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Greener Roads Ahead: Exploring the Benefits of Natural and Recycled Materials in Asphalt Binders

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Abstract

As the global road network development continues to grow at a very fast pace, improved asphalt binder modifier efficiency with reduced environmental impact becomes imperative. The current study explores the development of high-performance asphalt binders and achieving environmental sustainability through the use of natural fibers and waste tires in the form of crumb rubber. The main contribution of the research includes the analysis of the relationships between carbon emissions, energy usage, and economic impacts. Laboratory tests assessed the mechanical properties, flexibility, and viscosity of six asphalt binder modifications, including 3%, 5%, and 7% natural goat hair fibers; 8% goat hair ash; 8% crumb rubber; and 3%NF+5%CR. The most effective combination, 3%NF+5%CR, improved resistance to rutting, fatigue, and thermal cracks while reducing the level of CO₂ emissions during manufacturing by 2.8% (2,073 tons CO₂/yr). With the inclusion of tire recycling credit, net negative lifecycle emissions amount to -93.9 kg CO₂/ton, representing a 136.2 kg CO₂/ton reduction from the neat binder's 42.3 kg CO₂/ton (322% improvement). Multi-criteria TOPSIS approach integrating mechanical properties and life cycle environmental benefits, 8% Rubber Powder and 5% Rubber Powder with 3% Natural Fibers blends outperformed the traditional polymer modifier KTR-103. The blend of 5% Rubber Powder with 3% Natural Fibers obtained the optimal balance (ranked top two for performance and environment). Nationally for Iran (1.75 million tons/year asphalt binder consumption), this corresponds to production-phase CO₂ savings of 2,073 tons/year and lifecycle CO₂ improvement of 238,350 tons/year, with potential recycling of 87,500 tons/year of used tires (35% of all tire waste of Iran). Energy consumption was reduced by 14.6% for goat hair ash. Nevertheless, these findings from laboratory-scale tests require field validation. Natural

26 fiber combined with crumb rubber derived from waste tires provides an environmentally friendly
27 asphalt binder for infrastructure development.

28 Keywords: Asphalt Binders, Environmental Sustainability, Fibers, Kaya Identity, Rheological
29 Properties, High-Performance Materials

30 **1. Introduction**

31 Asphalt pavements are prone to numerous forms of distress that affect their service life and
32 maintenance costs. To address these challenges, scholars have explored modifying asphalt binders
33 with a variety of additives, including recycled and natural materials.

34 **1.1. Asphalt Pavement Distress and the Need for Modification**

35 Asphalt pavements frequently fail under heavy traffic loads and extreme temperature variations,
36 manifesting as rutting, fatigue, and thermal cracking (Azadedel & Solatifar, 2022). Rutting appears
37 within the tire path due to the effects of repetitive loading, particularly in warm weather conditions,
38 because of the low viscosity of the binder, which results in permanent deformation. Thermal cracking
39 is prevalent in cold regions as the asphalt becomes brittle and forms evenly spaced transverse cracks
40 because of thermal contraction. Fatigue cracking originates as longitudinal cracks within the tire
41 tracks and eventually develops into alligator cracking, primarily caused by traffic-related tensile
42 stresses on the bottom of the asphalt pavement (Behnood & Gharehveran, 2019). The rising cost of
43 repairing and renovating damaged pavements has driven extensive investigation to extend service life
44 and enhance resistance to rutting, fatigue, and thermal cracking. As asphalt binders play a vital role
45 in mixture performance, numerous efforts have focused on modifying binder properties with additives
46 (Fini et al., 2012; Arabani & Shabani, 2019) which enables binders to withstand greater stresses
47 before failure and enhances asphalt performance. Natural materials, industrial by-products, waste
48 materials, and engineered products are well-known categories of different modifiers of binders.
49 Reclaimed rubber products, fibers, catalysts, nanomaterials, polymers, and extenders are commonly
50 used (Rusbintardjo et al., 2013; Chen et al., 2023). While polymers are widely known for their higher

51 performance improvement, their petroleum-based origin, high cost, and environmental footprint have
52 motivated the search for sustainable alternatives.

53 **1.2. Environmental Drivers and Waste Management**

54 In line with sustainable development goals, the quick expansion of the transport sector has increased
55 the global footprint of pavements and highlighted the urgency to address associated environmental
56 issues, particularly regarding pollutant emissions and the accumulation of crumb rubber from waste
57 tires (Carpani et al., 2022). Due to high costs and storage requirements, from an environmental point
58 of view, effective management of the growing volume of discarded tires has become a challenge
59 (Presti, 2013; Padhan et al., 2017; Poovaneshvaran et al., 2020).

60 The 3Rs of environmental management: reduce, reuse, and recycle, offer an outline for promoting
61 eco-friendly binder additives in pavement construction. Materials such as crumb rubber from waste
62 tires (Putman & Amirkhanian, 2004), cigarette butts (Tataranni & Sangiorgi, 2021; Ahmadi Dehaghi
63 et al., 2024), and fibers (Guo et al., 2023) have been reported as the additives successfully utilized to
64 enhance asphalt mixture performance while supporting sustainability (Zarei et al., 2020; Rochlani et
65 al., 2022; Carpani et al., 2022).

66 **1.3. Crumb Rubber from Waste Tires**

67 As the rubber from waste materials or by-products has significant recycling value, the use of crumb
68 rubber from waste tires, as a widely used binder additive, is an excellent option to improve the
69 rheological properties of the asphalt binder and mitigate the environmental problems of the
70 transportation sector simultaneously (Hainin et al. 2015; Poovaneshvaran et al., 2020; Guo et al.,
71 2023). Subsequently, in addition to the notable performance benefits of using Crumb Rubber Modifier
72 (CRM) in asphalt, recycling waste tires promotes environmentally friendly material usage, enhancing
73 road sustainability (Milad et al., 2020). Crumb rubber, derived from waste tires (Carpani et al., 2022),
74 has been extensively utilized in the pavement industry as an asphalt modifier for over 50 years. From
75 a solid waste management perspective, waste tires require massive landfill areas and emit hazardous

pollutants during incineration. Using these additives mitigates disposal issues, addressing a major environmental management challenge worldwide. The use of crumb rubber additives in asphalt mixtures, as a high-value recycled material, may provide benefits for both the pavement and the environment. CRM improves mechanical properties by reducing temperature susceptibility (Hainin et al., 2015). Additional benefits include extended service life, enhanced rutting and fatigue resistance, reduced maintenance costs, lower energy consumption, and decreased noise pollution (Adhikari et al., 2000; Li et al., 2009; Mashaan et al., 2011; Guo et al., 2023). Based on existing research evaluating the performance of crumb rubber–modified binders (CRMB), different preparation factors (including mixing time, speed, and temperature), are usually kept constant to assess the effect of varying crumb rubber content. For instance, Azadedel and Solatifar (2022) studied the key factors affecting the viscosity of CRMB. They reported that to achieve optimal viscosity, crumb rubber content at 4% and mixing temperature at 160 °C were the most critical parameters, followed by a mixing speed of 57 Hz and a mixing time of 35 minutes. While neglecting any potential environmental impacts related to CRMB, their study focused primarily on the effect of crumb rubber content on the rheological properties of the modified binder.

