Long-Term Durability of Asphalt Shingle Roof Covers: Laboratory Degradation Characteristics

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Abstract. Asphalt shingles are the most common steep-slope roofing material used in the United States, due to their ease of installation and cost effectiveness. When installed in accordance with the manufacturer's recommendations, new shingles effectively prevent bulk water intrusion into the underlying components of the roof assembly and building enclosure by shedding water off the roof. During their service life, asphalt shingles may be subjected to various weather conditions such as extreme heat, thermal cycling, ultraviolet (UV) radiation, and freeze-thaw events, as well as direct mechanical loads such as wind-induced uplift forces and hail impact forces associated with thunderstorms. Published literature indicates that the ability of asphalt shingles to withstand direct mechanical loads may be compromised after weathering, therefore emphasizing the importance of assessing the effects of these conditions on their performance. This publication presents the laboratory observations of asphalt shingle roof coverings when subjected to UV radiation and various combinations of temperature and relative humidity. Characteristics such as discoloration, changes to mechanical properties, and chemical changes to the adhesive strip are discussed, in addition to the tests and spectroscopy tools used to quantify the changes due to accelerated laboratory weathering.

Keywords: Asphalt Shingles, Roof Cover, Laboratory Weathering, Roofing.

1 Introduction

Many post-hurricane field studies have noted significant losses to asphalt shingle roof coverings [1-11]. Some studies have noted that older asphalt shingle roofs exhibited a greater loss of shingles when compared to newer asphalt shingle roofs [1,3,4,6,8-11]. One of the studies [8] evaluated the wind damage mechanism of asphalt shingles, stating that the asphalt-based adhesive strip installed to adhere overlapping rows of shingles, and the distance from the adhesive strip to the leading edge of the shingle, are both critical parameters in resisting wind-induced uplift forces. They noted asphalt shingle roofs showed poor shingle adhesion and suggested this was due to the long-term weathering of the shingles which might have caused the adhesive strip to deteriorate. The study by Dixon et al. [6] also noted fully or partially unsealed shingles on in-service roofs. The effects of environmental conditions and outdoor weathering on roofing materials have been discussed by Berdhal et al. [12], who addressed the impacts of ultraviolet (UV) radiation, wind, rain, hail, snow, temperature fluctuations, and airborne pollutants. The authors emphasized the role of UV exposure in initiating the photodegradation process, ultimately leading to the oxidation of asphalt shingles. The contribution of humidity and elevated temperatures in accelerating the chemical reactions that lead to photodegradation were also discussed and considered by the authors as additional factors that increased the brittleness of asphalt shingles.

Accelerated laboratory weathering has been used to mimic the outdoor weathering of asphalt shingles, as reported by Terrenzio et al. [10], who compared metrics such as tensile strength, flexural strength, and molecular weight after weathering. Specimens were aged in a dark oven at 70 °C for one week. Using diffusion theory and comparing the laboratory samples to samples exposed outdoors in Houston, Minneapolis, and Philadelphia, the authors concluded that accelerated laboratory weathering resulted in similar behavior changes.

Identifying the exact chemical changes corresponding to specific laboratory weathering conditions might assist in increasing the longevity of the asphalt shingle products. This paper discusses the viability of pairing chemical characterization with accelerated laboratory weathering protocols to determine effects on asphalt shingles and the asphalt-based adhesive strip. As an applied example, attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) scans of a commercially available adhesive strip before and after laboratory weathering is presented, revealing the chemical changes that occur during weathering. The initial ATR-FTIR results are promising; however, further research is required to identify the changes resulting from multiple weathering conditions.

2 Common Asphalt Shingle Configurations

Commercially available asphalt shingles are constructed with four main components:

1- A chopped strand glass-fiber mat
2- Liquid applied asphalt
3- Mineral granules
4- Asphalt-based adhesive strip

The liquid applied asphalt is used to saturate the chopped strand glass-fiber mat, creating a water-resistant coating that can shed bulk water. It also provides an adhesive medium for the mineral granules which are scattered across the top surface of the saturated glass-fiber mat to protect the asphalt layer from UV exposure. The asphalt-based adhesive strip resists wind-induced uplift forces by adhering the leading edge of overlapping rows of shingles.

Fig. 1 presents representative three-tab and architectural asphalt shingles. Fig. 1 (a) shows the top surface of a three-tab shingle with the adhesive strip on top of the surface granules. The top surface of an architectural shingle is presented in Fig. 1 (b), but in this case, the adhesive strip is applied to the bottom surface of the architectural shingle, as shown in Fig. 1 (c).

