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Long-Term Aging of Recycled Asphalt Pavements: The Influence of Meteorological Conditions on Bitumen Properties Over 16 Years

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Abstract: The reuse of Reclaimed Asphalt Pavement (RAP) in road construction has become increasingly prevalent due to its potential environmental and economic benefits. The aging characteristics of RAP, particularly the degradation of its bitumen content, are critical for evaluating its suitability for future applications. The aging process is influenced by various meteorological factors, including solar radiation, temperature fluctuations, and precipitation. This study investigates the impact of these factors on the properties of bitumen in RAP, focusing on a pavement constructed between 2002 and 2005. After eight years of service, the pavement was milled and the material was stored in a stockpile for an additional eight years. The bitumen properties, specifically penetration and softening point, were measured at regular intervals over the 16-year period. Cumulative meteorological data, including temperature, solar radiation, and precipitation, were recorded and analysed in relation to the observed aging effects on the bitumen. The results demonstrated a linear correlation between the cumulative meteorological conditions and the degree of bitumen aging. Increased exposure to solar radiation and temperature fluctuations accelerated the aging process, while prolonged periods of precipitation appeared to have a moderating effect. These findings suggest that both the duration and intensity of exposure to specific environmental conditions must be considered when assessing the viability of using RAP in future pavement construction.

Keywords: Reclaimed asphalt pavement (RAP); Bitumen aging; Meteorological factors; Penetration test; Softening point

1 Introduction

Bitumen and aggregate are fundamental components in road construction. While aggregate forms the load-bearing structure [1], bitumen acts as a binder, providing cohesion [2]. Therefore, the rheological properties of bitumen are of critical importance. Traditional materials like basalt [3] and limestone [4] are frequently used in road construction, but the push for sustainability has increased the use of recycled materials such as RAP. Additionally, within the scope of sustainable transportation, the use of waste materials is also prevalent [5–8].

Bitumen is a highly viscous, black liquid essential for road construction [9]. Over time, exposure to weather conditions such as temperature, humidity, ultraviolet (UV) radiation, and air pollutants causes bitumen to age and degrade, leading to a reduction in road performance [10, 11]. The aging process is influenced by oxidation, the volatilization of lighter fractions, and molecular weight changes [12]. Understanding this aging process is crucial for maintaining road infrastructure and prolonging its service life. This study aims to establish a relationship between weather conditions and the aging of bitumen.

Higher temperatures accelerate the aging process, reducing the viscosity of bitumen and increasing its stiffness [12, 13]. This makes bitumen more brittle and susceptible to cracking, which can cause significant damage to road infrastructure. Similarly, humidity can exacerbate bitumen aging by allowing water to penetrate the binder, weakening its strength and cohesion [14]. Additionally, UV radiation from sunlight oxidizes and hardens the surface layer of bitumen, further leading to cracking and brittle behavior [15]. One of the primary concerns regarding asphalt pavements is the aging of asphalt binders, which can lead to significant performance issues such as fatigue cracking and thermal distress. Roy and Hossain [16], emphasize that the aging of asphalt binders is one of the major concerns of highway agencies as it can lead to premature distresses. Song et al. [17] investigated the aging mechanisms of low-grade hard asphalt and found that prolonged exposure to thermal oxygen aging and ultraviolet irradiation significantly diminishes the plasticity of asphalt. Moreover, the effects of meteorological conditions on the performance of asphalt mixtures are not limited to the aging process alone [18]. The incorporation of recycled materials into asphalt mixtures, such as low melting point recycled plastics, has gained traction due to its potential environmental benefits [19]. Additionally, the effects of additives on the aging behavior of asphalt mixtures have been explored [20].

A specific road section, where the pavement layers were milled, has been chosen as the focus of this study. The milled pavement layers were stored for potential reuse in new construction, referred to as RAP material throughout this paper. Information about the location of the road, as well as the basic properties of the aged and unaged bitumen, is provided in the following sections. Meteorological data, including sunshine duration, sun exposure, radiation, and precipitation, were collected from the Turkish State Meteorological Department to assess their effects on bitumen aging. The meteorological data are presented in the third section, and the relationship between these data and bitumen aging is explored in the final section.

2 Source of the Rap Material

The RAP material was obtained from a road between the Bursa province and the Karacabey district. As shown in Figure 1, the total length of the road is approximately 68 km, and the milled section lies between the 6+500 km and 25+000 km points. The bituminous base and binder layers of this road were constructed in 2002, while the wearing layer was completed in 2005. The bitumen used for all three construction layers had a penetration grade of 50/70.

