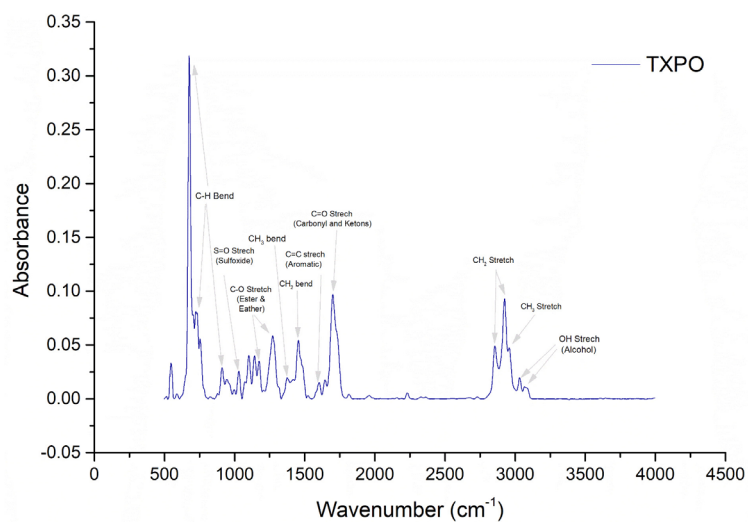


Figure 2: FTIR spectrum of Textile Pyrolysis Oil (TXPO).

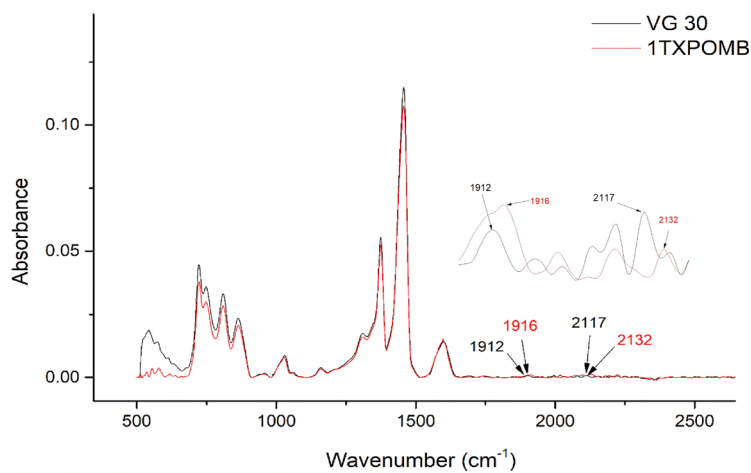


Figure 3: FTIR spectrum of base binder VG30 and 1TXPOMB.

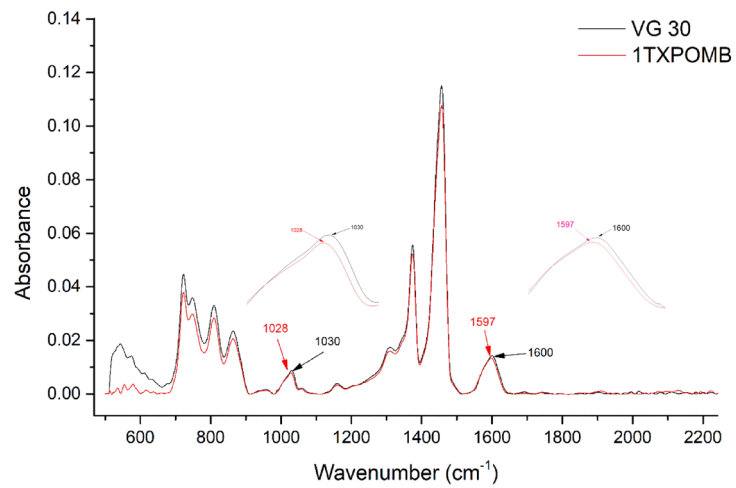


Figure 4: Shift in sulfoxide and aromatic peak in base binder VG30 and 1TXPOMB.