1.4. Natural and Animal-Based Fibers

In the same way, as ongoing research in the field of pavement engineering focuses on the exploration of eco-friendly approaches or materials, the use of fibers in paving materials has gained more attention. Natural fibers, derived from raw materials in nature, can be categorized into three main types based on their origin: plant-based, animal-based, and mineral-based (Guo et al., 2023). The lower energy use, cost-effectiveness, renewability, and biodegradability make these fibers a sustainable additive (Abiola et al., 2014). Moreover, their reinforcing properties, low adverse environmental impacts, and availability make them suitable for enhancing the binders and asphalt mixture properties (Arabani & Shabani, 2019). Fiber additives act as reinforcing materials, contributing to improving the mix’s cohesion, reducing reflective or fatigue cracking, and increasing resistance to permanent deformations (Putman & Amirkhanian, 2004). Additionally, fibers can serve

102 as stabilizers, minimizing the drain-down effects in asphalt mixtures, particularly in porous asphalt
103 mixtures that are typically rich in asphalt binders (Ma et al., 2018; Tataranni and Sangiorgi, 2021).
104 In this context, incorporating fibers is akin to adding fine aggregates to the asphalt mixtures (Guo et
105 al., 2023), which additionally helps prevent asphalt bleeding. Overall, the inclusion of fibers can
106 modify the viscoelasticity of asphalt, increase the dynamic modulus and creep compliance, and
107 enhance rutting performance, water stability, freeze-thaw resistance, and cracking resistance (Ye et
108 al., 2008; Su et al., 2019). Yousif et al. (2022) explored the effects of sheep wool on the physical and
109 rheological properties of asphalt binders, demonstrating the remarkable enhancement of rutting
110 resistance, stiffness, and elasticity. Goat hair is an outstanding type of animal-based fiber, being
111 widely available in the Middle East (such as Iraq and Iran) as a waste product connected with meat
112 and dairy production of goats. Goat hair fiber can withstand tensile strength similar to that of sheep's
113 wool (Salehi et al., 2013), making it possible to use it effectively for reinforcement. Moreover, goat
114 hair has been reported as hydrophobic, which makes it better than other fibers in terms of moisture
115 resistance. Despite these advantages, the use of animal-based fiber additives as binder modifiers
116 remains limited due to a knowledge gap. Hence, to pave the way for more sustainable solutions, there
117 is potential room for further investigation of environmentally friendly binder modifications using
118 animal-based fibers.

119 **1.5. Research Gaps and Objectives**

120 A knowledge gap has limited the use of animal-based fiber additives as binder modifiers , despite the
121 mentioned advantages. There has not been any systematic study regarding the use of goat hair as a
122 modifier for asphalt, evaluating effects on performance and determining its environmental impacts
123 when used solely or along with crumb rubber. As such, there is still room for research on
124 environmentally sustainable binder modification through the use of animal fibers.

125 The particular goals of this research work therefore include: (i) to investigate the rheological and
126 mechanical performance of goat hair fibers in modified asphalt binders at different dosage levels; (ii)
127 to determine the effects of goat hair fibers when used in conjunction with crumb rubber; and (iii) to

128 analyze the environmental and economic consequences of using these additives through life cycle
129 assessment and Kaya Identity approach. In addition, the current study contributes towards a number
130 of Sustainable Development Goals set out by the United Nations by creating a sustainable and high-
131 performance asphalt binder. This is because the utilization of goat hair fibers which are agricultural
132 by-products and crumb rubber from waste tires is consistent with SDG 12 (Responsible Consumption
133 and Production). In relation to SDG 9 (Industry, Innovation and Infrastructure), this study makes an
134 improvement on infrastructure because of the increase in pavement performance, while the noise-
135 reduction capacity aligns well with SDG 11 (Sustainable Cities and Communities). Most importantly,
136 the net negative CO₂ lifecycle emissions that have been achieved via tire recycling credits help in
137 meeting SDG 13 (Climate Action).

138 This paper is organized into four sections: Section 2 presents the materials and methods, Section 3
139 discusses the results and environmental impact assessment, and Section 4 concludes with key findings
140 limitations and recommendations.

141 **2. Materials and Methods**

142 Rutting, thermal cracking, and fatigue cracking are among the three main distress affecting the asphalt
143 pavements. Rutting occurs in the wheel path due to traffic load, especially in hot seasons when binder
144 viscosity decreases. As for cold climates where asphalt becomes glassy, thermal cracking is more
145 common due to extreme temperature changes, leading to uniformly spaced cracks. Focusing on traffic
146 load impacts, fatigue cracking starts as longitudinal cracks and progresses to alligator cracking
147 (Behnood & Gharehveran, 2019). Modifying asphalt binders has remarkable effects in enhancing the
148 durability, mechanical strength, and rheological properties of pavements, along with advancing
149 environmental sustainability in the transportation industry. Goat hair and crumb rubber are considered
150 to be evaluated as the asphalt binders' additives in this study. The details are as depicted in Fig. 1.

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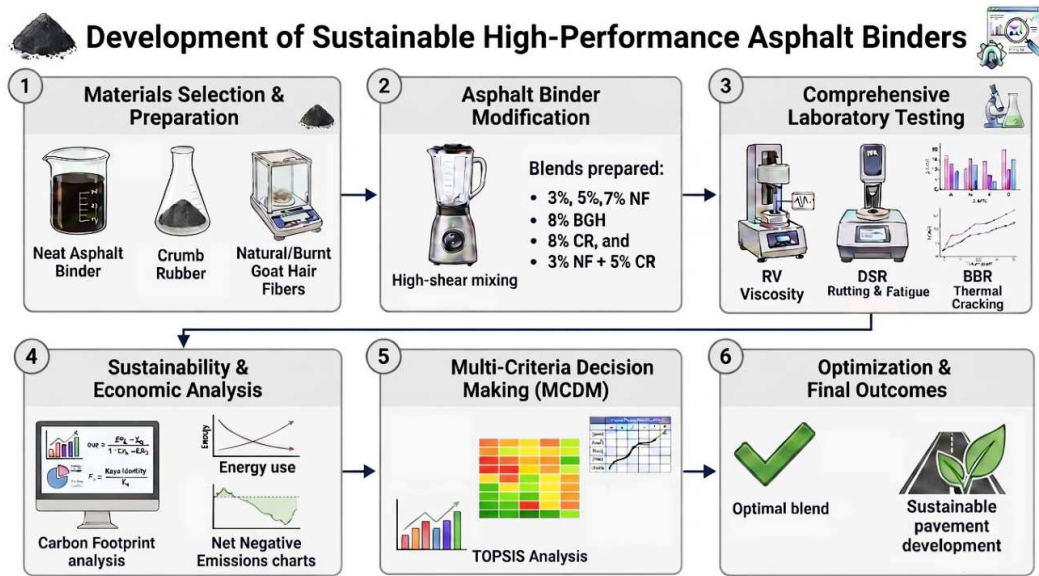


Fig. 1. The flowchart of evaluating natural and recycled materials in sustainable pavement development

2.1. Materials

2.1.1. Base Binder

The base binder (40/50) was selected to assess the rutting, thermal cracking, and fatigue cracking, three main distress mechanisms addressed in this study (as outlined in Section 1.1). The following sections describe the additives and the methods employed to evaluate their effectiveness.

Table 1. Properties of base binder used in this study

Asphalt properties	Specification	40/50
Penetration (0.1 mm)	ASTM-D5	43
Softening point (°C)	ASTM-D36	54.7
Viscosity at 135 °C (cP)	ASTM-D4402	800
Ductility (25 °C, 5 cm/min)	ASTM-D113	>100
Specific gravity (Dmn1)	ASTM-D2024	1.04

2.1.2. Additives

Additives used in this study include goat hair and crumb rubber, which are explained in the following sections.

