Jestr

Journal of Engineering Science and Technology Review 18 (2) (2025) 88- 97

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Preparation and Road Performance of Waterborne Polyurethane Chromatic Aberration Repair Coatings for Pavement Applications

Min Yang[1], Xiaoni Ding[2], Juan Qiao[1], Linfei Zhao[3,4] and Hongjun Jing[3,4,*]

[1]*Highway Bureau of Shaanxi Province, Xi'an 710068, China*
[2]*Bingtuan Xingxin Vocational and Technical College, Tiemenguan 841007, China*
[3]*College of Architecture and Civil Engineering, Xi'an University of Science and Technology, Xi'an 710054, China*
[4]*Road Engineering Research Center, Xi'an University of Science and Technology, Xi'an 710054, China*

Received 2 January 2025; Accepted 23 March 2025

Abstract

To minimize the color difference between the newly repaired surface and the existing pavement after pothole patching and enhance both the aesthetic appeal and driving safety of the road, this study developed a new chromatic aberration repair coating for road use with waterborne polyurethane (WPU) as the base liquid. WPU was designed and synthesized using isophorone diisocyanate, polyhydric alcohols, and relevant additives. Color paste and fillers were incorporated into the base liquid to create a chromatic aberration repair coating with various color gradations. The micromechanism of the coating material was analyzed by infrared spectrum test, differential scanning calorimetry (DSC), and derivative thermogravimetry (DTG). The water resistance, acid–alkali resistance, skid resistance, and abrasion resistance of the coating were investigated by immersion, pendulum friction coefficient, and paint film abrasion tests. The results indicate that, WPU dispersion liquid is successfully synthesized with favorable thermal properties, meeting practical application standards. The coating exhibits excellent water, acid–alkali, skid, and abrasion resistance, all of which comply with established requirements. The developed chromatic aberration repair coating using WPU demonstrates good pavement performance and color-retaining capacity. It effectively enhances the aesthetic quality and safety performance of the pavement. The study provides a scientific basis for further research into the preparation and application of WPU coating, pavement beautification, and measures for improving road safety.

Keywords: Road engineering, Chromatic aberration repair, Infrared spectrum test, Asphalt pavement, Performance research

1. Introduction

Recently, road maintenance has received significant attentions and supports due to rapid national economic development and increasing traffic demands. However, road maintenance in China continues to face substantial challenges due to the dramatic rise in traffic. In particular, damage to asphalt pavements is escalating, with potholes emerging as one of the most common and challenging problems to repair completely. Restrictions in current construction technology and practical field conditions lead to inconsistencies in repair quality. Additionally, due to the exposure and aging of old pavement over the years, significant chromatic aberration occurs between new and old materials during repairs. This chromatic aberration negatively affects the visual appeal of the repaired pavement. This condition increases visual judgment errors for drivers and makes it difficult for them to accurately assess the pavement's condition, thereby influencing their driving decisions. Chromatic aberration after the repair of pits and cracks causes visual and psychological effects during high-speed driving, seriously affecting driving safety. By exploring driving behavior data, several scholars have identified multiple causes of road traffic accidents, including road environmental factors and human decision-making factors [1–3]. Pavement conditions are found to significantly influence the severity of traffic collisions, and emotions significantly affect decisions and behaviors [4,5]. A questionnaire survey of 752 drivers was carried out, and 86.7% of respondents indicated that chromatic aberration after pothole repairs on pavement affects driving safety. This finding demonstrates that drivers are highly sensitive to chromatic aberration caused by pothole repairs on roads and generally believe that such variations affect their safety. Therefore, preparing a coating to reduce chromatic aberration caused by asphalt pavement repairs has significant practical importance.

Mixture repair has become the main maintenance means for asphalt diseases [6]. However, traditional repair technologies often overlook the issue of chromatic aberration in the pavement after repairs, resulting in obvious visual differences between the repaired region and the original pavement. Chromatic aberration not only destroys the overall integrity of roads but also may cause distractions to drivers and increase driving risks. Researchers have conducted extensive studies on asphalt pavement repair from various perspectives, including structural design philosophy, repair material selection, functionality, and bonding strength [7–9]. Moreover, numerous effective maintenance strategies have been proposed [10–12]. By optimizing the formula and techniques of coating materials, research scholars have successfully developed multiple asphalt pavement coating materials with excellent performance. However, the preparation of a coating material that can alleviate chromatic aberration after pavement repair and its subsequent pavement performance need to be further studied.

*E-mail address: 434935645@qq.com

doi:10.25103/jestr.182.11

In this study, a chromatic aberration repair coating with multiple color gradations was developed and prepared. The micromechanism of the coating material was analyzed by infrared spectrum test, derivative thermogravimetry (DTG), and differential scanning calorimetry (DSC). The water resistance, acid–alkali resistance, skid resistance, and abrasion resistance of the coating were investigated by immersion, pendulum friction coefficient, and paint film abrasion tests. This study provides a solid foundation for further research on chromatic repair coatings made from waterborne polyurethane (WPU) for road applications.