Figure 1. Location of the road section (Map data: Google, TerraMetrics, Mapa GISrael-22.03.2023)

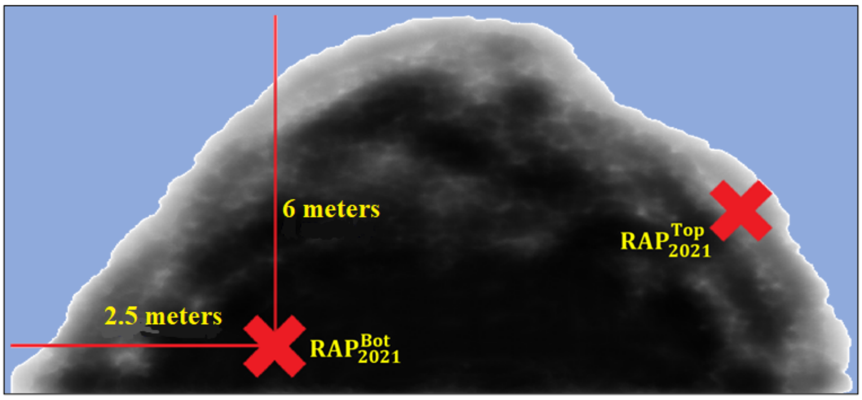

Figure 2. RAP sample locations obtained from the stockpile on 2021 where all three layers are mixed

In 2013, after 11 years of service, the road was milled, and RAP materials from all three layers were stored for eight years in an open field mixed stockpile. Tests were conducted on the RAP material immediately after the milling process in 2013, and again in 2021 after the eight years of storage. To determine the effects of stockpiling on bitumen aging, RAP samples were collected from two different locations within the stockpile: one from the surface and one from deeper within the stockpile, 6 meters deep and 2.5 meters inside (Figure 2). The gradation and bitumen content are detailed in Table 1, with gradation curves for the bituminous base, binder, and wearing layers shown in Figure 3, Figure 4, and Figure 5.

Table 1. RAP extraction test results after milling, 2013

Extraction		Pavement Layers					
		Bituminous Base		Binder		Wearing	
		RAP	Design	RAP	Design	RAP	Design
Sieve Size, mm	37.5	100	98.6	100	100	100	100
	25.4	100	81.7	100	91.7	100	100
	19.0	98.1	73.3	100	86.1	100	100
	12.5	87.2	63.5	93.4	62.3	92.9	91.0
	9.50	75.9	57.6	84.7	57.2	85.4	79.0
	4.75	50.1	39.9	60.8	47.0	62.4	47.0
	2.00	30.2	28.1	36.7	26.9	38.1	32.0
	0.0425	14.9	13.1	16.9	9.0	16.7	14.0
	0.177	10.4	9.4	12.0	5.3	11.7	10.0
	0.075	7.5	4.6	8.8	3.4	8.4	4.0
Bitumen, %		3.62	3.5	4.0	4.3	4.06	4.95