164 2.1.2.1. Goat Hair Fiber

165 Goat hair is a protein fiber (Table 2), well-known for its strength, and historically used in clothing
166 and weaving. It serves as an additive to mortar to prevent cracking (so-called Saroj). This type of fine
167 animal-based fiber with a second-class use, is abundant in Middle East countries (such as Iran and
168 other regions with similar characteristics). The raw samples of the goat hair were collected through
169 field sampling from the pastoral nomads living in the mountains of Azerbaijan. This was done during
170 the normal activity of herding and shearing goats, in collaboration with local goat farmers practicing
171 the traditional management of livestock. The goat hair used in this study was made up of fibers that
172 had been harvested manually by the herders in the process of their normal hair gathering.

173

174 **Table 2.** Recycled goat hair fiber analysis results as an asphalt binder modifier (Laboratory analysis, Urmia University)

Specification	Result
Color	Gray
Grade	Recycled
Pattern	Raw
Specific gravity	1.5
Moisture regain	0.06 cm ³ /g

175

176 To prepare the additive for laboratory use, a thorough cleaning process was followed by a mechanical
177 crumb phase to preserve the mechanical and chemical properties. For burnt fiber samples, the cleaned
178 fibers were incinerated and the ash was ground to a fine powder.

179 2.1.2.2. Crumb Rubber

180 The rubber products used in this study are mainly waste tires, which are abundant in many developing
181 and developed countries and are not biodegradable. The CR utilized in this study was sieved to a
182 45/50 mesh (sourced from Sadra Co., Iran). The properties of the used CR are listed in Table 3.

183

184 **Table 3.** Crumb rubber analysis results as asphalt binder modifier (Azadedel & Solatifar, 2022)

Test	Specification	Result
Polymer analysis	ASTM D3677 (ASTM, 2015)	Natural rubber
Thermal analysis (%)	ASTM E1131 (ASTM, 2014)	Natural rubber: 52.16 ± 2 Carbon black: 45.36 ± 2

		Ash: 2.30 ± 2
Ash (%)	-	4 ± 2
Volatiles at 105 °C (%)	-	0.3

2.1.2.3. Styrene Butadiene Styrene Polymer

Styrene Butadiene Styrene Polymer here labeled as KUMHO KTR 101 is a linear block copolymer based on styrene and butadiene (Table 4).

Table 4. Styrene Butadiene Styrene Polymer specifications as asphalt binder modifier (Kumho Petrochemical, 2020)

Specification	Result
Molecular structure	Linear (S B S)
Viscosity at 25 °C	560 cps
Specific gravity	0.95

2.2. Samples' Preparation

The methods used to prepare binders were different depending on the additive type, as per literature and preliminary tests. The preparation of binders reinforced with natural fibers involved heating the base binder to 165 °C, manually adding the fibers to prevent clumping, and performing high shear mixing at 5000 rpm for 20 min. Preparation of CR modified binders involved heating the base binder to 180 °C, adding crumb rubber manually, mixing at 86 Hz for 28 min, and conditioning at 180 °C for 30 min to make sure that the rubber was fully swollen. For the combination of the two additives (3%NF+5%CR), the crumb rubber was added first and mixed at 180 °C for 28 min, followed by fiber addition and mixing at 165 °C for 10 min at 5000 rpm. Burnt fiber samples followed the same protocol as natural fiber samples. All samples were conditioned at 135 °C for 30 min to remove any air bubbles.

2.3. Experimental Plan

Different tests were conducted on the prepared samples in this study, categorizing them into three main groups (conventional tests, aging procedure, and rheological tests); the details are presented in the following sections. All tests were performed in triplicate, and the reported values are the average of three measurements.

207 **2.3.1. Conventional Tests**

208 Penetration and softening point tests are among the conventional tests. To provide a numerical
209 indication of the asphalt's behavior at different temperatures, as per AASHTO T49 (AASHTO, 2007),
210 a penetration test measures the vertical penetration of a standardized steel needle into an asphalt
211 sample (with a load of 100 g at 25 °C over a period of 5 seconds). The softening point is representative
212 of the thermal stability of asphalt. According to the AASHTO T53 standard (AASHTO, 2009), it is
213 conducted to identify the temperature at which the binder transitions from a solid to a liquid. The
214 ductility of asphalt is measured by the elongation in a standard briquet before breaking (Wang et al.,
215 2020). The test is conducted by stretching the samples (with 10 cm and 20 cm sizes) at a rate of 5
216 cm/min once they reach the specified length before being cut in the middle. After 2 hours, the
217 sample's reversibility is measured. With a stretch exceeding 100 cm, the ASTM-D113 standard's
218 requirements are met (ASTM, 2017).

219 **2.3.2. Aging Procedures**

220 To replicate the short-term aging of the samples, a rolling thin-film oven (RTFO) was utilized (at 163
221 °C for 85 minutes period). Then the resulting residues were analyzed using a dynamic shear rheometer
222 (DSR) test.

223 **2.3.2.1. Rolling Thin Film Oven (RTFO) Test**

224 To simulate short-term aging, the Rolling Thin Film Oven (RTFO) test is conducted in 85 minutes to
225 prepare an aged binder adhesive for subsequent experiments. Under AASHTO T240 (AASHTO,
226 2021), the samples are heated to 163 °C and, while rotating at 15 rpm, are exposed to a pressurized
227 air jet (4000 mL/min).

228 **2.3.2.2. Pressure Aging Vessel (PAV) Test**

229 The Pressure Aging Vessel (PAV) test replicates the effects of long-term aging conditions (over a 5-
230 to 10-year period). Per the AASHTO R28-06 (AASHTO, 2006b), the binder samples obtained from
231 the RTFO test were transferred to the PAV, exposing them to compressed air with a pressure of (2.1

232 ± 0.1) MPa. By setting the internal temperature of the vessel to a predetermined 100 °C (consistent
233 with AASHTO R28 requirements for 40/50 binder), the temperature and pressure of the vessel were
234 held for 20 h $\pm$ 10 min before the test to reach a more accurate simulation (Arabani & Shabani, 2019).

235 **2.3.3. Rheological Tests**

236 Rheological tests conducted in this study include Rotational Viscosity (RV), Dynamic Shear
237 Rheometer (DSR), and Bending Beam Rheometer (BBR) tests.

238 **2.3.3.1. Rotational Viscosity (RV) Test**

239 The Rotational Viscosity (RV) test assesses the binder's fluidity at high temperatures, ensuring the
240 fluidity of the binder for pumping and mixing under hot mixing circumstances (Azadedel & Solatifar,
241 2022). Typically conducted at a temperature of 135°C based on the AASHTO T316 standard
242 (AASHTO, 2013), the RV test on unaged samples quantifies their viscosity (Asphalt Institute, 2007).

243 **2.3.3.2. Dynamic Shear Rheometer (DSR)**

244 A dynamic shear rheometer (DSR) test was conducted on asphalt binders according to AASHTO
245 T315 (AASHTO, 2012a). To better understand the performance characteristics under different
246 conditions, not only unaged samples at 52°C but also RTFO-aged samples at 58°C were considered
247 in this test. The increase in temperature would be 6°C. DSR test evaluates asphalt's adhesiveness and
248 measures its rheological properties, including Complex Shear Modulus (G^*) and Phase Angle (δ) at
249 high and medium temperatures, incorporating rutting and fatigue parameters.

250 **2.3.3.3. Bending Beam Rheometer**

251 The Bending Beam Rheometer (BBR) test measures the susceptibility of asphalt binder to thermal
252 cracking at low temperatures during its service life. Two primary components of the test are the creep
253 stiffness $S(t)$ (a measure of the binder's resistance against constant loading, so-called creep), and the
254 m -value (a measure of binder rigidity changes during the loading process) (Arabani & Shabani, 2019).
255 BBR test was done at -10°C, which is the temperature for the low-temperature PG grade of the base

256 binder according to AASHTO T313. The beam samples had the dimensions 127 mm × 12.7 mm ×
257 6.35 mm and were kept in the test water bath for 60 minutes before the test began. A load of 100g
258 was maintained for 240 seconds, and the creep stiffness $S(t)$ and m -value were obtained after 60
259 seconds (Wang et al., 2022).