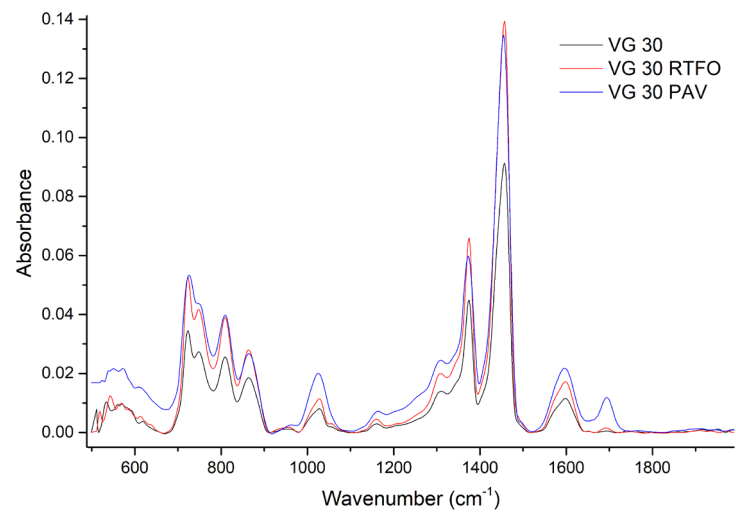


Figure 5: FTIR spectrum of VG30 in different ageing conditions.

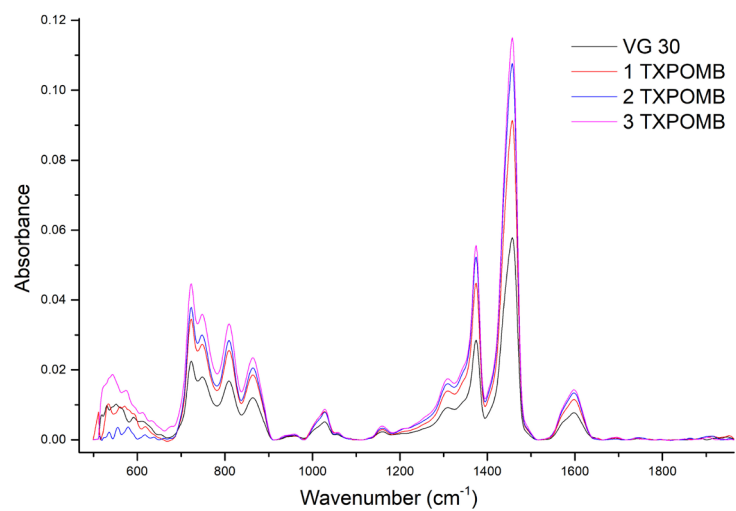


Figure 6: FTIR spectra of VG30 and TXPOMB in unaged condition.

Figure 6 shows the effect of adding TXPO in a base binder in dosages 1, 2, and 3%, and it is observed that due to the addition of TXPO in VG30 binder, the absorbance of all considered functional groups increases in unaged conditions. Also, as the percentage of TXPO increases, the absorbance of the base binder increases. The effect of adding TXPO in a base binder in the RTFO-aged condition is shown in Figure 7, where adding TXPO leads to a decrease in absorbance of the functional group after ageing compared to the RTFO-aged base binder. The impact of TXPO addition in PAV-aged conditions is shown in Figure 8. The absorbance of carbonyl at 1700 cm^{-1} and 1028 cm^{-1} decreases for 1% TXPO addition and increases for further modification. A similar increase is observed for the aromatic functional group, corresponding to 1600 cm^{-1} , whereas a corresponding decrease in the aliphatic function group at 1375 cm^{-1} and 1456 cm^{-1} is observed in Figure 8.

3.3. Impact of the modification process of TXPOMB

The absolute value of the indices calculated for unaged, RTFO-aged, and PAV-aged conditions for base and TXPOMB is analysed to understand the ageing during modification. Because of their greater susceptibility to oxidation, the carbonyl and sulfoxide indices are key indicators of bituminous binder ageing. Figure 9 shows the carbonyl and sulfoxide index for VG30 and TXPOMB in unaged, modified, and RTFO-aged conditions. This indicates that the TXPOMB did not undergo ageing during modification, as evidenced by the decreased