2. State of the art

With respect to the application of polyurethane (PU) coatings, Du et al. [13] investigated a PU coating with superhydrophobic properties, self-repair capabilities, and electrical properties. A two-layer structure was formed by incorporating PU/carbon nanotube (CNT) composition and low-surface-energy coupling agent-modified CNTs. Their findings revealed that the coating achieved a self-repair efficiency of 100.47% within 1 h at a water contact angle of 60° and demonstrated electrical conductivity. Simulation revealed that fluorine atoms promoted the formation of hydrogen bonds. Chen et al. [14] synthesized two types of highly crosslinked aliphatic PU using two types of di-isocyanate trimmers. Their performance in adsorption and penetration of dimethyl methyl phosphonate and 2-chloroethyl ethyl sulfide (CEES) was analyzed by dissipative quartz crystal microbalance and gas chromatography. CEES exhibited stronger re-adsorption due to its high polarity; by contrast, the desorption and re-adsorption of alicyclic structure PU were minimal, and the penetration was lowest, which reduced adsorption and penetration. Yuan et al. [15] prepared a PU-based organic coating substrate and synthesized $Ti_3C_2T_x$-PANI composite fillers. They found that the coating could decrease noise by 25–30 dB and maintained good corrosion resistance after immersion in a NaCl solution for 50 days. The coating demonstrates great potential in reducing noise and preventing corrosion of marine devices. Bakhshandeh et al. [16] prepared a PU coating and explored the influences of material parameters on ice resistance. They discovered that a low Young's modulus is advantageous for reducing ice adhesion and that significant ice dispersion can be achieved by adjusting surface energy. To sum up, PU coating has wide application, excellent performance, and clear advantages. The key to preparing a PU coating lies in the formulation of the PU emulsion. Hence, the study of PU emulsion preparation is of particular importance. Sui et al. [17] prepared a fluorination WPU emulsion and characterized its structure and performance through several tests. They found that increasing the usage of hydroxypropyl polydimethylsiloxane (HP-PDMS) first increased and then decreased grain size, reduced transmissivity, improved thermostability and phase separability, and lowered crystallinity. Fluorine and silicon enriched the surface of the thin film, which increased the water contact angle to 105.95°, decreased water absorption to 11.1%, and enhanced water resistance. After 15 wt% HP-PDMS was added, the tensile strength and tear strength of the coating leather were 935 N and 130 N, respectively. The coating had good hydrophobicity, aging resistance, and mechanical performance. Lai et al. [18] prepared a lignin-based waterborne polyurethane (LWPU) emulsion through the polymerization of polypropylene glycol and isophorone diisocyanate using unmodified industrial alkali lignin (AL) as a chain extender and found that the maximum lignin content reached 24.68 wt%. The LWPU film was uniform, and increasing AL decreased grain size and lowered zeta potential. The emulsion was stable at pH 5–12. AL increased thermostability and tensile strength and enhanced the resistance to ultraviolet radiation aging. LWPU emulsion is a new type of bio-based PU material. Obviously, research on the preparation of PU emulsion is well developed, with strong performance and promising application prospects. Therefore, investigating the use of PU as a pavement coating is particularly important.

In their study on the use of PU as a pavement coating, Yang et al. [19] prepared a phosphorescent road marking (PRM) coating using solvent-free PU and fluorescent powder and evaluated its durability using an accelerated wear test. They found that PRM-0.75 and PRM-1.0 could emit light continuously for 6 h and had 35 minutes (min) of abrasion resistance. They were superior to traditional road marking lines (30 min), and PRM-0.75 performed better. Miao et al. [20] synthesized cross-linkable endothermic WPU for solar reflection coatings on asphalt pavement. Compared with waterborne epoxy resin and polyacrylate emulsion, the synthesized cross-linkable endothermic WPU had a better cooling effect and lowered the internal temperature of asphalt concrete by 7 °C–11 °C, along with excellent abrasion resistance. This achievement is an important advancement in reflection coatings. In conclusion, PU-based coatings have been widely used in road engineering. However, further research is needed to develop PU coating materials that can reduce chromatic aberration of pavement after repairs. Currently, there is insufficient research on the preparation of PU dispersion liquid and color paste to alleviate chromatic aberration of asphalt pavement after repairs. Selecting appropriate methods to verify the accuracy of PU dispersion liquid synthesis results, as well as assessing its thermal stability and the micromechanism of phase state transformation at room temperature, is also essential. Furthermore, thorough research is required on the acid–alkali resistance and skid resistance of PU as a pavement coating.

To address existing research gaps, this study prepared a WPU dispersion liquid using stepwise polymerization and the acetone process [21,22], to which color fillers and an appropriate amount of color paste were added, creating a beautifying coating for chromatic aberration repair on pavement. The micromechanism of the coating materials was analyzed using infrared spectroscopy, DSC, and DTG. The water resistance, acid–alkali resistance, skid resistance, and abrasion resistance of the coating were tested using immersion, pendulum friction, and paint film abrasion tests. This study aims to prepare a WPU chromatic aberration repair coating with multiple color gradations suitable for pavement, designed to relieve chromatic aberration after asphalt pavement repairs, thereby enhancing the aesthetic appeal and driving safety of roadways.

The remainder of this study is organized as follows. Section 3 introduces the raw materials, details the specific preparation steps, and outlines the performance testing methods for the coating. Section 4 provides a comprehensive analysis of the micromechanism, durability, skid resistance, and abrasion resistance of the coating, closing with an overview of its various properties. Section 5 indicates the key conclusions of this study.

3. Methodology

3.1 Raw materials and coating preparation

The WPU beautifying coating mainly consisted of a PU base solution, color paste, and fillers. The PU base solution was the essential raw material for the coating, and it consisted of PU dispersion liquid, modifiers, solvents, additives, and other components.

3.1.1 Raw materials

Primary reagent: Isophorone diisocyanate (IPDI), Aladdin Reagent Co., Ltd.; Primary reagent: Polyethylene glycol 400 (PEG 400), Sinopharm Chemical Reagent Co., Ltd.; Hydrophilic chain extender: 2,2-dihydroxy-methyl butyric acid (2,2-DMBA), Shanghai Aladdin Biochemical Technology Co., Ltd.; Solvent: Acetone (Table 1), Sinopharm Chemical Reagent Co., Ltd.; Catalyst: Dibutyltin dilaurate (DBTDL), Sinopharm Chemical Reagent Co., Ltd.; Branched chain extender: Trimethylolpropane (TMP), Sinopharm Chemical Reagent Co., Ltd.; Light stabilizer: 2,4-dihydroxy benzophenone UV-0, Sinopharm Chemical Reagent Co., Ltd.; Water stabilizer: E-51 epoxy resin (Table 2), Sinopharm Chemical Reagent Co., Ltd.; Auxiliary agent: 593 curing agent (Table 3), Sinopharm Chemical Reagent Co., Ltd.; Defoamer/leveling agent: Polydimethylsiloxane, Shenzhen Dayang New Material Co., Ltd.

Table 1. Performance parameters of acetone

Appearance	Molecular weight	Density (g/ml, 25 °C)	Viscosity (mPa·s, 25 °C)	Solubility
Colorless and transparent liquid state	58.08	0.7899	0.316	Soluble in various organic solvents

Table 2. Performance parameters of E-51 epoxy resin

Appearance	Epoxy (g/mol)	Density (g/ml, 25 °C)	Viscosity (mPa·s, 25 °C)	Inorganic (mg/kg)
Transparent uniform fluid	180–210	1.11	10000–16000	≤50

Table 3. Performance parameters of curing agent

Model	Molecular weight	Relative density	Viscosity (mPa·s, 25 °C)	Appearance	Total amine value/ mgKOH/g
593	217.13	0.985	90–150	Colorless and transparent liquid state	500–700

3.1.2 Particle representation

(1) Preparation of WPU dispersion liquid

The WPU dispersion liquid was prepared using stepwise polymerization and the acetone method. The following are the detailed steps:

1) Dehydration: The raw materials, such as PEG, were dried in an oven at temperatures below 120 °C for 24 h to eliminate moisture.