260 **2.4. Environmental Evaluation**

261 The Kaya identity (KI) (Kaya, 1989), a classic mathematical model, has been utilized by the
262 Intergovernmental Panel on Climate Change (IPCC) as a tool to analyze emission scenarios with a
263 focus on energy use reduction and carbon intensity of human activities. Highlighting the linking of
264 environmental, economic, and demographic factors through a relatively simple calculation, KI has
265 been frequently used to estimate anthropogenic carbon emissions and environmental evaluation of
266 particularly different sectors of industry (O'Mahony, 2013; Pui and Othman, 2019). The Kaya
267 identity breaks down the governing forces of carbon emissions into components including carbon
268 intensity, energy intensity, GDP per capita, and population (Eq. 1).

$$C = \frac{C}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P \quad (1)$$

269 Where C is carbon emission, E is total energy use, GDP is gross domestic product, and P is population
270 (Kaya, 1989; O'Mahony, 2013).

271 Here, considering the particularity of the transportation industry as a main industry, we proposed the
272 extended Kaya identity to decompose the driving factors of road pavements' primary attributes (Eq.
273 2). For the Iranian transportation sector, the Kaya identity components for the base year 2020 were
274 obtained from international data sources. The energy intensity (E/GDP) was 10 MJ per USD of GDP
275 (PPP) (World Bank, 2020), GDP per capita (GDP/P) was \$15,119 (PPP) (World Bank, 2020), and
276 the population (P) was 87.7 million (UN, 2020). Furthermore, the transportation sector contributes
277 approximately 8% of Iran's GDP (Statistical Center of Iran, 2020), providing a direct link for
278 assessing the economic impact of pavement modifications.

$$RP = \frac{RP}{GDP} \times \frac{GDP}{P} \times P = RPE \times EO \times P \quad (2)$$

where “ GDP ” and “ P ” are used to decompose the road pavement (RP). The rationale for decomposing the driving factors of road pavement by using the elements “ GDP ” and “ P ” stems from their remarkable impact on promoting infrastructure and the associated economic growth, especially in developing countries (Chen et al., 2019; Wang et al., 2020). Therefore, road pavement (RP) is stated as the product of road pavement utilization efficiency (RPE), economic output (EO), and population (P).

The theoretical framework used by Acheampong (2018), used in industrial sectors (Osobajo et al., 2020; Karamouz et al., 2023), is utilized to estimate the effect of using the modified asphalt binders on economic growth. This approach indicates that carbon emissions increase proportionally with economic growth (reporting a 1.63% global economic growth increase as a result of a 1% carbon emissions increase). As for more precise results, this ratio should be estimated for the different geographical areas, to derive the economic impact of carbon emissions based on historical data available in information sources (such as the World Bank), carbon emissions changes and the ratio of changes in GDP, as a proxy for economic growth, are estimated (Eq. 3). It is noteworthy that a rough projection of carbon emission on the industrial portion of GDP is made to test the decoupling emissions and economic growth as a political concern in many developing regions.

$$\frac{\Delta GDP}{GDP_{Base\ Year}} = P\% \times \frac{\Delta CE}{CE_{Base\ Year}} \quad (3)$$

Where, $P\%$ is the economic impact ratio of carbon emissions, ΔGDP is the change in gross domestic product (million USD), $GDP_{Base\ Year}$ is the gross domestic product in the base year (million USD), $\frac{\Delta GDP}{GDP_{Base\ Year}}$ is the change ratio of gross domestic product (million USD per million USD), ΔCE is the carbon emissions change (thousand tons of carbon), $CE_{Base\ Year}$ is the carbon emissions in the base year (thousand tons of carbon), and $\frac{\Delta CE}{CE_{Base\ Year}}$ is the change ratio of carbon emissions (thousand tons of carbon per thousand tons of carbon).

2.4.1. System Boundary and Scope

The environmental evaluation in this study follows the Life Cycle Assessment (LCA) approach with a cradle-to-gate boundary, along with the end-of-life credit for waste diversion (ISO 14040, 2006a; ISO 14044, 2006b). The system boundary (see Figure 2) is defined by:

- Raw materials: base binder (40/50), goat hair fibers, crumb rubber made from waste tires, and energy from grid electricity in the manufacturing process;
- Binder manufacturing processes: heating to 165-180 °C, high shear mixing at 5000 rpm, short-term aging (RTFO), and long-term aging (PAV);
- End-of-life credit: prevented emissions as a result of waste diversion, i.e., not incinerated or disposed of in landfills, i.e 2,700 kg CO₂/ton of crumb rubber (Gağol et al., 2015; Lyu et al., 2024).

In terms of the conversion of energy use to CO₂ emissions, the specific grid emission factor of 0.67 kg CO₂ per kWh (Global Carbon Project, 2020) is used.

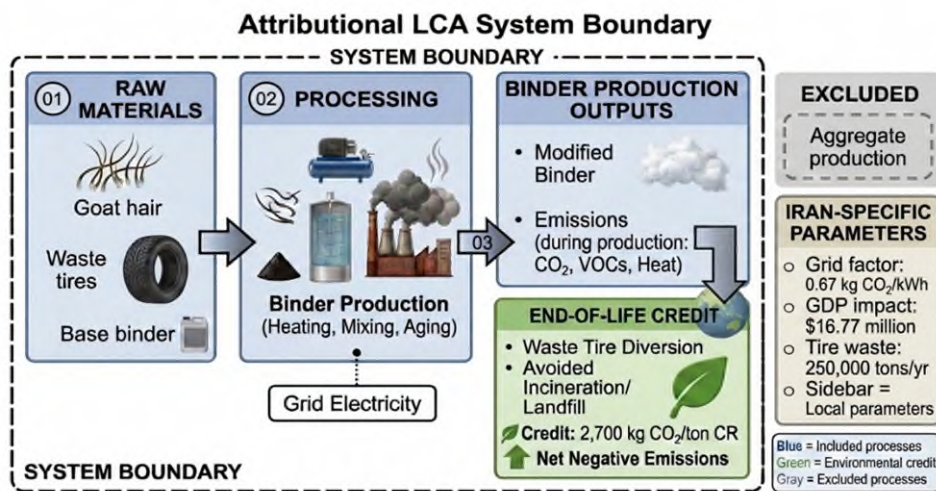


Fig. 2. System boundary for the attributional life cycle assessment (LCA) of modified asphalt binders.

As shown in Fig. 2, the system boundary does not consider the processes mentioned below due to lack of data and binder-level scope of the current research: Mining and manufacturing of aggregate; Transportation (of feedstock to asphalt plant and binder to construction site); Use of construction

320 machinery (for paving and compaction); Capital equipment of asphalt plant; Service life of pavement
321 and maintenance operations; End-of-life management of pavement (recycling or disposal).

322 2.4.2. Data Sources and Assumptions

323 To create a quantitative basis for the environmental assessment, data for Iran were collected for the
324 base year 2020. This year was selected for the following reasons: the year constitutes the latest dataset
325 that can be obtained from global resources (the World Bank, United Nations, Global Carbon Project);
326 this year can be considered as the pre-COVID baseline and thus does not include any distortions in
327 economy/energy numbers caused by the pandemic; it corresponds to the most recent planning cycle
328 in Iran.