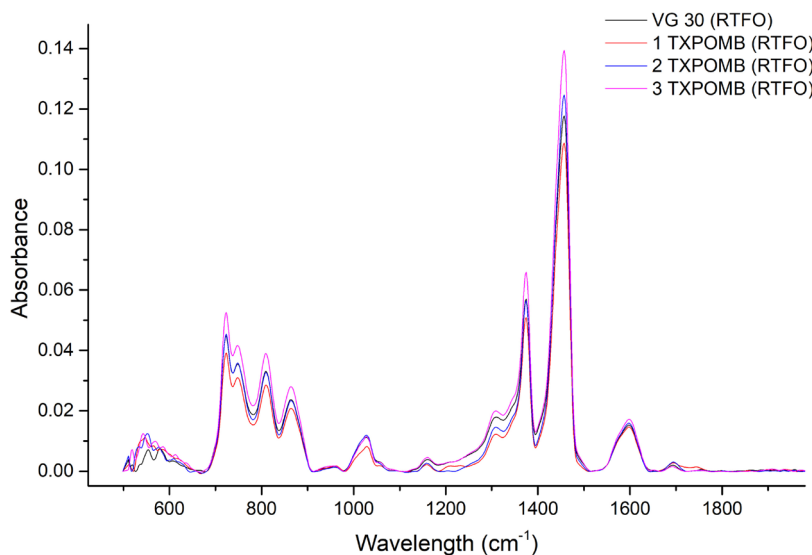


Figure 7: FTIR spectra of VG30 and TXPOMB in RTFO-aged condition.

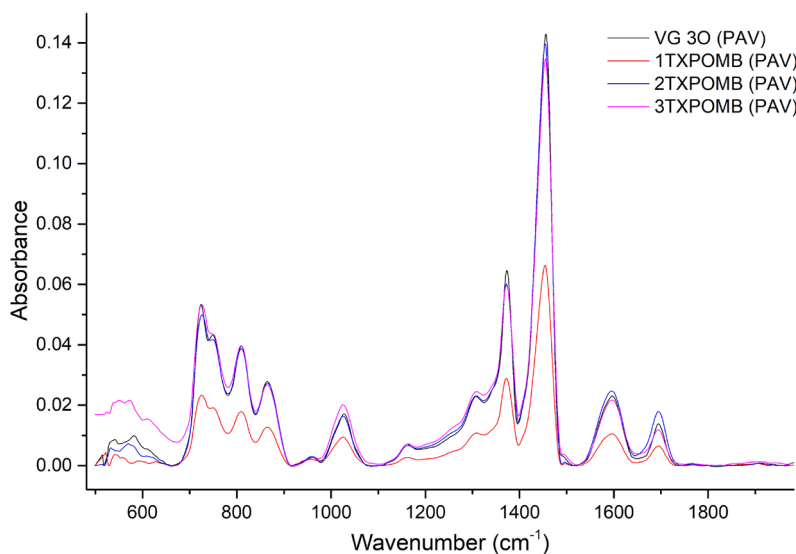


Figure 8: FTIR spectrum of VG30 and TXPOMB in PAV-aged condition.