2) Prepolymerization: Monomer PEG400 (0.01 mol) was added to a three-neck flask and placed in an oil bath. The stirring device was installed, and the condensation tube was connected to enable the reaction between PEG 400 and IPDI. The reaction should proceed for 2 h at 75 °C with the catalysis effect of DBTDL. After full mixing, PU prepolymerization substances were gained.

3) Introduction of hydrophilic monomer: 2,2-DMBA (0.015 mol) was introduced as a hydrophilic chain extender and reacted at 75 °C for 2 h.

4) Chain extension: The TMP system (0.012 mol) was added and reacted for 2 h, which introduced a PU macromolecular chain into the benzene ring.

5) Neutralization: If the viscosity was too high, an appropriate amount of acetone was added to reduce the viscosity and increase the reaction rate. After completing the chain extension, the system temperature was adjusted to 50 °C. A determined amount of 2,4-dihydroxy benzophenone was then added continuously and allowed to react for 2 h. This step was followed by 1 h of neutralization with 0.015 mol TEA. During this time, the stirring rate of the system was also increased.

6) Emulsion dispersion: Deionized water (20 mL) was added to the dispersion liquid and emulsified for 20 min. Acetone was removed through rotary evaporation in a water bath at 45 °C, and WPU dispersion liquid was acquired.

(2) Preparation of coating base solution

WPU dispersion liquid and epoxy resin were combined in a beaker in specific proportions. A diluent was added, and the mixture was stirred with a blender for 1 h. Later, the mixture was taken out and cooled to room temperature. Additives such as curing, defoaming, and flatting agents were added to the mixed resin one by one, followed by thorough stirring. Afterward, the mixed resin was then cured at 25 °C in a vacuum oven to obtain the base liquid of the PU coating.

(3) Preparation of color paste

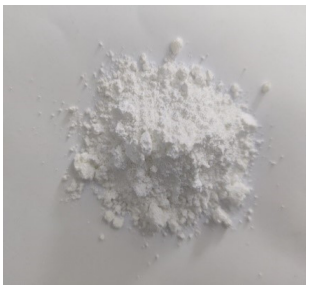
1) Ingredients: The paints were accurately weighed according to a specific formula, and appropriate amounts of dispersing agent and carrier were prepared.

2) Prepolymerization: A specific amount of dispersing agent was added to deionized water and thoroughly mixed at room temperature to ensure uniform dissolution of the dispersing agent. Next, an appropriate quantity of defoaming agent and corrosion remover was added to the solution, and the mixture was stirred continuously until fully mixed. Finally, paints such as carbon black and titanium dioxide (Fig. 1) were slowly added to the homogenous mixture following a predetermined mass ratio. The mixture was stirred continuously to promote uniform distribution of the paints within the matrix, completing the accurate preparation of the predispersing agent.

3) High-efficiency refining of the predispersed mixture was performed using a sand mill or bead mill to ensure the particle size of the pigments was less than 5 μm.

4) A stabilizer was added to prevent secondary aggregation of paint grains and ensure that the color paste had good storage stability.

(a)

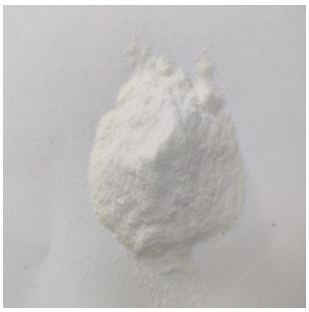


(b)

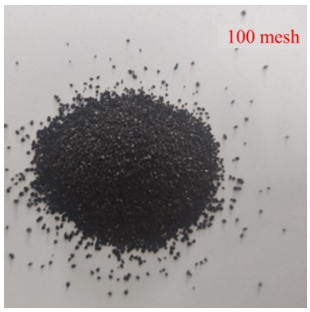
Fig. 1. Clustering result for the karate network. (a) Carbon black. (b) Titanium dioxide

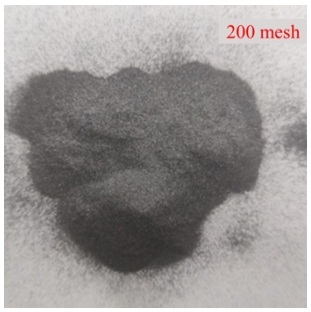
(4) Preparation of cosmetic coating

In accordance with the performance requirements of asphalt pavement coatings and the gray level of the original asphalt pavement during damage repair, an appropriate amount of color paste was added to the base liquid of the PU coating. In addition, a delustering agent (Fig. 2a) was added and stirred thoroughly for 30 min, providing the WPU beautifying coating with different gray levels. After stirring, it could then be applied in construction, with carborundum particles (Fig. 2b) scattered evenly.



(a)





(b)

Fig. 2. Fillers. (a) Delustering agent. (b) Carborundum

3.2 Test method

3.2.1 Infrared spectrum test

Various organic chemical substances, including isocyanates, polyhydric alcohols, catalysts, and chain extenders, show distinct infrared absorption spectra. The characteristic absorption peak of WPU dispersion liquid was measured using infrared spectroscopy, with a spectral range of 4000–500 cm^{-1}. The specific ingredients in PU can be identified by recognizing typical absorption peaks of certain functional groups.

3.2.2 Differential scanning calorimetry

DSC was used to measure the crystallization temperature, melting point, and glass transition temperature of PU. DSC can also be used to investigate several thermal phase processes, such as curing, oxidation, decomposition, and phase transitions. A 5 mg dried sample of WPU dispersion liquid was placed in the DSC tester, and nitrogen was supplied. The temperature was maintained at 200 °C. The test began at −60 °C, with the temperature increasing at a rate of 10 °C per minute to observe the glass transition temperature [23].

3.2.3 Durability test

To ensure that the coating remains effective over a long period, its durability, including water resistance, acid resistance, and alkali resistance, will be tested. The durability of the coating was evaluated according to the *Determination of resistance to water of films (GB/T 1733-1993)*, *Pavement Marking Paint (JT/T 280-2022)*, and Regulations for *Determination for alkali resistance of film of - Architectural paints and coatings (GB/T 9265-2009)*.