329

330 **Table 5.** Kaya Identity Components for Iran (Base Year 2020)

Component	Symbol	Value	Unit	Source
Energy Intensity	E/GDP	10	MJ per USD (PPP)	World Bank (2020)
GDP per capita	GDP/P	15,119	USD (PPP)	World Bank (2020)
Population	P	87,723,443	People	UN (2020)
Transport sector share of GDP	-	8	%	Statistical Center of Iran (2020)
Economic carbon intensity	C/GDP	0.67	kg CO ₂ /USD	Global Carbon Project (2020)

331

332 These values allow for a basis to estimate baseline carbon emissions using the Kaya identity model.
333 In particular, the contribution of the transportation sector to GDP becomes extremely important since
334 it allows one to link the estimated carbon emissions related to pavement modification with the effects
335 on the economy. The economic carbon intensity of Iran (0.67 kg CO₂/USD of GDP) is almost twice
336 the average carbon intensity of the world (0.37 kg CO₂/USD). Then the GDP values in 2030 are
337 calculated under different scenarios (Eq. 4). As a rough assumption, the ratio of total GDP to total
338 population is equivalent to the ratio of industrial GDP to the population involved in or affected by
339 industrial activities.

$$CR = \frac{GDP_{Sc.x} - GDP_{Base Year}}{GDP_{Base Year}} = \frac{GDP_{Sc.x}}{GDP_{Base Year}} - 1 \quad (4)$$

340 where CR is the carbon emission changes (Percentage), $GDP_{Sc. x}$ is the GDP of the transportation
341 sector in a given year x as a result of implementing a scenario (Sc.), $GDP_{ind, Base Year}$ is the GDP of the

transportation sector in the base year, and. The GDP is expressed in billion USD. In the next step, the modified asphalt binders' impact on the carbon emissions is estimated to indicate the changes in carbon footprint of the transportation sector through pavement modification on different scales.

2.5. Multi-Criteria Decision Analysis (TOPSIS)

To determine the trade-off between mechanical performance and environmental sustainability systematically, the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methodology (Hwang & Yoon, 1981) was utilized. The decision matrix comprised eleven criteria that included eight mechanical performance factors (penetration, softening point, ductility, viscosity, rutting resistance, fatigue resistance, creep stiffness, and m-value), as well as three environmental criteria (energy reduction, CO₂ reduction, and life cycle CO₂ improvement). Utilizing the min-max normalization, the Environmental Benefit Index (EBI) was implemented as a composite measure:

$$EBI = 0.6 \times \text{Norm (Net Lifecycle CO}_2 \text{ Improvement)} + 0.4 \times \text{Norm (Tire Diversion Potential)} \quad (5)$$

where **Norm()** denotes:

$$\text{Norm}(x_i) = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \quad (6)$$

The 60/40 weight allocation system is reflective of the higher significance attached to climate change mitigation (principal issue) over the secondary issue of solid waste management, in line with the concepts of IPCC (2022) and UNEP (2021). Equal weights were used for all eight performance metrics. The reasoning behind such an approach is that: (1) there was no precedent regarding the significance of any of these eight metrics; (2) the Superpave specifications regarded the three distress mechanisms (rutting, fatigue, and thermal cracking) as equally important; and (3) it was required to avoid subjective bias. Five scenarios on weights were analyzed to test the robustness of TOPSIS rankings to different performance-environment priorities:

- **Scenario 1:** 100% performance, 0% environment → performance-only baseline.
- **Scenario 2:** 70% performance, 30% environment → performance-dominant.

- **Scenario 3 (Primary):** 60% performance, 40% environment → balanced sustainability.
- **Scenario 4:** 50% performance, 50% environment → environment-dominant.
- **Scenario 5:** 0% performance, 100% environment → environmental-only baseline.

This key composite ranking method employs a weighting structure of 60% performance versus 40% environment, which can be called a “balanced sustainability” system where the environment does play an important role but is not decisive, in line with established sustainability systems for infrastructure (Muench et al., 2011). TOPSIS calculations followed the standard procedure (Hwang & Yoon, 1981; Behzadian et al., 2012):

Step 1: Vector normalization: The decision matrix was normalized using vector normalization to eliminate scale effects (Jahan & Edwards, 2015):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (7)$$

Step 2: Weighted normalization:

$$v_{ij} = w_j \times r_{ij} \quad (8)$$

Step 3: Ideal and anti-ideal solutions:

$$A^+ = \{(\max_i v_{ij} \text{ for benefit criteria}), (\min_i v_{ij} \text{ for cost criteria})\} \quad (9)$$

$$A^- = \{(\min_i v_{ij} \text{ for benefit criteria}), (\max_i v_{ij} \text{ for cost criteria})\}$$

Step 4: Euclidean distance calculation:

$$D_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}; D_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (10)$$

Step 5: Closeness coefficient and ranking:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (11)$$

By ranking in descending order based on C_i values, the higher values suggesting better performance, ranking of alternatives as per Scenario 3 (primary composite ranking) was provided under the main

findings; whereas scenarios 1-5 (sensitivity analysis). All the calculations have been carried out through the use of R software (Version 4.3.1).

3. Results and Discussion

Conventional tests included penetration (ASTM-D5), softening point (ASTM-D36), and ductility (ASTM-D113) tests, followed by other rheological tests on different samples. In the context of CR additives, prior studies facilitated the refinement of processing conditions by providing insights resulting in the CR-modified binder's effectiveness. Regarding the optimal production process of CR-modified binder, derived by Azadedel and Solatifar (2022), the CR dosage and mixing parameters (mixing temperature, mixing time, and speed) in this study were selected based on the mentioned studies. However, there was no research on goat hair as binder additives, leading to the different dosage inclusions in preparing the samples. The samples were prepared as (a) 3%, 5%, 7% natural fibers with base binder, (b) 8% rubber powder and base binder, (c) 8% rubber powder + 3% natural fibers with base binder, and (d) 8% burnt natural fiber powder with base binder.

3.1. Results of Conventional Tests

Despite widespread modern SHRP tests, Penetration Grade, Softening Point, and Ductility tests remained the primary evaluation of asphalt's hardness, permeability, and elongation. The results are depicted in Fig. 3.

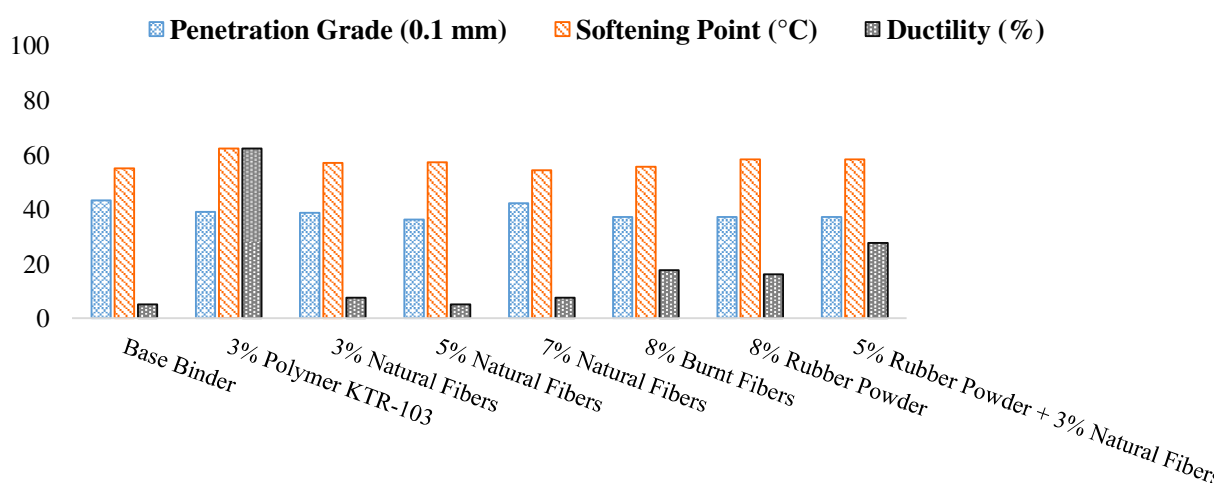


Fig. 3. Estimated values of the conventional tests (Penetration Grade, Softening Point, and Ductility)