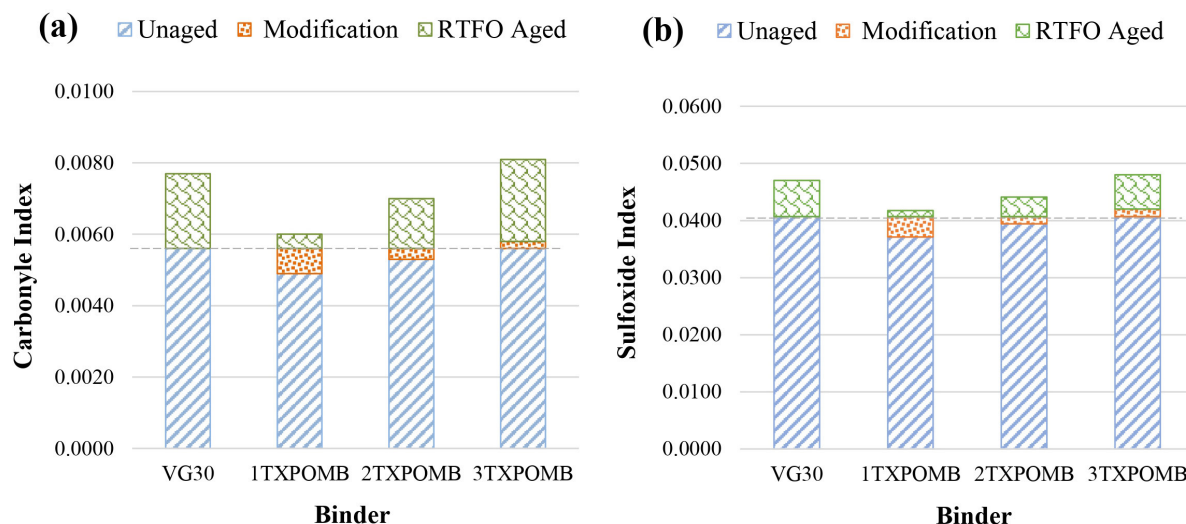


Figure 9: (a) Carbonyl and (b) Sulfoxide Index in unaged, modification, and RTFO aged condition for the base and modified binder.

carbonyl and sulfoxide index. Notably, there is a substantial reduction in carbonyl content, escalating from 0.0056 to 0.0049 and 0.0053 for VG30, 1TXPOMB and 2TXPOMB, respectively. Similarly, the sulfoxide index decreases from 0.041 to 0.037 and 0.039 for VG30, 1TXPOMB and 2TXPOMB, respectively. Meanwhile, for 3% modification of the TXPO binder, it undergoes ageing due to the modification process as carbonyl and sulfoxide index increase to 0.057 and 0.042, respectively. Since $C=O$ is produced by oxidation of ketones and $S=O$ by oxidation of sulfur or sulfide present in base and TXPO, the low concentration of these components in the TXPO may be the reason for this decline in carbonyl and sulfoxide index.

3.4. Impact of TXPO modification

The bond indices corresponding to different function group bonds observed in the base and TXPOMB binders are shown in Figure 10 to better understand oxidation during modification and ageing in the binders. Figure 10 (a) shows that due to TXPO modification with VG30, the carbonyl index decreases for 1TXPOMB due to a smaller quantity of carboxylic acid and ketone existing in the TXPO. The reactive functional group esters in the TXPO have converted the sulfoxide group to the sulfide group in the 1TXPOMB, as indicated by the decrease in sulfoxide index for 1TXPOMB.

The aromatic index decreases for 1TXPOMB; this could be because the base binder contains a higher percentage of aliphatic molecules than TXPO, resulting in a decrease of the polar doubly bonded molecules existing in the TXPO, leading to a reduction in $C=C$ bonds. The corresponding increase in aliphatic index is also observed in the Fig. 10 (d) for 1 TXPO modification. Further modification leads to an increase in the aromatic index and a corresponding decrease in the aliphatic index for 2TXPOMB and 3TXPOMB. Adding TXPO to base binder VG 30 decreases the sulfoxide index observed in Figure 10 (b), corresponding to sulfoxide decomposition while modification. Further addition of TXPO increases the sulfoxide index associated with the oxidation of sulfides present in the TXPO. The aliphatic index decreases for 2TXPOMB and 3TXPOMB because TXPO absorbs light fractions of the aliphatic functional group in base bitumen during mixing. The production of aromatic compounds is related to a corresponding decrease in aliphatic functional group. Similarly, Figures 10 (c) and (d) show an increase in the aromatic index and a decrease in the aliphatic index, respectively.

3.5. Influence on the ageing of binder

The FTIR index shown in Figure 10 assesses the effect of RTFO and PAV ageing on the base and TXPO-modified binders. Carbonyl, sulfoxide, and aromatic index have been found to increase with RTFO ageing and to continue increasing after PAV ageing. In contrast, the aliphatic index has decreased with RTFO and PAV ageing. After RTFO and PAV ageing, the $I_{C=O}$ and $I_{S=O}$ in 1TXPOMB and 2TXPOMB are lower than that of VG30; however, it increases for 3TXPOMB modification, meaning that 1% and 2% TXPO modification increases the ageing resistance of VG30, than that of 3TXPOMB. The increase in carbonyl and sulfoxide index due to RTFO ageing in VG 30, 1TXPOMB, 2TXPOMB and 3TXPOMB is 37.5%, 22%, 32%, 40% and 15.3%, 8%, 12%, 17% respectively. For PAV ageing, the increase in carbonyl index after RTFO ageing is observed as 67.5%, 51.7%,