(1) Water resistance test

In accordance with the technical requirements in *Pavement Marking Paint (JT/T 280-2022)*, the paints were immersed in water for 48 h. The coating was considered to have passed the test if no abnormal phenomena were observed. The water resistance of the coating was tested using the immersion method, based on the *Determination of resistance to water of films (GB/T 1733-1993)*. The procedure is as follows:

1) Preparation of specimens: The Marshall specimens with WPU coating were placed in a container, with the coating facing downward.

2) Immersion test: The coating specimens were completely immersed in deionized water, with additional water added to ensure complete submersion. The immersion time was set for 48 h. During the test, the water temperature was kept constant, generally around room temperature.

3) Drying: After 48 h, the specimens were removed, and residual water was absorbed using filter paper. Phenomena such as peeling, bubbling, or color variation of the coating were observed and recorded.

(2) Alkali resistance test

The alkali resistance of the coating material was tested in accordance with the technical requirements in *Pavement Marking Paint (JT/T 280-2022)*. The test aimed to verify the stability of the coating in a saturated solution of calcium hydroxide. No abnormal reaction was observed during the immersion test for 48 h. Additionally, the alkali resistance of the coating was evaluated with reference to the *Test Standards for alkali resistance of film of - Architectural paints and coatings (GB/T 9265-2009)*. The specific test steps are as follows:

1) Preparation of alkaline solution: In accordance with the test requirements, a specific concentration of alkali solution was prepared. Typically, a $Ca(OH)_2$ or KOH solution was used to simulate an alkaline environment under

practical conditions. Deionized water was added for dilution. The solution was left to stand for 48 h, and then the upper clear layer was collected for later use.

2) Preparation of specimens: The Marshall specimens with WPU coating were placed in a container, with the coating facing downward.

3) Immersion in solution: The coated surface was fully immersed in the prepared alkaline solution for 48 h.

4) Sampling and cleaning: After immersion, the specimens were removed and thoroughly cleaned with deionized water to eliminate any residual alkaline solution on the surface. Subsequently, the specimens were dried naturally or under controlled conditions.

5) Observation and records: Phenomena such as softening, bubbling, crumbling, color change, or peeling were observed and recorded.

(3) Acid resistance test

For the evaluation of acid resistance, since no specific regulation on acid resistance exists in *Pavement Marking Paint (JT/T 280-2022)*, similar test steps for alkali resistance were followed, except for replacing the immersion solution with diluted hydrochloric acid for 48 h. The specific steps are as follows:

1) Preparation of acid solution: Diluted hydrochloric acid solution (0.1 mol/L) was added to the container and stirred thoroughly. After 48 h, it was kept for later use.

2) Placing of specimens: The processed Marshall specimens were placed in a container, with the coating facing downward.

3) Adding solution: The dilute hydrochloric acid solution was added to the container so that 2/3 of the specimens were immersed.

4) Result record: Specimens were removed after 48 h, and the residual water was absorbed. Meanwhile, the occurrence of softening, bubbling, pulverization, color change, or peeling was observed.

3.2.4 Skid resistance test

To ensure the safety of road driving, improving skid resistance during the design and preparation of PU coating for asphalt pavement is crucial. The skid resistance of asphalt pavement is mainly evaluated based on the swing value. In this study, a pendulum tribometer was employed to measure and analyze the skid resistance of the coating on asphalt pavement. Three groups of specimens with varying coating contents were selected, each tested three times. The mean value from these tests was used as the statistical result. According to the Regulations on *Field Test Methods of Highway Subgrade and Pavement (JTG 3450-2019)*, if the test temperature differs from the standard, temperature correction is required for the results. The correction standards are shown in Table 4. Specimens with a swing value of 45 or higher are considered qualified. The detailed test was carried out in accordance with the above standards and requirements.

3.2.5 Wear resistance test

According to the regulations in Abrasive Resistance Evaluation for *Paints and varnishes - Determination of resistance to abrasion - Rotating abrasive rubber wheel method (GB/T 1768-2006)*, the actual wear loss of the coating surface due to vehicle traffic was simulated using a paint film abrasion meter. In the test, the rotation speed of the paint film abrasion meter was set to 90 r/min. The sample tray had a diameter of 100 mm and a central hole diameter of 6.2 mm. The grinding wheel had a diameter of 50 mm and a central hole diameter of 16 mm. The applied loads were 500 g, 50 g, and 1000 g.

Table 4. Correction of swing value and temperature

Temperature/°C	0	5	10	15	20	25	30	35	40
Corrected value	−6	−4	−3	−1	0	+2	+3	+5	+7

In this study, coating materials with different mixing ratios were applied to each specimen to analyze the wear loss of the coating before and after the test. Four schemes were designed for comparative analysis: unprocessed reference specimens (blank control group), specimens with PU base solution, specimens with PU base solution + paints, and specimens with PU base solution + colored fillers. In Scheme 4, carborundum was selected as the colored filler, with mixing ratios set to 0.2, 0.3, and 0.4 kg/m^2. Considering both coating content and skid resistance, the preset thickness of the coating was determined to be 0.5 kg/m^2. The coating was then applied uniformly to the specimen surfaces. In accordance with the curing time requirements for beautification materials, the wear loss test was initiated after the coating had fully cured and achieved the expected strength. Regular recording and analysis of performance changes in the coating during the test were necessary.

4. Result analysis and discussion

4.1 Micromechanism analysis of coating materials

4.1.1 Infrared spectrum analysis

A distinct absorption peak of carbonyl is shown in the infrared spectra of WPU specimens in Fig. 3(a). This peak is in the wavenumber range of 1700–1750 cm^{-1}, indicating the presence of carbamido (−NHCO−) or ester groups (−COO−) in WPU. The intensity of this peak reflects the content and polymerization degree of carbonyl groups in WPU. The peak at 2960 cm^{-1} represents the antisymmetric stretching vibration of C–H, attributed to PEG 400 and IPDI. The peak at 1460 cm^{-1} represents the shear and deformation vibration of C–H. The peak at 1540 cm^{-1} indicates the stretching vibration of C–C and the bending vibration of N–H. The peak at 1090 cm^{-1} denotes the stretching vibration of C–O–C bonds in PEG. In Fig. 3(b), the characteristic desorption peak of −NCO disappears, indicating that WPU was successfully synthesized. The absorption peaks in the above-infrared spectra confirm that the WPU dispersing liquid was successfully synthesized.