399 Fig. 3 indicates that all samples have lower penetration grades than the base binder. Additionally,
400 except for the 7% natural fiber sample (which had a negligible impact on the penetration of the base
401 binder), all samples have higher softening points, as a representative of enhanced performance. Based
402 on the results, KTR-103 polymer has the lowest penetration grade (and highest softening point), with
403 a 23.2 Softening point difference, followed by the combination of 3% Natural Fibers + 5% Rubber
404 Powder, 8% Rubber Powder, and 5% Natural Fibers, all with 21-degree differences. Next are the 8%
405 Goat hair ash (18.3-degree difference), 3% Natural Fibers (11.7-degree difference), and 7% Natural
406 Fiber (12-degree difference). At the same time, the base binder is at the bottom (11.7 degrees).
407 Concluding that following, polymer KTR-103, the next three samples fall within an acceptable range.
408 The results of the ductility test (Fig. 3) show that most of the samples represent either similar elasticity
409 to the base binder or marginal increases. Regarding the unsatisfactory elasticity of the fibers in
410 comparison to the polymer, goat hair ash shows a positive trend, highlighting the improvement
411 compared to rubber powder. The highest elasticity value (5.27 percent) was shown by the sample
412 containing 3% Natural Fibers and 5% Rubber Powder.

413 **3.2. Rheological Properties of Modified Asphalt Binder**

414 The effects of additive type and content on rutting, fatigue, and thermal cracking for the asphalt
415 binders used in this study are as follows.

416 **3.2.1. Viscosity**

417 Therefore, the viscosities are crucial for performance of the binders. High viscosity can make coating
418 of aggregates difficult when mixing while very low viscosity, although useful for coating, will allow
419 asphalt to flow during transportation and storage. The results of the RV test are depicted in Fig. 4.

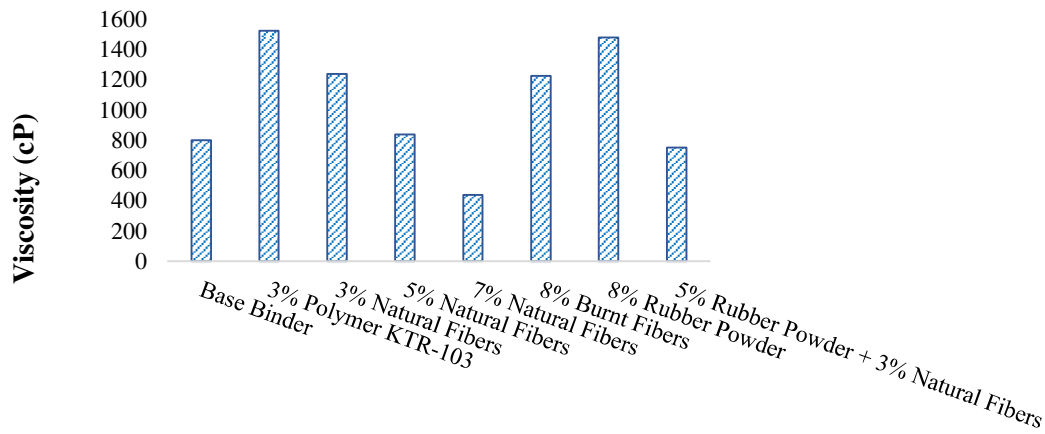


Fig. 4. Estimated values of the viscosity (Rotational Viscosity Test)

Based on the results (Fig. 4), KTR-103 has the maximum viscosity value which is recorded as 1525 cP (1.525 Pa·s) with rubber powder having 1481 cP. The viscosities of 3% Natural Fibers, Goat Hair Ash, and 5% Natural Fibers have been recorded to be 1238 cP, 1225 cP, and 837 cP, respectively. The blend of 5% rubber powder and 3% natural fibers has viscosity at 750 cP, whereas the viscosity of the base binder is at 800 cP. For the lowest component, 7% natural fibers result in 438 cP of viscosity. The viscosity results indicate that natural fibers generally reduce binder viscosity compared to the base binder. The significant drop suggests that the presence of higher concentrations of fibers causes the breakdown of the asphalt structure. The lowering of the viscosity value can be attributed to two possible reasons. Firstly, in a case where the fiber content is as high as 7%, the interaction value between the fibers and asphalt may be exceeded, in such a way that the extra fibers become obstacles to the continuous asphalt phase. Secondly, the natural goat hair fibers have oil and protein on their surfaces, which interact with the light parts of asphalt.

The results obtained coincide with those noted by Li et al. (2022), when working with plant-based fibers in high doses; however, the reasons behind that phenomenon differ, due to the fact that animal-based fibers consist of proteins. As a practical consequence, it follows from this that while low fiber content (3–5%) ensures reinforcement, high doses of fibers ($\geq 7\%$) impair the cohesion of the binder, which is important for its coating activity.

3.2.2. Rutting Resistance Analysis

The higher plasticity resistance homogeneity of asphalt and a lower asphaltene content is essential for asphalt, as a viscoelastic material. Due to the Superpave specifications, the rutting parameter ($G^*/\sin \delta$), as a governing metric, plays an essential role in the evaluation of the permanent deformation performance of asphalt binders. Generally, binders with higher values of the rutting parameter exhibit enhanced resistance to rutting and asphalt satisfies the standard requirement when the rutting parameter is higher than 1.0 kPa (Yousif et al., 2022). The results are indicated in Fig. 5.

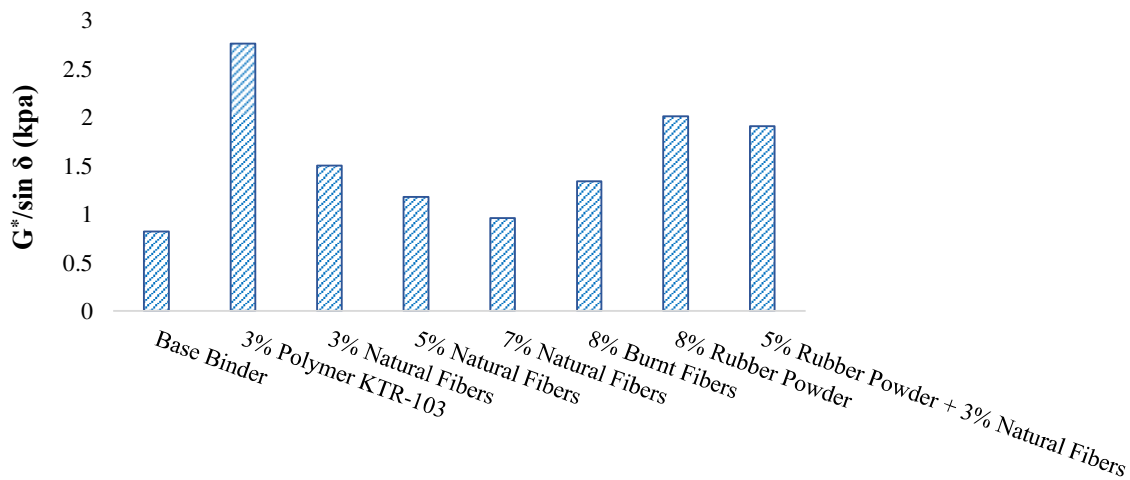


Fig. 5. Estimated values of the Rutting Parameter (Dynamic Shear Rheometer Test)

According to the results, for unaged 40-50 asphalt, the $G^*/\sin \delta$ value is 0.82 kPa, (lower than the standard 1.0 kPa), and the highest value is for polymer KTR-103 at 2.76 kPa. Fig. 5 demonstrates that increasing the percentages of natural fibers (3, 5, and 7%) decreases $G^*/\sin \delta$ (1.500, 1.177, and 0.958 kPa), though higher than base asphalt. While having 8% goat hair ash, the rutting parameter reaches 1.336 kPa, the combination of 3% natural fibers + 5% rubber powder results in 1.905 kPa. Remarkable improvements are experienced by adding 8% rubber powder (2.008 kPa), showing the best performance against rutting at 76 °C.