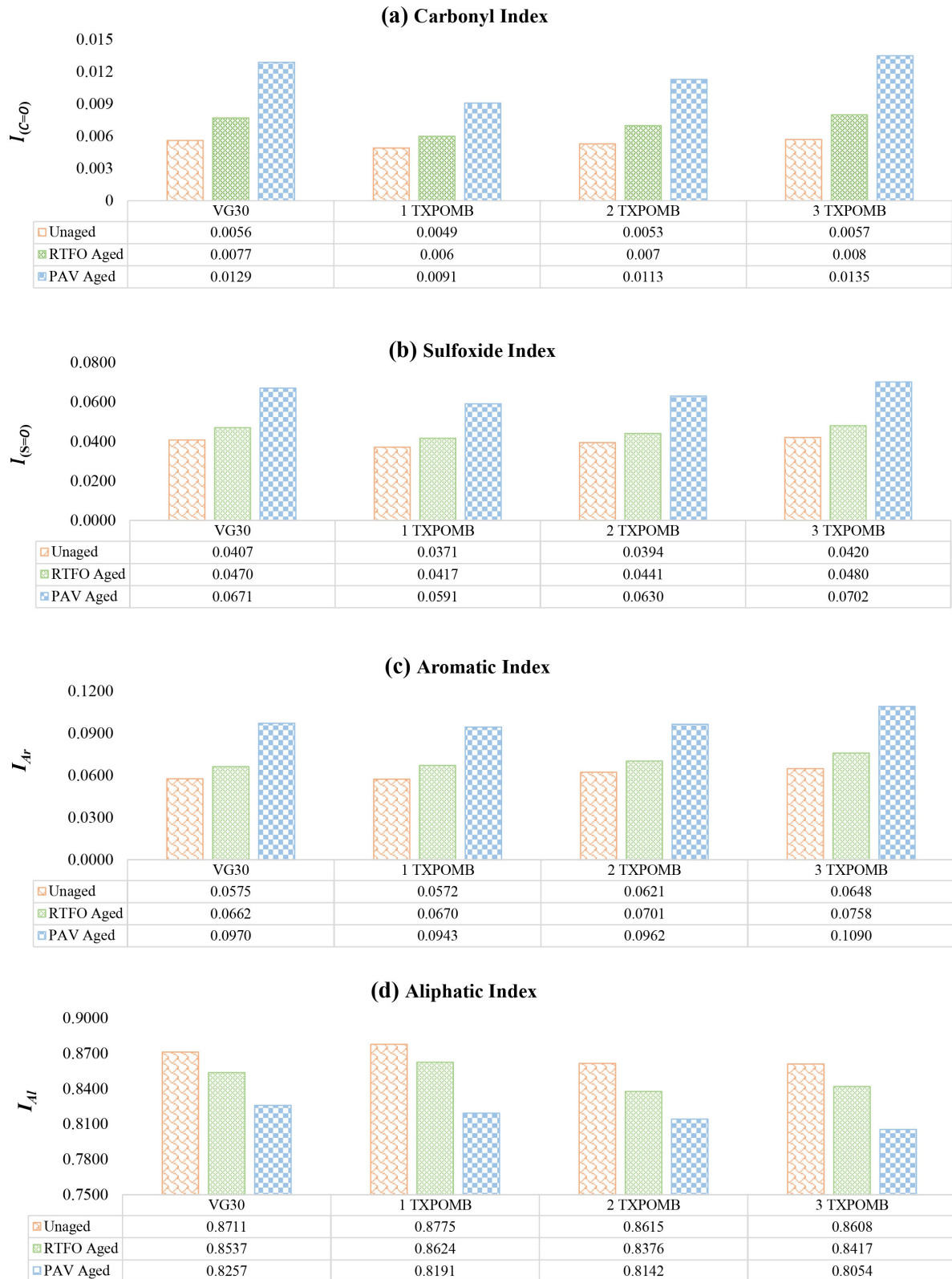


Figure 10: (a) Carbonyl Index, (b) Sulfoxide Index, (c) Aromatic Index, and (d) Aliphatic Index of binders at different ageing conditions.