4.1.2 Thermal performance analysis

In the detailed analysis of the thermal properties of WPU dispersing liquid, the thermostability and glass transition temperature (*Tg*) of the dry coating were assessed using DSC and DTG. The results are shown in Fig. 4. Concerning the practical application needs of PU dispersing liquid, maintaining good mobility and preventing phase changes at room temperature are crucial. According to the data from the DSC curve, the glass transition temperature in the soft section of PU ranged from −20 °C to 0 °C. This value assured the high elasticity of the dispersing agent under normal service conditions and prevented the influence of molecular chain movement on its performance, implying

excellent flexibility and tenacity. The melting temperature was between 150 °C and 160 °C, suggesting that PU began to turn into a viscous state and the molecular chain began to decompose. In a word, the temperature for decomposition of the PU dispersing agent exceeded 100 °C, which could completely support the temperature of the test system.

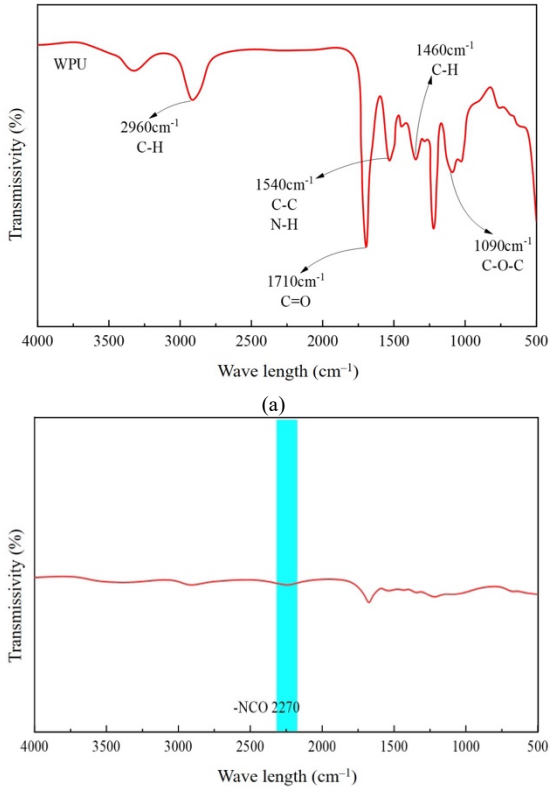
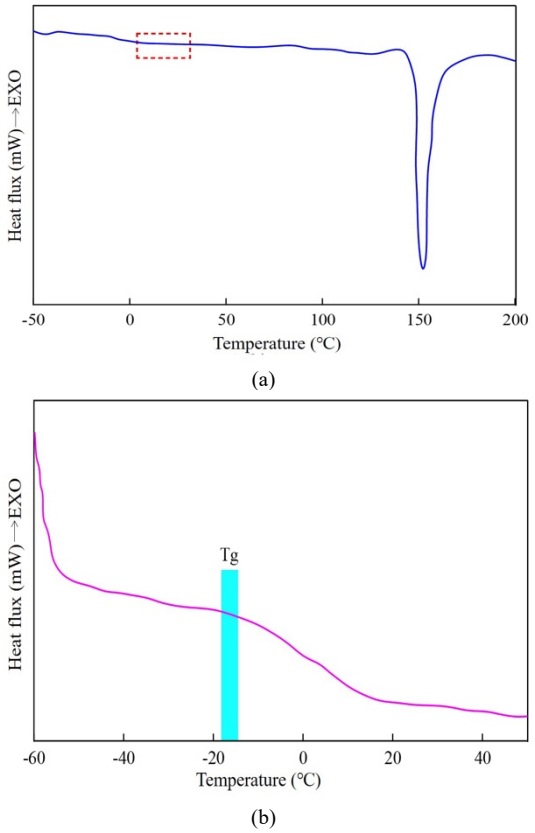


Fig. 3. Infrared spectrum of WPU. (a) WPU. (b) Synthesis process of WPU dispersion



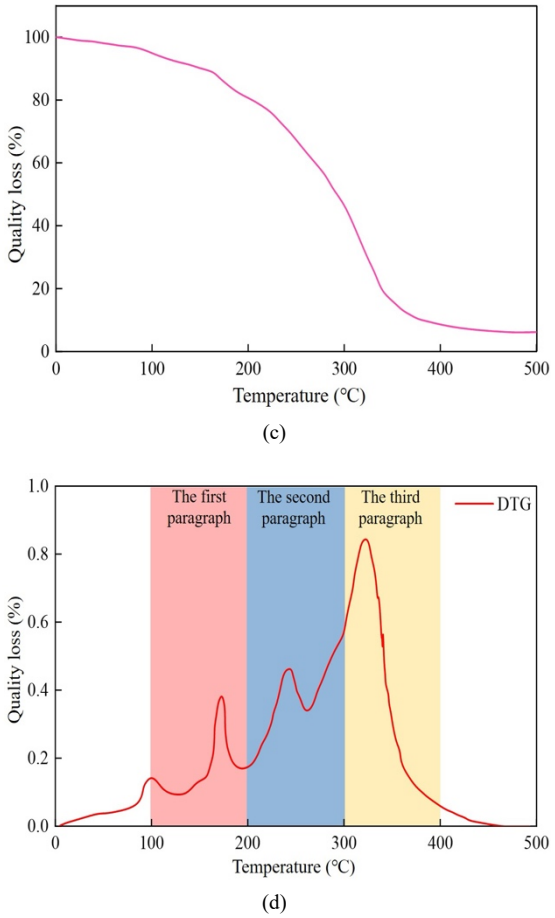


Fig. 4. Thermal stability analysis of linear WPU. (a) DSC curve. (b) DSC curve. (c) Tg curve. (d) DTG curve