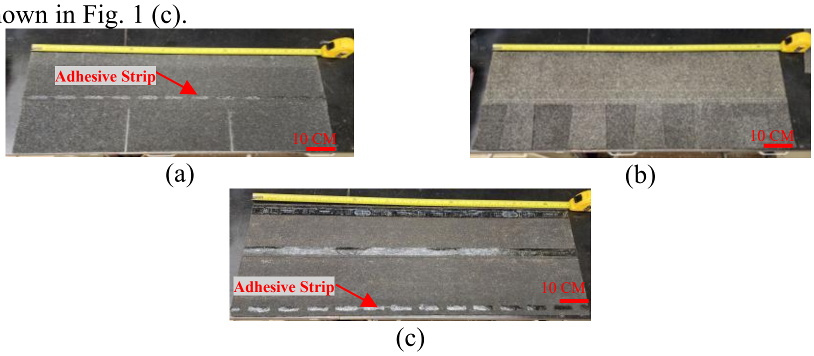


Fig. 1. (a) Top surface for a three-tab shingle. (b) Top surface for an architectural shingle. (c) Bottom surface for an architectural shingle.

3 Laboratory Weathering Protocols and Observations

3.1 Laboratory Weathering Protocols and Devices

The objective of laboratory accelerated weathering protocols is to subject laboratory specimens to outdoor conditions in a controlled manner. Conditions such as ultraviolet radiation (UV), elevated temperatures, drying and saturation cycles, rainfall, and biological build up are discussed in published weathering standards, with the primary objective of obtaining a unified weathering procedure, rather than precisely replicating outdoor weathering conditions. **Table 1** presents current ASTM weathering standards that are applicable to asphalt shingles.

Table 1. ASTM Laboratory Weathering Standards that May be Applied to Asphalt Shingles

Standard ID	**Name**
ASTM G151 – 19 [14]	Exposing Nonmetallic Materials in Accelerated Test Devices that use Laboratory Light Sources.
ASTM D4798 [15]	Accelerated Weathering Test Conditions and Procedures for Bituminous Materials (Xenon-Arc Method).
ASTM D4799 [16]	Accelerated Weathering Test Conditions and Procedures for Bituminous Materials (Fluorescent UV, Water Spray, and Condensation Method).
ASTM D7897 [17]	Laboratory Soiling and Weathering of Roofing Materials to Simulate Effects of Natural Exposure on Solar Reflectance and Thermal Emittance.

ASTM D4798 [15] and ASTM D4799 [16] describe several laboratory weathering cycles that may be applied to asphalt shingles. One key difference between the two standards is the UV light source, as ASTM D4798 [15] requires a xenon-arc exposure, while ASTM D4799 [16] specifies a florescent UV light source. Furthermore, cycle B of ASTM D4798 [15] includes a cooling step which is conducted after completion of the weathering protocol, while ASTM D4799 [16] does not incorporate a cooling step. Table 2 presents the two cycles described in ASTM D4798 [15] that are designed to be conducted in increments of 24-hours. Both standards require the use of a device that capable of spraying water during the test, while ASTM D4798 [15] specifies a water temperature of 7.2 °C ± 2.5 °C.

Table 2. ASTM D4798 Weathering Cycles

<table>
<tr><th>Cycle</th><th>Step #1 – UV</th><th colspan="4">Step #2 – Spray and UV</th></tr>
<tr><td>A-1</td><td rowspan="2">51 min at 60 °C ± 2.5 °C</td><td colspan="4">9 min front</td></tr>
<tr><td>A-2</td><td colspan="4">9 min front and back</td></tr>
<tr><th>Cycle</th><th>Step #1 – Spray and UV</th><th>Step #2 – UV</th><th>Step #3 – Spray and UV</th><th>Step #4 – UV</th><th>Step #5</th></tr>
<tr><td>B-1</td><td>60 min front</td><td rowspan="2">90 min at 60 °C ± 2.5 °C</td><td>120 min front</td><td rowspan="2">990 min at 60 °C ± 2.5 °C</td><td rowspan="2">180 min at -18 °C ± 5.0 °C</td></tr>
<tr><td>B-2</td><td>60 min front and back</td><td>120 min front and back</td></tr>
</table>

ASTM D4799 [16] specifies six weathering cycles that vary in the intensity of UV exposure and the presence of water spray. However, the condensation duration and temperature are approximately constant throughout the six weathering cycles. Table 3 presents a summary for the six weathering cycles.