61.4%, 68.8% and for sulfoxide index is 45.9%, 40.4%, 42.9%, 48.1% for VG 30, 1TXPOMB, 2TXPOMB and 3TXPOMB respectively. This also observed that the evolution of these indices in 1TXPOMB and 2TXPOMB is less as compared to base binder VG 30, i.e. the addition of 1 & 2% TXPO retards the ageing process of the base binder. The optimum content of TXPO is 2% in terms of ageing resistance, as it shows a decrease in carbonyl and sulfoxide index in unaged RTFO and PAV-aged conditions compared to the base binder. The 2% TXPO modification with the base binder improves its ageing resistance. The $I_{C=O}$ and $I_{S=O}$ values increase for 2 and 3% TXPO modification, signifying a reduction in ageing resistance as the concentration of TXPO increases in the VG30 binder. This results from the increased percentage of TXPO, which is oxidation-prone, along with an increase in the concentration of carbon and sulfur.

The carbonyl index increases after RTFO ageing and significantly during PAV ageing; it is also observed in FTIR spectra, where the carbonyl functional group, which corresponds to 1700 cm^{-1} , becomes marginally apparent during RTFO ageing and significantly noticeable during PAV ageing. The increase in the aromatic index is observed for VG 30 and TXPOMB after RTFO and PAV ageing. During ageing, light fractions of bituminous binder volatiles and aliphatic chains form aromatic rings, which lead to an increase in the I_{Ar} and a corresponding decrease in the I_{Al} . The same phenomenon is observed for the aromatic and aliphatic index in Figures 10 (c) and 10 (d), respectively.

4. CONCLUSIONS

This study assesses the impact of modification of textile pyrolysis oil and its impact on the ageing behaviour of bituminous binders. The corresponding peaks of carbonyl, sulfoxide, aliphatic, and aromatic functional groups were considered to examine the evolution during ageing. By identifying these functional group bond indices, it was discovered that FTIR spectroscopy was the most effective method for quantifying and analysing the oxidation products due to the ageing of binders. The conclusions of the study include the following ones.

- The base binder VG30 and textile pyrolysis oil FTIR spectra exhibit variations in their chemical composition, resulting in distinct functional groups. Shifts in the peak indicate the chemical reaction between TXPO and VG 30 binder after modification. The FTIR spectra also show that the carbonyl index increases significantly after RTFO and PAV ageing.
- The impact of the modification process was examined for TXPOMB when compared with base binder VG30. The 1% and 2% TXPO modifications did not age the base binder, as carbonyl and sulfoxide indices decreased during modification, and mass change is also within limits. The optimum content of TXPO is 2% in terms of ageing resistance, as it shows a decrease in carbonyl and sulfoxide index in unaged RTFO and PAV-aged conditions compared to the base binder. The 2% TXPO modification with the base binder improves its ageing resistance. PAV ageing has contributed more to carbonyl formation than RTFO ageing.
- Base binder VG30 and TXPOMB exhibited an increase in carbonyl, sulfoxide, and aromatic index for RTFO and PAV ageing. However, the modified binder's rate of growth is less than that of the base binder. Compared to the base binder, RTFO and PAV ageing increase the aromatic index and decrease the aliphatic index of TXPOMB.

Modifying the bitumen with textile pyrolysis oil presents a sustainable solution by enhancing the ageing resistance of binders and facilitating the efficient disposal of solid waste. This approach not only addresses environmental concerns but also improves the performance and longevity of the bituminous materials.

5. ACKNOWLEDGMENTS

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6. BIBLIOGRAPHY

- [1] ATHIAPPAN, K., MURUGASAN, R., MAKENDRAN, C., *et al.*, "Mechanical properties of asphalt mixtures containing reclaimed asphalt incorporating Acrylonitrile Butadiene Styrene (ABS)", *Matéria (Rio de Janeiro)*, v. 28, n. 4, pp. e20230201, 2023. doi: <http://doi.org/10.1590/1517-7076-rmat-2023-0201>.
- [2] DEHOUCHE, N., KACI, M., MOKHTAR, K.A., "Influence of thermo-oxidative aging on chemical composition and physical properties of polymer modified bitumens", *Construction & Building Materials*, v. 26, n. 1, pp. 350–356, 2012. doi: <http://doi.org/10.1016/j.conbuildmat.2011.06.033>.