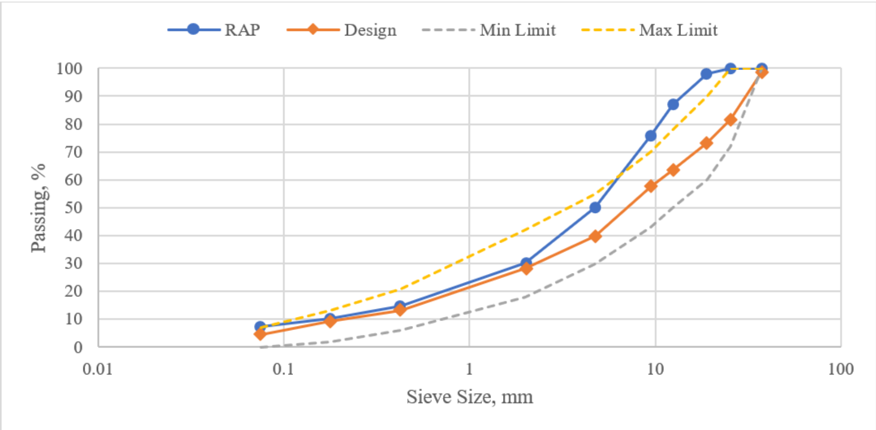

Figure 3. Gradation of RAP material of bituminous base layer and design

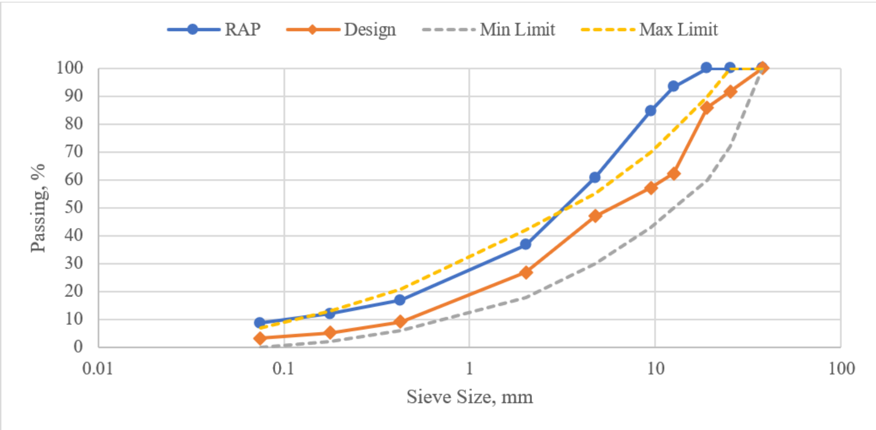

Figure 4. Gradation of RAP material of binder layer and design

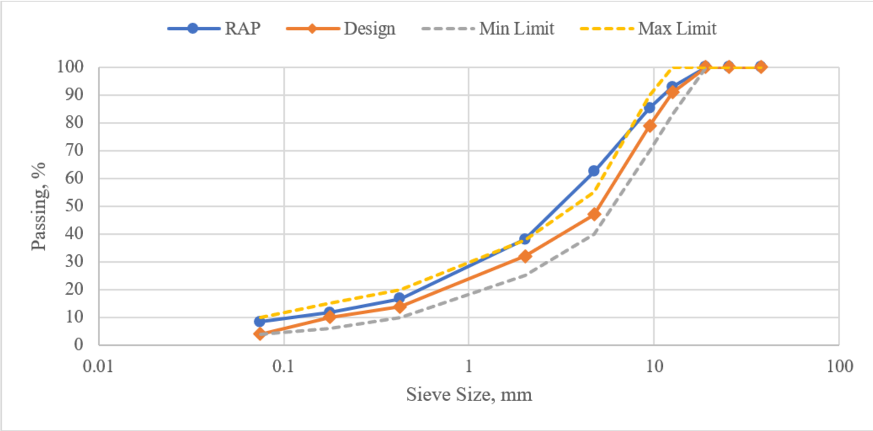

Figure 5. Gradation of RAP material of wearing layer and design

After the road was milled in 2013, the milled asphalt material (RAP) was stored in a homogenized built-up stockpile for eight years. By the end of this period, the gradation of the mixed stockpile and the bitumen content were measured and are shown in Figure 6. The bitumen content was found to be 3.62% and 3.63% by weight for $\mathrm{RAP}_{2021}^{\mathrm{Top}}$ and $\mathrm{RAP}_{2021}^{\mathrm{Bot}}$, respectively. The changes in RAP gradation over time are depicted in Figure 7.