Table 3. ASTM D4799 [16] Weathering Cycles

Cycle	Step #1 – UV	Step #2 – Spray	Step #3 - Condensation
A	4h at 60 °C ± 2.5 °C	-	4h at 50 °C ± 2.5 °C
B	20h at 60 °C ± 2.5 °C	-	4h at 50 °C ± 2.5 °C
C	20h at 80 °C ± 2.5 °C	-	4h at 50 °C ± 2.5 °C
D	4h at 60 °C ± 2.5 °C	15 min	3.75h at 50 °C ± 2.5 °C
E	20h at 60 °C ± 2.5 °C	15 min	3.75h at 50 °C ± 2.5 °C
F	20h at 80 °C ± 2.5 °C	15 min	3.75h at 50 °C ± 2.5 °C

The choice of weathering cycle determines the appropriate weathering device. Weathering cycles specifying a duration of water-spray must be conducted in a device capable of producing a uniform water spray for a duration of 15 min, throughout the length of the weathering protocol. Fig. 2 presents an example for two available laboratory weathering devices, where Fig. 2 (a) shows NIST's custom Simulated Photodegradation via High Energy Radiant Exposure (SPHERE) [18] device which is capable of precisely controlling humidity and temperature while exposing specimens to high-irradiance UV radiation, rapidly accelerating the weathering process. A commercially available accelerated weathering tester is presented in Fig. 2 (b). Using eight UVA 340 fluorescent lamps, the QUV device exposes specimens to ultraviolet radiation while controlling temperature. Separate condensation cycles can be conducted at a specified condensation temperature, in addition to water spray cycles.

(a) (b)

Fig. 2. (a) NIST's SPHERE. (b) Commercial* Laboratory Accelerated Weathering device. **Disclaimer: Certain commercial products or equipment are described in this paper to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that it is necessarily the best available for the purpose.*

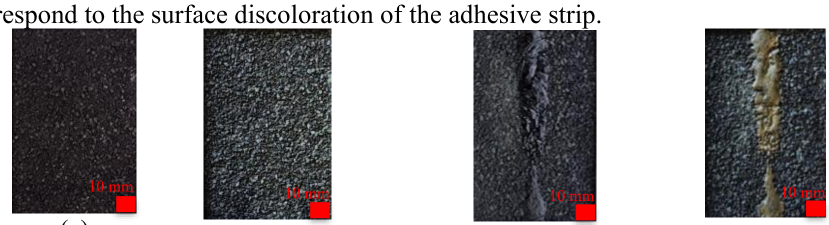
To investigate the effect of laboratory weathering on asphalt shingles, pilot asphalt shingle and asphalt-based adhesive specimens sourced from a commercially available asphalt shingle were subjected to 4h of condensation at 55 °C ± 2 °C followed by UV exposure at 45 °C ± 2 °C for one week in a commercial accelerated weathering device. At locations where the mineral granules are absent due to granule loss or between neighboring granules, the liquid applied asphalt material is exposed to UV radiation. Due to the mineral granules, assessing the effect of UV exposure on the liquid applied asphalt material used to saturate the glass fiber mat using ATR-FTIR is challenging. Considering that the asphalt-based adhesive presents a similar composition to the liquid applied asphalt saturant, the asphalt adhesive was exposed to UV radiation in the pilot study to assess the chemical changes that may occur to the liquid applied asphalt material used to saturate the glass fiber mat. This represents a worst-case scenario which may occur if an asphalt shingle losses a significant amount of neighboring mineral granules leading to the exposure of the liquid applied asphalt saturant to UV radiation. When asphalt shingles are properly installed, the adhesive strip is shieled from UV radiation. An ATR-FTIR device was used to examine the asphalt-based adhesive before and after weathering. The initial observations of the pilot laboratory weathering study are presented in the following section. A parallel study is underway to assess the chemical and mechanical changes that may occur to asphalt shingles and asphalt-based adhesives due to thermal weathering only, as prolonged exposure to elevated temperatures may accelerate the chemical reactions occurring due to environmental weathering.

Accelerated Laboratory Weathering Observations

Accelerated laboratory weathering may produce cosmetic changes to asphalt shingles and the asphalt-based adhesive strip, often appearing in the form of discoloration, which indicates chemical changes may have occurred. Preliminary discoloration observations to an asphalt shingle and an asphalt-based adhesive strip are presented below as non-exhaustive examples for the possible discoloration.

Discoloration – Asphalt Shingle and Asphalt-Based Adhesive Strip

Fig. 3 (a) and Fig. 3 (b) present images for an asphalt shingle specimen prior to and after laboratory weathering. Fig. 3 (b) shows the lighter appearance for the asphalt shingle which may be caused by photobleaching of the surface due UV exposure, or possibly mineral deposits from the condensation cycles. Fig. 3 (c) and Fig. 3 (d) present an asphalt-based adhesive strip before and after laboratory weathering using a commercial weathering device and show discoloration of the adhesive strip after weathering. FTIR measurements presented later in this section demonstrate chemical changes that correspond to the surface discoloration of the adhesive strip.