4.2 Durability analysis

4.2.1 Analysis of water resistance test

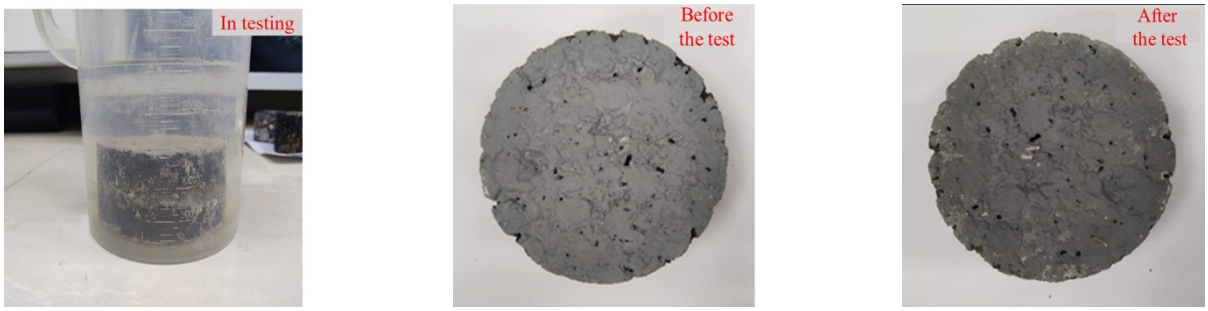
Based on Fig. 5 and Table 5, after immersion in water for 48 h, the WPU coating surface exhibited no bubbling, color change, wrinkles, or peeling. This indicates that the WPU coating could maintain a good appearance under immersion conditions and exhibited good water resistance.

Table 5. Test results for the water resistance of the coating

Immersion time	Coating content (kg/m^2)	Water resistance			
		Color change	Bubbling	Wrinkle	Fallig off
48 h	0.5	No	No	No	No
	0.7	No	No	No	No
	0.9	No	No	No	No

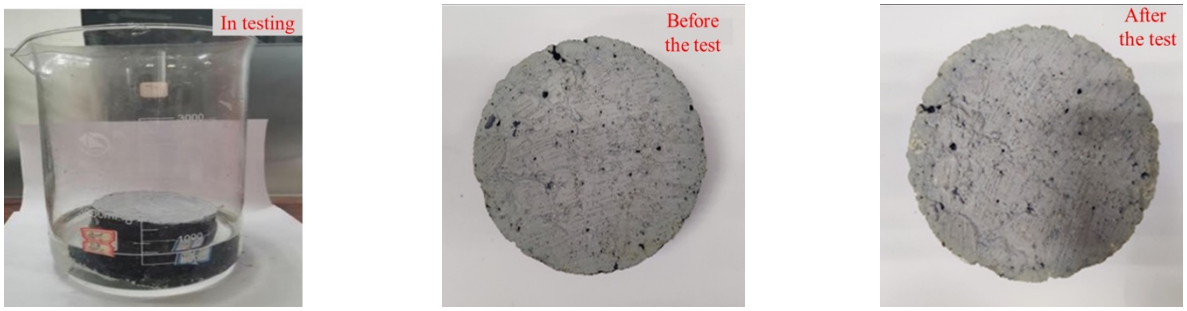
4.2.2 Analysis of alkali resistance test

After immersion in a $Ca(OH)_2$ saturated solution for 48 h, no bubbles, color changes, or wrinkles were found on the surface of the specimens with WPU coating, as indicated in Fig. 6 and Table 6. Moreover, no peeling of the coating was detected. Hence, in an alkaline environment, the WPU coating could maintain an intact appearance and demonstrate excellent alkali resistance.



(a) (b)

Fig. 5. Water resistance test. (a) Water resistance test. (b) Effect before and after water resistance test



(a) (b)

Fig. 6. Alkali resistance test. (a) Alkali resistance test. (b) Effect before and after alkali resistance test

Table. 6. Test results for the alkali resistance of the coating

Immersion time	Coating content (kg/m^2)	Alkali resistance
48 h	0.3	Coating integrity, without color change, peeling, and bubbling
	0.5	Coating integrity, without color change, peeling, and bubbling
	0.7	Coating integrity, without color change, peeling, and bubbling

4.2.3 Analysis of acid resistance test

From Fig. 7 and Table 7, the specimens with WPU coating kept complete coating on the surface after being immersed in the diluted hydrochloric acid solution for 48 h, without color changes, peeling, mild bubbles, or falling off. This result proved that WPU coating could maintain a good appearance under acid conditions, and it had strong acid resistance.

(a) (b)

Fig. 7. Acid resistance test. (a) Acid resistance test. (b) Effect before and after acid resistance test

Table 7. Test results for the acid resistance of the coating

Immersion time	**Coating content (kg/m^2)**	**Acid resistance**
48 h	0.5	Coating integrity, without color change, peeling, and mild bubbling
	0.7	Coating integrity, without color change, peeling, and mild bubbling
	0.9	Coating integrity, without color change, peeling, and mild bubbling

4.3 Analysis of skid resistance

The significant relationship between coating content and pavement skid resistance is highlighted in Table 8 and Fig. 8. As the coating content increased from 0 kg/m^2 to 1 kg/m^2, the mean swing value obviously declined from 72 to 39. Although increasing coating content could relieve the chromatic aberration of pavement to some extent, it exerted negative effects on the skid resistance of pavement. With the increase in coating content, the skid resistance of pavement decreased gradually. The swing value of the surface coating decreased to 49 when the coating content was set to 0.2 kg/m^2. Although the skid performance of specimens fluctuated greatly because of the coating, it still met the basic standards of BPN≥45. The reasons were analyzed as follows. On the one hand, the coating could not cover all microvoids of the pavement when the coating content was low, resulting in limited influences on the texture depth of the pavement. On the other hand, TiO_2 fillers that adhered to the coating surface increased the friction coefficient of the surface, thus enhancing the skid resistance. However, the

skid resistance was approximate to or lower than the standard requirements when the coating content reached 0.4 kg/m^2 or higher. With the further increase in coating content, the skid resistance decreased quickly, failing to meet the standard requirements of BPN≥45

Table 8. Test records of the skid resistance of pavement using a pendulum tester

Basic information	Instrument model			Weather type	Air temperature (°C)		Humidity (%)
	BM-III type			Sunny	25		50
Coating dosage (kg/m^2)	Swing value/BPN			Average swing value/BPN	Temperature under wet state of the specimen surface (°C)	Temperature correction value	Swing value at the standard temperature of 20 °C
0	69	71	70	70	25	+2	72
0.2	48	47	46	47	25	+2	49
0.4	44	42	43	43	25	+2	45
0.6	42	42	42	42	25	+2	44
0.8	42	41	40	41	25	+2	43
1.0	40	41	39	40	25	+2	42
1.2	39	37	38	38	25	+2	40
1.4	37	36	38	37	25	+2	39

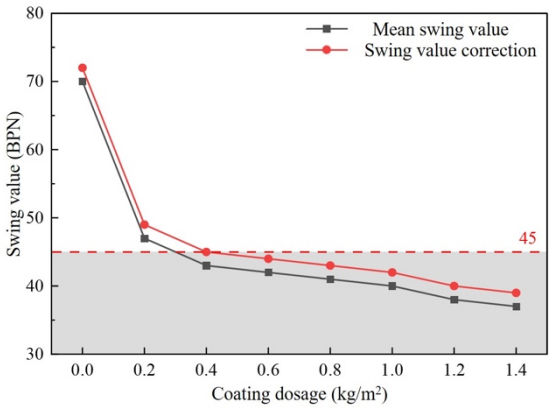


Fig. 8. Variation curve of swing value with coating dosage.