3.2.3. Fatigue Resistance Analysis

To evaluate the resistance of asphalt binders against fatigue cracking at average temperatures, the parameter $G^* \times \sin \delta$ is estimated. After RTFO and PAV processes (refer to section 2.3.2), the values

of this parameter were evaluated in response to temperature fluctuations of 37 °C (as shown in Fig. 6).

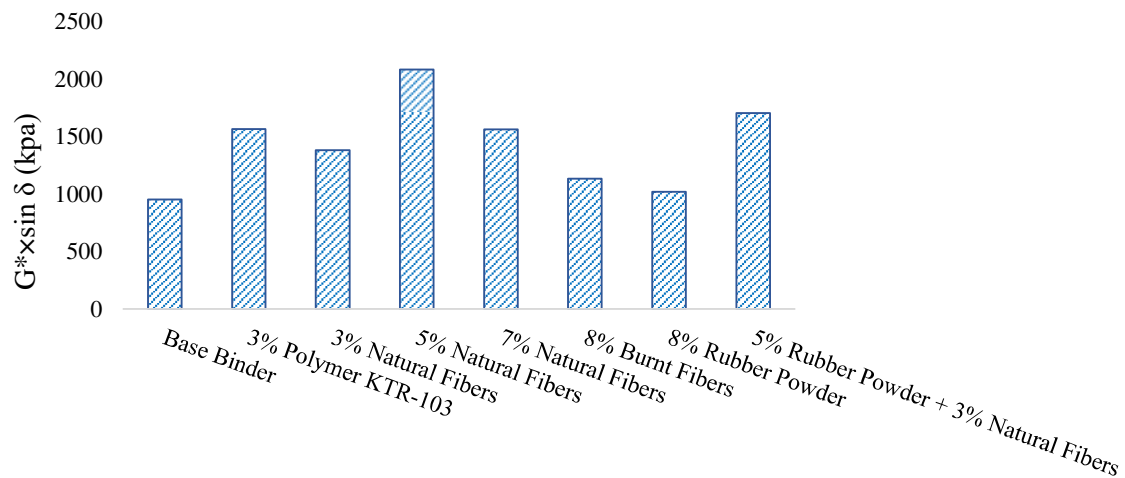


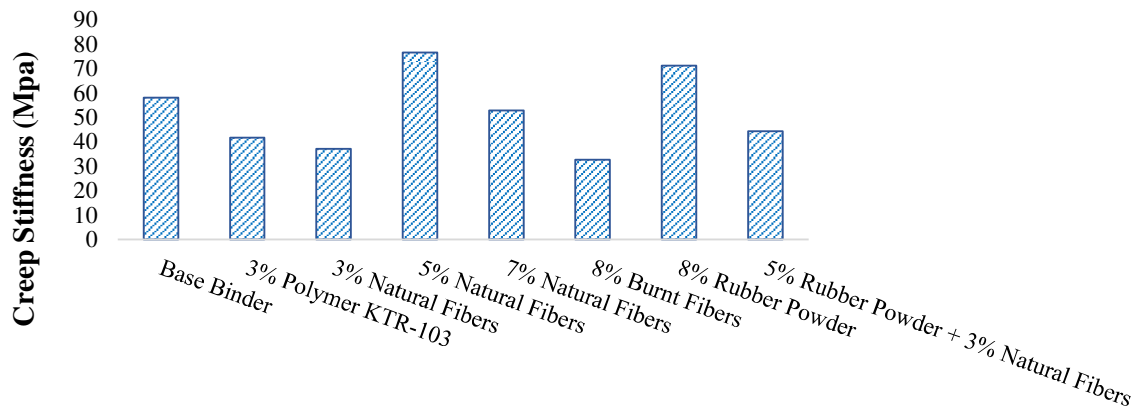
Fig. 6. Estimated values of $G^* \times \sin \delta$ at the temperature of 37 °C (Dynamic Shear Rheometer Test)

Fig. 6 indicates that incorporating the additives improved the fatigue resistance of asphalt binders. Based on the findings, all samples experienced a reduction in resistance relative to the maximum threshold of 5000 kPa. This may be corresponded to the asphalt's aromatic oils absorption by the additive particles. The absorption process makes them swell and ultimately enhances the flexibility of the asphalt matrix.

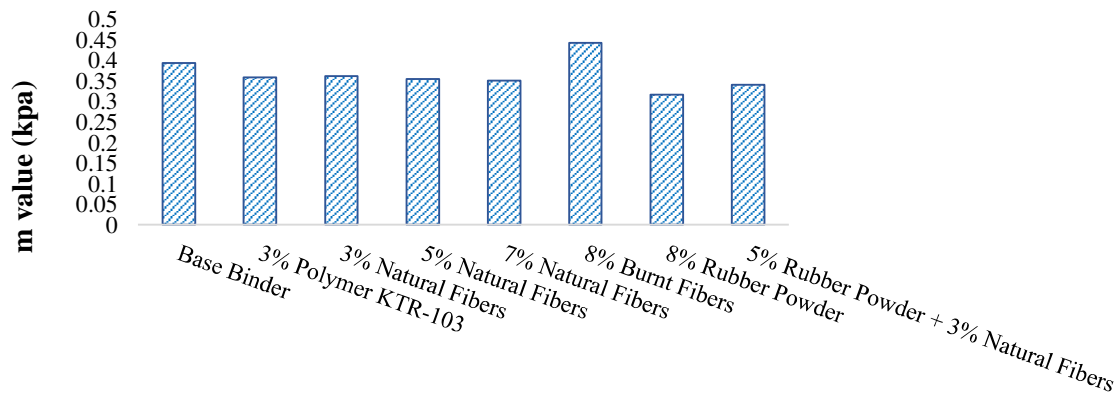
The base binder has the lowest value of 952.82 kPa, while the addition of 5% natural fibers results in the highest fatigue resistance value of 2081.1 kPa. Notably, the resistance of 1020 kPa was shown by samples with 8% rubber powder, compared to those with 8% goat hair ash (showing 1132 kPa), and samples with 3% natural fibers (showing 1381.9 kPa). These results represent the unsatisfactory performance of KTR-103 (with a value of 1565.6 kPa) compared to the three mentioned samples.

3.2.4. Low Temperature Cracking Resistance

The evaluation of the asphalt behavior in cold temperatures is conducted by investigation of creep stiffness and stiffness change rate over time (performed at -10 °C). For optimal performance, creep stiffness should be below 300 MPa, and the stiffness change rate over 60 seconds should be above 0.3 (Golalipour, 2020). The findings are shown in Fig. 7.