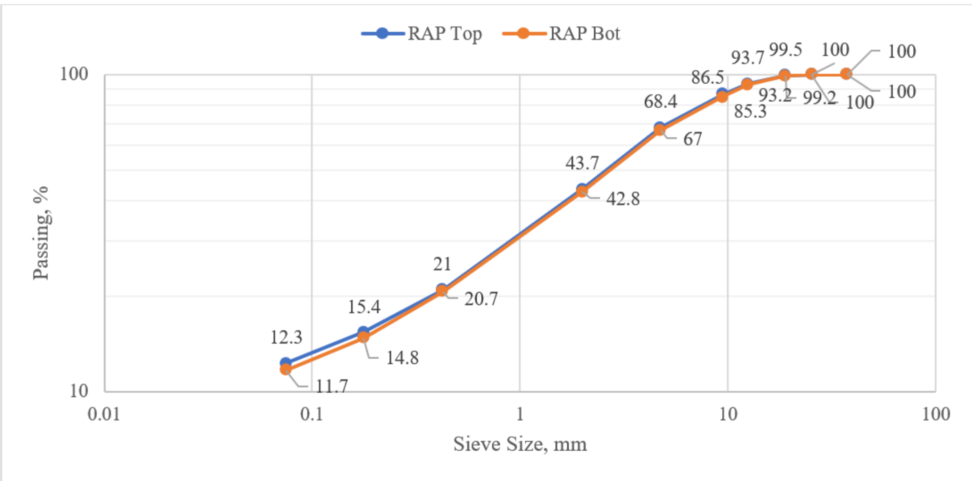

Figure 6. Gradation of mixed RAP material after long-term storing, 2021

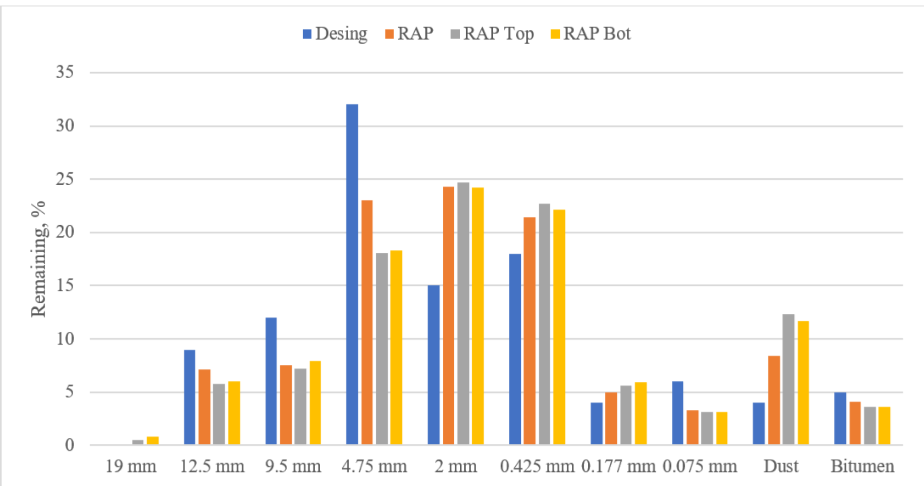

Figure 7. Change on RAP gradation and bitumen content in time

As seen in Figure 7, the bitumen content decreases over time. While the design value was approximately 5%, the long-term stored RAP contains about 3.6% bitumen. Considering the basic bitumen properties, such as penetration and softening point values in 2021, aging makes the bitumen less extractable, possibly contributing to the formation of "black rocks". This decrease occurred over a 16-year period. Additionally, the largest portion of the aggregate was between the 9.5 mm and 4.75 mm sieve sizes. Due to the milling process, the rate of coarse aggregate decreased significantly, while the fine aggregate and dust content increased. One notable observation is the presence of 19 mm-sized aggregates, which were absent in both the design and RAP but appeared in small amounts in $\mathrm{RAP}_{2021}^{\mathrm{Top}}$ and $\mathrm{RAP}_{2021}^{\mathrm{Bot}}$. This can be explained by the fact that the long-stored RAP was a mixture of materials from the bituminous base, binder, and wearing layers. The basic properties of the bitumen are provided in Table 2. Interestingly, the bottom RAP sample aged more than the top sample, despite the expectation that the top sample would experience more aging due to direct sun exposure and higher temperatures. One possible explanation is that the bottom sample was exposed to water for longer, resulting in more frequent freeze-thaw cycles, which could have accelerated the aging process.

Table 2. Basic rheological bitumen test results

Parameter	Neat Bitumen	RAP_{2013}	$\mathrm{RAP}_{2021}^{\mathrm{Top}}$	$\mathrm{RAP}_{2021}^{\mathrm{Bot}}$
Penetration, 0.1 mm @ 25°C	52	30	2	< 2
Softening Point, °C	49.2	62	> 90	#N/A

3 Meteorological Data

Figure 8. Location of the Bursa meteorological station (Map data: Google, TerraMetrics – 22.03.2023)

Table 3. Meteorological data for station 17116 between the years 2005 – 2021

Year	Sunshine Duration (hour)	Sun Exposure $\left(\frac{\mathrm{cal}}{\mathrm{cm}^2}\right)$	Radiation $\left(\frac{\mathrm{kW}\times\mathrm{hour}}{\mathrm{m}^2}\right)$	Precipitation $\left(\mathrm{mm} = \frac{\mathrm{kg}}{\mathrm{cm}^2}\right)$
2005	2136.6	109874.8	1358.3	735
2006	2232	121411.8	1341.8	525.4
2007	2009.4	123415.7	1412.7	602.6
2008	1153	125989.6	1444.5	585.6
2009	1537	117751.7	1346.7	689.4
2010	1861.2	116358.4	1359	1290.4
2011	1939.4	110603.7	720.6	538.2
2012	1771.2	107101.8	241.4	700.4
2013	1356.4	113026.9	1294.8	1266
2014	1663.9	123884.9	1418.9	842.6
2015	1934.3	81781.6	916.1	672.6
2016	2067.4	120430.9	1376.3	672.6
2017	1921.9	117076.8	1294.3	563.8
2018	1691.3	122167.6	1396.7	658.2
2019	2306.9	38532.7	1418.3	435.9
2020	1395.4	132686.3	1441.3	545.2
2021	1706	128399.9	1476.6	681.1