4.4 Wear resistance analysis

Based on the analysis of Table 9 and Fig. 9, the following conclusions can be drawn:

(1) Effects of different coating content on wear loss

Group A: No coating treatment was applied to the original track plate specimens, resulting in a wear loss of 1.6 g/m^2. This condition provided a benchmark for comparing wear loss changes after coating.

Group B + Group C: The coating content in both groups of specimens was 0.5 kg/m^2. The wear losses of these two groups were 1.1 and 0.9 g/m^2, lower than those of the original track plate specimens. Thus, the PU-based coating could effectively reduce wear loss, and the skid resistance was enhanced with the addition of paints.

Groups $D_1/D_2/D_3$: In the three groups of specimens, the basic coating content was 0.5 kg/m^2, and all specimens were reinforced with different amounts of carborundum (0.2, 0.3, and 0.4 kg/m^2). The results indicated that the wear loss increased from 3.1 g/m^2 to 4.4 g/m^2. As carborundum content increased, wear loss also increased.

(2) Effects of wear loss on the skid performance of the coating

Group B + Group C: The swing value decreased to less than that of Group A. This result proved that the combination of these materials could not only provide an essential pavement beautification effect but could also maintain good skid resistance and abrasion resistance.

Groups $D_1/D_2/D_3$: With the increase in carborundum content, the swing value increased, indicating that adding carborundum improved the initial skid resistance of the coating effectively. However, the wear loss of these combinations increased accordingly. That is, adding carborundum increased the wear loss of the coating, although it increased the initial skid resistance of the coating. In other words, the initial skid resistance of the coating was increased at some cost of abrasive performance. Hence, the appropriate balance between skid resistance and abrasion resistance shall be ensured during design and choice of coating materials. Finally, the optimal carborundum content was found to be 0.3 kg/m^2.

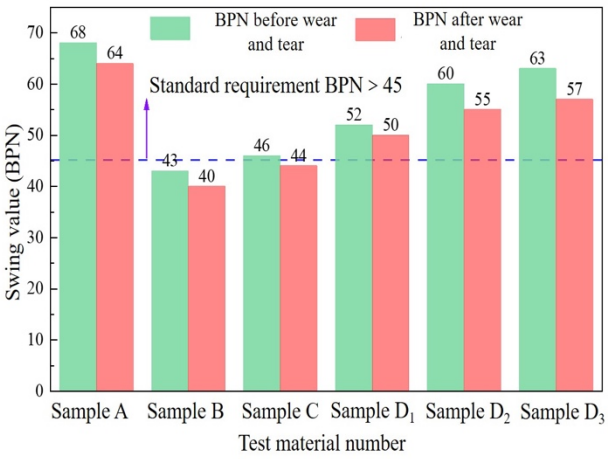


Fig. 9. Swing value after the wear resistance test of different material combinations.

Table 9. Mass loss of different material combinations

Number	Material type	Brushing quantity (kg/m^2)	PrewearG$_0$ (g)	PostwearG$_1$ (g)	Wear loss (g/m^2)	Swing value/BPN	
						Pre-wear	Post-wear
A	Original rutted plate specimen	-	200	198.4	1.6	68	64
B	PU-based liquid coating	0.5	202	200.9	1.1	43	40
C	PU-based fluid + pigment	0.5	202	201.1	0.9	46	44
D_1	PU-based liquid + pigment + 0.2 carborundum	0.5	205	201.9	3.1	52	50
D_2	PU-based liquid + pigment + 0.3 carborundum	0.5	206	202.5	3.5	60	55
D_3	PU-based liquid + pigment + 0.4 carborundum	0.5	207	202.6	4.4	63	57

5. Conclusions

To prepare a beautifying coating that alleviates chromatic aberration after asphalt pavement installation, this study formulated a coating using WPU as the base liquid with added color paste and fillers. The microstructure of the coating materials, as well as the durability, skid resistance, and abrasion resistance of the coating, were tested. The following major conclusions can be drawn as followings:

(1) The microstructure of the WPU dispersing liquid and the characteristic peaks of its functional groups were thoroughly analyzed by infrared spectral test, which confirmed the accuracy of the synthesis results. DTG and DSC were conducted with dry coating materials to explore the thermostability and glass transition temperature of the WPU dispersing liquid. The results indicated that the PU dispersing liquid did not undergo phase changes at room temperature, meeting the requirements for practical applications.

(2) For enhancing the performance of pavement coating, the skid resistance of the coating must be optimized while maintaining a reasonable interval of coating content. An appropriate balance must be kept between skid resistance and abrasion resistance during the design and choice of coating materials. In this study, the optimal carborundum content was determined to be 0.3 kg/m^2. The WPU coating could keep a good appearance and exhibited good durability after immersion in water, acid, and alkaline solutions.

(3) The prepared WPU chromatic aberration repair coating showed good pavement performance. It could relieve the chromatic aberration of asphalt pavement effectively and keep its colors, thus enabling improved driving safety of drivers and pavement beauty.

In analyzing the pavement performance of the prepared coating, limited by practical traffic conditions, the WPU coating was applied to Marshall specimens to test water resistance. The prepared Marshall specimens may require further optimization. Hence, an extensive study on the durability of the WPU coating on real pavement is necessary, which will provide deeper insights into pavement performance.

References

[1] H. Singh and A. Kathuria, "Analyzing driver behavior under naturalistic driving conditions: A review," *Accid. Anal. Prev.*, vol. 150, Feb. 2021, Art. no. 105908, doi: 10.1016/j.aap.2020.105908.

[2] V. Van-Huy, N. Hoang-Tung, and H. Kubota, "Effects of mixed traffic flow and time pressure on violated driving behaviors of bus drivers," *Ergonomics*, vol. 67, no. 12, pp. 1958-1979, Jun. 2024.