- [3] HOFKO, B., ALAVI, M.Z., GROTHE, H., *et al.*, “Repeatability and sensitivity of FTIR ATR spectral analysis methods for bituminous binders”, *Materials and Structures*, v. 50, n. 3, pp. 187, 2017. doi: <http://doi.org/10.1617/s11527-017-1059-x>.
- [4] LU, X., ISACSSON, U., “Effect of ageing on bitumen chemistry and rheology”, *Construction & Building Materials*, v. 16, n. 1, pp. 15–22, 2002. doi: [http://doi.org/10.1016/S0950-0618\(01\)00033-2](http://doi.org/10.1016/S0950-0618(01)00033-2).
- [5] PETERSEN, J.C., GLASER, R., “Asphalt oxidation mechanisms and the role of oxidation products on age hardening revisited”, *Road Materials and Pavement Design*, v. 12, n. 4, pp. 795–819, 2011. doi: <http://doi.org/10.1080/14680629.2011.9713895>.
- [6] PIPINTAKOS, G., LOMMAERT, C., VARVERI, A., *et al.*, “Do chemistry and rheology follow the same laboratory ageing trends in bitumen?”, *Materials and Structures*, v. 55, n. 5, pp. 146, 2022. doi: <http://doi.org/10.1617/s11527-022-01986-w>.
- [7] MIRWALD, J., WERKOVITS, S., CAMARGO, I., *et al.*, “Investigating bitumen long-term-ageing in the laboratory by spectroscopic analysis of the SARA fractions”, *Construction & Building Materials*, v. 258, pp. 119577, 2020. doi: <http://doi.org/10.1016/j.conbuildmat.2020.119577>.
- [8] ASEMANI, M., RABBANI, A.R., “Detailed FTIR spectroscopy characterization of crude oil extracted asphaltenes: curve resolve of overlapping bands”, *Journal of Petroleum Science Engineering*, v. 185, pp. 106618, 2020. doi: <http://doi.org/10.1016/j.petrol.2019.106618>.
- [9] PATIL, D., HEDAOO, N., “Application of waste biaxially oriented polypropylene sandwiched graphene to enhance properties of asphalt mixes via a wet process”, *Materials Today: Proceedings*, 2023. doi: <http://doi.org/10.1016/j.matpr.2023.05.037>.
- [10] WANG, H., LIU, X., APOSTOLIDIS, P., *et al.*, “Effect of laboratory aging on chemistry and rheology of crumb rubber modified bitumen,” *Materials and Structures*, v. 53, no. 2, 2020. doi: <http://doi.org/10.1617/s11527-020-1451-9>.
- [11] DE LA ROCHE, C., VAN DE VEN, M., “Development of a laboratory bituminous mixtures ageing protocol”, *Advanced Testing and Characterization of Bituminous Materials*, v. 103, pp. 37–41, 2009.
- [12] ZOU, Y., YU, J., HUANG, X., *et al.*, “Impact of aging on molecular structure of asphalts from different crude oils”, *Journal of Testing and Evaluation*, v. 50, n. 3, pp. 1390–1402, 2022. doi: <http://doi.org/10.1520/JTE20210744>.
- [13] TARSI, G., VARVERI, A., LANTIERI, C., *et al.*, “Effects of different aging methods on chemical and rheological properties of bitumen”, *Journal of Materials in Civil Engineering*, v. 30, n. 3, pp. 04018009, 2018. doi: [http://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002206](http://doi.org/10.1061/(ASCE)MT.1943-5533.0002206).
- [14] JING, R., VARVERI, A., LIU, X., *et al.*, “Laboratory and field aging effect on bitumen chemistry and rheology in porous asphalt mixture”, *Transportation Research Record: Journal of the Transportation Research Board*, v. 2673, n. 3, pp. 365–374, 2019. doi: <http://doi.org/10.1177/0361198119833362>.
- [15] MO, Z., “Study on the performance and aging low temperature performance of GO/SBS modified asphalt.”, *Matéria (Rio de Janeiro)*, v. 28, n. 3, pp. e20230151, 2023. doi: <http://doi.org/10.1590/1517-7076-rmat-2023-0151>.
- [16] CHAUDHARI, Y.G., SHINDE, S.E., HEDAOO, N.A., “Investigating the characteristics of bitumen treated with textile pyrolysis oil”, In: *International Conference on Structural Engineering and Construction Management* (pp. 907–916). Cham, Springer Nature Switzerland, 2023.
- [17] BHAGAT, N.T., HADOLE, H.P., RANADIVE, M.S., “Oxidative aging characterization of pyro-oil modified binders using fourier transform infrared spectroscopy”, *Advances in Science and Technology Research Journal*, v. 17, n. 1, pp. 140–149, 2023. doi: <http://doi.org/10.12913/22998624/159056>.
- [18] KHAPNE, V., HADOLE, H., RANADIVE, M., “Assessment of anti-stripping property of pyro-oil modified bituminous mixes using surface free energy approach,” In *International Conference on Transportation and Development 2020: Highway and Airfield Pavements – Selected Papers from the International Conference on Transportation and Development 2020*, 2020. doi: <http://doi.org/10.1061/9780784483183.013>.
- [19] HADOLE, H.P., SURYAWANSHI, S.D., KHAPNE, V.A., *et al.*, “Moisture damage resistance of short-term aged pyro-oil-modified bitumen using rolling thin film oven by surface free energy approach”, *Journal of Materials in Civil Engineering*, v. 33, n. 10, pp. 04021268, 2021. doi: [http://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003872](http://doi.org/10.1061/(ASCE)MT.1943-5533.0003872).
- [20] KULKARNI, S.B., RANADIVE, M.S., “Modified cutback as tack coat by application of pyro-oil obtained from municipal plastic waste: experimental approach”, *Journal of Materials in Civil Engineering*, v. 32, n. 5, pp. 04020100, 2020. doi: [http://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003079](http://doi.org/10.1061/(ASCE)MT.1943-5533.0003079).