The meteorological data used in this study were obtained from the Turkish State Meteorological Service. The data include sunshine duration (2002–2021), sun exposure (2002–2021), radiation (2005–2021), and precipitation (2005–2021) from the Bursa station (Station number 17116). The location of the meteorological station is shown in Figure 8. The cumulative meteorological values for the years between 2005 and 2021 are presented in Table 3.

4 Relation Between Meteorological Data and Bitumen Aging

Given that there are only three data points for the bitumen—neat bitumen (before milling), RAP immediately after milling (2013), and RAP after long-term storage (2021)—the meteorological data were condensed into two intervals. The yearly data were summed for the years 2005–2012 (first interval) and for the years 2013–2021 (second interval). Figure 9 illustrates the relationship between bitumen penetration, softening point, and meteorological conditions over time.

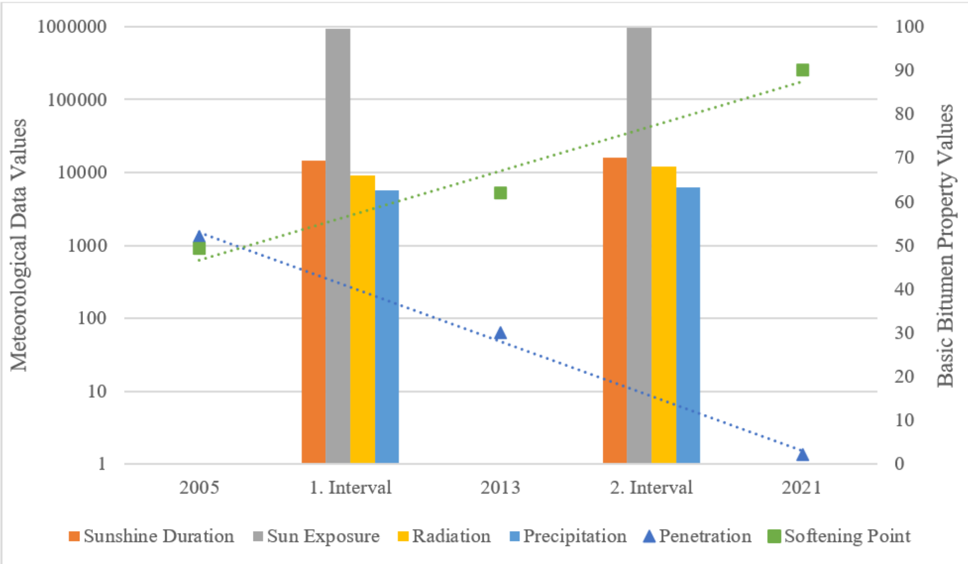

Figure 9. Change on penetration and softening point comparing to meteorological data

This analysis reveals a correlation between the meteorological data and the aging of the bitumen, as indicated by changes in penetration and softening point values. Higher sun exposure, radiation, and precipitation between the two intervals are associated with greater aging of the RAP.

5 Conclusion

This study investigated the effects of meteorological conditions on bitumen aging over time. The meteorological data were divided into two primary intervals, and the penetration and softening point of bitumen were measured at various stages: before usage, after service life, and after long-term storage. The results demonstrated that sunshine duration, sun exposure, radiation, and precipitation increased by approximately 9.5%, 4.8%, 30.4%, and 11.8%, respectively, between the two intervals. The penetration and softening point values also changed linearly with these time frames, highlighting the importance of meteorological data in understanding bitumen aging.

The aging rate of bitumen changes over time, meaning that the rejuvenators required to reuse RAP material will also vary depending on the degree of aging. Future studies should focus on identifying suitable rejuvenators and other measures to counteract the aging process in RAP material for sustainable road construction.

Author Contributions

Conceptualization, S.T. and E.E.; Methodology, S.T., M.S., S.K., E.E. and F.E.; Formal analysis, E.E.; Writing-original draft preparation, E.E. and F.E.; writing-review and editing, S.T., M.S., E.E., F.E., T.D., G.M. and K.E.; visualization, S.K., E.E., F.E. and K.E.; supervision, S.T. and M.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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