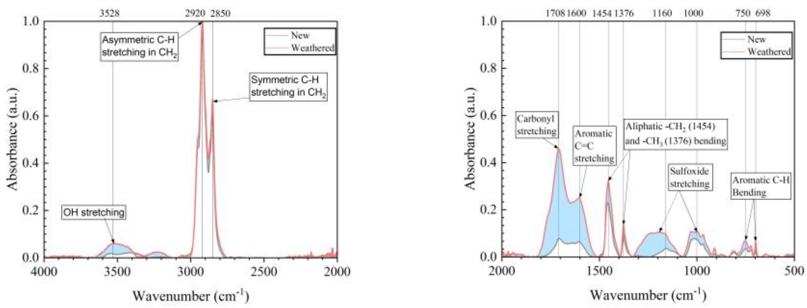


(a) (b) (c) (d)

Fig. 3. (a) Shingle before laboratory weathering. (b) Shingle after laboratory weathering. (c) Adhesive strip before laboratory weathering. (d) Adhesive strip after laboratory weathering.

Chemical Changes – Asphalt-Based Adhesive Strip

Mechanical tests such as tension tests, tear tests, and nail pull-through tests are commonly conducted after laboratory weathering to quantify possible changes to mechanical properties of materials. In the case of shingles, the mechanical changes are due to chemical changes occurring in the materials used to construct the asphalt shingles and asphalt-based adhesive. Understanding the chemical changes is necessary to obtain a complete perspective on the effect of specific weathering conditions on the chemical and mechanical performance of the asphalt shingles. As an applied example, initial ATR-FTIR scans were conducted on the asphalt-based adhesive strip presented in Fig. 3 (c) and Fig. 3 (d) and are shown in Fig. 4 by the full spectrum analysis. Fig. 4 (b) shows the oxidation of the asphalt-based adhesive strip, characterized by an increase in the intensities of the sulfoxide functional group at 1000 cm^{-1} the sulfone functional group at 1160 cm^{-1}, and the carbonyl stretching at the 1708 cm^{-1}.



(a) (b)

Fig. 4. (a) ATR-FTIR absorbance spectra between 2000 cm^{-1} and 4000 cm^{-1} for the adhesive strip before and after laboratory weathering presented in Fig. 3. (b) ATR-FTIR absorbance spectra between 500 cm^{-1} and 2000 cm^{-1} for the adhesive strip before and after laboratory weathering presented in Fig. 3.

4 Discussion

The chemical changes occurring to asphalt shingles due to outdoor weathering may negatively impact their physical and mechanical properties, leading to a reduction in the service life for an asphalt shingle, or a higher likelihood of damage in high wind events. Assessing the level of discoloration provides some insight on the level of weathering and provides a basis for comparison between specimens. Current weathering protocols do not isolate various weathering conditions, and weathering cycles can contain two or more conditions conducted in series which creates a challenge in identifying the contribution of each condition to the overall chemical changes that occur due to weathering. To understand the change in mechanical performance due to a specific weathering condition, the chemical degradation must be captured. Previous literature has paired accelerated laboratory weathering with mechanical characterization techniques such as tensile tests, tear tests, nail pull-through tests, peel adhesion tests, and a limited number of studies incorporated chemical characterization techniques such as ATR-FTIR spectroscopy. Based on the initial findings of the pilot study, this paper suggests that chemical characterization can be used to understand changes to materials that undergo current and future weathering practices. ATR-FTIR was successful in measuring the chemical changes that occurred in an asphalt-based adhesive resulting from accelerated weathering on the pilot specimens. In the future, NIST's SPHERE [18] could be utilized to expose asphalt shingles and asphalt-based adhesives to individual or combined weathering conditions including different levels of relative humidity, UV exposure, and specimen temperature, thus allowing for the development of relationships between the chemical and mechanical changes occurring during those specific, isolated weathering events.

5 Summary

Detailed experimental research is required to investigate the effect of chemical changes caused by UV and other weathering factors on asphalt shingles, which may explain why they are commonly damaged in high wind events, including those below design level. Further insight is needed to understand the combined and individual effects of heat and humidity on asphalt shingle performance. In addition to ATR-FTIR, complementary techniques are required to capture the chemical changes occurring throughout the degradation process of asphalt shingles, enabling the correlation of chemical changes with changes in mechanical characteristics and overall performance.

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