[3] K. Bucsuházy, E. Matuchová, R. Zůvala, P. Moravcová, M. Kostíková, and R. Mikulec, "Human factors contributing to the road traffic accident occurrence," *Transp. Res. Proc*., vol. 45, pp. 555-561, Jan. 2020, doi: 10.1016/j.trpro.2020.03.057.

[4] Y. Wang and W. Zhang, "Analysis of roadway and environmental factors affecting traffic crash severities," *Transp. Res. Proc*., vol. 25, pp. 2119-2125, Apr. 2017, doi: 10.1016/j.trpro.2017.05.407.

[5] X. Zhang, R. Chang, X. Sui, and Y. Li, "Influences of emotion on driving decisions at different risk levels: An eye movement study," *Front. Psychol*., vol. 13, Feb. 2022, Art. no. 788712, doi: 10.3389/FPSYG.2022.788712.

[6] S. Kocak and S. W. Haider, "Performance and cost evaluations of 100% recycled hot asphalt mixtures for pothole patching applications in flexible pavements," *Constr. Build. Mater*., vol. 392, Jun. 2023, Art. no. 131921, doi: 10.1016/J.CONBUILDMAT.2023.131921.

[7] S. Wang *et al*., "Dynamic behavior of crack sealant bonding interface in the asphalt pavement crack repair structure under moving vehicle load," *Case. Stud. Constr. Mat*., vol. 18, Jan. 2023, Art. no. e01821, doi: 10.1016/J.CSCM.2022.E01821.

[8] X. Chen and H. Wang, "Asphalt pavement pothole repair with recycled material and preheating: Laboratory and field evaluation," *J. Cleaner, Prod*., vol. 434, Jan. 2024, Art. no. 140410, doi: 10.1016/J.JCLEPRO.2023.140410.

[9] T. Wang *et al*., "Advanced cold patching materials (CPMs) for asphalt pavement pothole rehabilitation: State of the art," *J. Cleaner Prod*., vol. 366, Jul. 2022, Art. no. 133001, doi: 10.1016/J.JCLEPRO.2022.133001.

[10] T. M. Phan, J. H. Kim, H. J. Kim, and D. W. Park, "Automated repair of asphalt pavement cracks and potholes utilizing 3D printing and LiDAR scanning," *Constr. Build. Mater.*, vol. 450, Oct. 2024, Art. no. 138748, doi: 10.1016/J.CONBUILDMAT.2024.138748.

[11] X. Chen, H. Wang, and G. Venkiteela, "Asphalt pavement pothole repair using the pre-heating method: An integrated experiment and modeling study," *Transp. Res. Rec.*, vol. 2677, no. 11, pp. 1-12, Nov. 2023.

[12] W. Huang, S. M. Liang, and Y. Wei, "Surface deflection-based reliability analysis of asphalt pavement design," *Sci. China: Technol. Sci*., vol. 63, no. 9, pp. 1824-1836, Jan. 2020.

[13] X. Du *et al*., "A novel polyurethane coating with triple functions: Superhydrophobicity, self-healing and electroconductibility," *Surf. Interfaces*, vol. 55, Nov. 2024, Art. no. 105451, doi: 10.1016/J.SURFIN.2024.105451.

[14] X. Chen, H. Li, and G. Wang, "Exploring the chemical permeation resistance and surface adsorption properties of polyurethane coatings," *Langmuir*, vol. 40, no. 49, pp. 26274-26282, Nov. 2024.

[15] X. Yuan *et al*., "A novel $Ti_3C_2T_x$-PANI composite polyurethane coating with dual corrosion resistance and noise reduction functionality," *Prog. Org. Coat.*, vol. 197, Oct. 2024, Art. no. 108860, doi: 10.1016/J.PORGCOAT.2024.108860.

[16] E. Bakhshandeh, S. Sobhani, R. Jafari, and G. Momen, "From theory to application: Innovative ice-phobic polyurethane coatings by studying material parameters, mechanical insights, and additives," *Surf. Interfaces*, vol. 51, Jun. 2024, Art. no. 104545, doi: 10.1016/J.SURFIN.2024.104545.

[17] Z. Sui, Y. Li, Z. Guo, Q. Zhang, Y. Xu, and X. Zhao, "Preparation and properties of polysiloxane modified fluorine-containing waterborne polyurethane emulsion," *Prog. Org. Coat.*, vol. 166, Mar. 2022, Art. no. 106783, doi: 10.1016/J.PORGCOAT.2022.106783.

[18] Y. Lai, Y. Qian, D. Yang, X. Qiu, and M. Zhou, "Preparation and performance of lignin-based waterborne polyurethane emulsion," *Ind. Crops Prod.*, vol. 170, Jul. 2021, Art. no. 113739, doi: 10.1016/J.INDCROP.2021.113739.

[19] X. Yang *et al*., "Mechanical properties, luminescent properties, and durability of solvent-free polyurethane-based phosphorescent road markings on asphalt pavements," *Constr. Build. Mater*., vol. 414, Jan. 2024, Art. no. 135053, doi: 10.1016/J.CONBUILDMAT.2024.135053.

[20] C. Miao *et al*., "A super-cooling solar reflective coating with waterborne polyurethane for asphalt pavement," *Prog. Org. Coat.*, vol. 165, Mar. 2022, Art. no. 106741, doi: 10.1016/J.PORGCOAT.2022.106741.

[21] D. Cantero, E. Pinilla-Penalver, A. Romero, and L. Sánchez-Silva, "Synthesis of waterborne polyurethane aerogels-like materials via freeze-drying: an innovative approach," *J. Mater. Sci*., vol. 58, no. 21, pp. 9087-9102, May. 2023.

[22] M. Špírková, J. Hodan, J. Kredatusová, R. Poręba, M. Uchman, and M. Serkis-Rodzeń, "Functional properties of films based on novel waterborne polyurethane dispersions prepared without a chain-extension step," *Prog. Org. Coat.*, vol. 123, pp. 53-62, Oct. 2018, doi: 10.1016/j.porgcoat.2018.06.014.

[23] Y. Mochiduki, N. Yoshikura, M. Enomoto, S. Tokino, K. Shirai, and M. Kobayashi, "Non-staining resistance to dyes and odors of synthetic leathers composed of polyurethane resins with different glass transition temperatures," *Text. Res. J.*, vol. 94, no. 21-22, pp. 2457-2466, Nov. 2024.