- [21] KOLISETTY, R.K., CHORE, H.S., “Utilization of waste materials in construction activities: a green concept”, *International Journal of Computers and Applications*, 2013.
- [22] IDH, SATTVA , *Unveiling India's Textile Waste Landscape: A Cost Analysis*, IDH, 2023. <https://www.idhsustainabletrade.com/publication/unveiling-indias-textile-waste-landscape-a-cost-analysis/>.
- [23] MIRANDA, R., SOSA-BLANCO, C., BUSTOS-MARTÍNEZ, D., *et al.*, “Pyrolysis of textile wastes. I. Kinetics and yields”, *Journal of Analytical and Applied Pyrolysis*, v. 80, n. 2, 2007. <http://doi.org/10.1016/j.jaap.2007.03.008>.
- [24] SURYAWANSHI, S.D., HADOLE, H.P., RANADIVE, M.S., “Evaluation of moisture susceptibility of pyro-oil modified bitumen by surface free energy approach”, In: *Lecture Notes in Civil Engineering*, 2021. doi: http://doi.org/10.1007/978-981-15-9988-0_33.
- [25] BHAGAT, N.T., HADOLE, H.P., RANADIVE, M.S., *et al.*, “Effect of high-density polyethylene pyro-oil modification on chemical, rheological, and damping properties of binders”, *Journal of Materials in Civil Engineering*, v. 36, n. 2, pp. 4023555, 2024. doi: <http://doi.org/10.1061/JMCEE7.MTENG-16536>.
- [26] AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM D 2872-12e1: *Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)*, West Conshohocken, ASTM, 2004.
- [27] AMERICAN SOCIETY FOR TESTING AND MATERIALS, *ASTM D6521-13: Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)1*, West Conshohocken, ASTM, 2008.
- [28] GAMARRA, A., OSSA, E.A., “Thermo-oxidative aging of bitumen”, *The International Journal of Pavement Engineering*, v. 19, n. 7, pp. 641–650, 2018. doi: <http://doi.org/10.1080/10298436.2016.1199876>.