(a)



(b)

Fig. 7. Estimated values of low temperature cracking resistance (Bending Beam Rheometer Test), a) creep stiffness (s), and b) stiffness change rate over time (m value)

According to the findings (Fig. 7), two samples: 3% natural fibers (with 37 MPa), and 8% goat hair ash (with 32.56 MPa), show lower stiffness than KTR-103 polymers (with 41.54 MPa), showing performance enhancement at low temperatures. As for the three other samples (with a much higher stiffness than the polymer), it is noteworthy that the sample with 3% natural fibers + 5% rubber powder had a stiffness nearly equal to the polymer, indicating its effectiveness in enhancing asphalt's low temperature cracking resistance. Regarding the behavior of the samples under different conditions and tests, overall, as rubber powder absorbs aromatic oils, the asphaltenes and viscosity increase using this binder additive, with undissolved particles further improving viscosity, therefore the high-temperature performance grade (PG) and stiffening the asphalt increase (refer to Table 4 for

more details). Meanwhile adding natural fibers (goat hair) to asphalt functions differently from rubber powder additives. While increasing natural fibers lowers viscosity by reducing asphaltene content, burning the fibers breaks molecular bonds, and the combined loss of oils and more dissolved materials increases viscosity. Combining rubber powder and natural fibers balances viscosity and enhances elasticity, $G^*/\sin \delta$, and the $s(t)$ and $m(t)$ variables. Results indicate that natural fibers and rubber powder enhance rutting resistance at high temperatures, mitigate fatigue cracking at moderate temperatures, and address thermal cracking. Using natural fibers alone, generally lowers viscosity, improving aggregate mixing but increasing the risk of material flow during compaction. Their high tensile strength minimizes rutting, fatigue, and thermal cracks at low temperatures. These findings are consistent with previous studies (Table 6).

Table 6. Additives' effect on asphalt performance-based behavior

Additives	Performance aspects			
	Rutting Resistance	Fatigue Resistance	Thermal Cracking Resistance	Viscosity
Crumb Rubber (CR)	↑ (Mashaan et al., 2011; Yousefi Kebria et al., 2015; Sutanto et al., 2018; Singh et al., 2019; Bilema et al., 2019; Bayagoob & Füleki, 2022)	↑ (Giuliani & Merusi, 2010; Ameri et al., 2017; Singh et al., 2019; Bayagoob & Füleki, 2022)	↑ (Gopal et al., 2002; Sebaaly et al., 2003; Lyu et al., 2024)	↑ (Thodesen et al., 2009; Wang et al., 2012; Li et al., 2018; Azadedel & Solatifar, 2022)
Natural Fibers	↑ (Ye & Wu, 2009; Alrajhi, 2012; Qadir, 2014) (Li et al., 2022)	↑ (Tapkın et al., 2009; Ahmed, 2012; Wang et al., 2020; Shanbara et al., 2020)	↑ (Tapkın et al., 2009; Ahmed, 2012; Wang et al., 2020; Shanbara et al., 2020); ↓ (Li et al., 2022)	↑ (Ye & Wu, 2009; Alrajhi, 2012) (Li et al., 2022)

The literature review (Table 6) confirms that both crumb rubber and natural fibers generally improve rutting and fatigue resistance, though their effects on thermal cracking and viscosity vary. Crumb rubber consistently increases viscosity due to the absorption of light oil fractions and rubber swelling, while natural fibers show mixed effects depending on fiber type, content, and treatment (e.g., burning reduces viscosity due to molecular breakdown). The combined use of crumb rubber and natural fibers

507 in this study achieved a synergistic effect, balancing viscosity while enhancing all performance
508 parameters, which is consistent with the results of previous investigations.

509 **3.3. Environmental Impact Analysis**

510 Waste tires contribute to environmental pollution, and their management, particularly through
511 incineration, results in greenhouse gas emissions, their reuse and recycling can significantly help
512 approach sustainable development goals. These effects align with lower energy use and GHG
513 emissions, resource protection, and environmental conservation. Moreover, noise pollution can be
514 reduced using CR as an additive. All these contribute to making the pavements more environmentally
515 friendly (Table 7).

516

517 **Table 7.** Additives effect on asphalt behavior (environmental aspects)

Additives	Environmental Aspects		
	Noise Reduction (Sound Absorption)	Pollutant Emission	Energy Use
Crumb Rubber (CR)	3 dB (Paje et al., 2013); 1–3 dB (Mavridou & Kehagia, 2017); 500–1000 Hz (Xu et al., 2022); Sound Absorption Coefficient of 0.2 (Bozkurt & Yılmaz Demirkale, 2020); 0.5 (Smirnova et al., 2021)	↑ VOCs primarily BTEX (benzene, toluene, ethylbenzene, and xylenes) and sulfur compounds (Gagol et al., 2015); ↑ xylene and toluene (Yang et al., 2019)	↑ (Pouranian et al., 2020; Xie et al., 2024); ↓ (Lyu et al., 2024)
Natural Fibers	Sound Absorption Coefficient of 0.15 (Bozkurt & Yılmaz Demirkale, 2020); 0.94 (Colorado et al., 2022)	↓ 4.0%–6.5% VOCs (Chang et al., 2024)	-

518

519 As for natural fibers (like wool and hair) additives, as they contain proteins with diverse chemical
520 structures and properties, their use results in reduced asphaltene content and prevents aging. Natural
521 fibers are categorized as environmentally sustainable additives as their production processes generate
522 little to no carbon dioxide. Therefore, they are commonly referred to as green fibers. The use of these
523 fibers may cause a remarkable reduction in GHG emissions at the end of lifecycle (compared to other
524 additives) and are not harmful to health post-use. Goat hair's high heat resistance acts as a barrier
525 against heat transfer and asphalt aging. When burned, wool forms an insulating char with self-

extinguishing properties, emitting fewer toxic substances. Aggregates in asphalt are hydrophilic, whereas natural goat hair fibers, being hydrophobic, aid in preventing pavement deterioration.

3.3.1. Energy Consumption and Carbon Emissions

For calculating the energy use corresponding to each of the mentioned binders, the energy consumption of the high-shear mixer was calculated based on the mixing conditions (180°C temperature, 28 min mixing time, 86 Hz stirring rate). Carbon dioxide emissions were calculated using the country's electricity emission coefficient of 0.67 kg CO₂ per kWh (Global Carbon Project, 2020). Using the Kaya identity factors determined in Section 2.4 ($E/GDP = 10 \text{ MJ/USD}$, $GDP/P = \$15,119$, $P = 87.7 \text{ million}$) on the energy consumption figures, carbon emissions figures have been calculated and are shown in Table 8 below.

Table 8. Energy Consumption and Carbon Emissions for Modified Asphalt Binders

Sample	Energy Use (MJ/ton)	Energy Reduction vs. Neat (%)	CO ₂ Emissions (kg/ton)	CO ₂ Reduction vs. Neat (%)
Neat Binder	184.5	-	42.3	-
3% Natural Fibers	176.2	4.5	40.4	4.5
5% Natural Fibers	168.9	8.5	38.7	8.5
7% Natural Fibers	162.3	12.0	37.2	12.1
8% Crumb Rubber	191.8	-4.0	43.9	-3.8*
8% Goat hair ash	157.6	14.6	36.1	14.7
3% NF + 5% CR	179.5	2.7	41.1	2.8**
KTR-103 Polymer	215.4	-16.7	49.4	-16.8

Note: The CR-modified binder has elevated energy usage since prolonged mixing time is necessary for both rubber expansion and (b) integration.

** The 3%NF+5%CR blend shows a 2.8% reduction in production-phase emissions. When the tire recycling credit is included, the net lifecycle improvement is 136.2 kg CO₂/ton (322% relative improvement over neat binder), as discussed in Section 3.3.2.*

According to the findings, samples containing goat hair ash resulted in maximum decrease in energy consumption (14.6%) as compared to those containing 7% natural fiber (12.0%), 5% natural fiber (8.5%), and 3% natural fiber (4.5%). The sample of crumb rubber at 8% level showed increase in energy consumption because of the increased mixing period and increased viscosity. In a similar way, KTR-103 polymer had the highest value of energy consumption because of increased viscosity.

549 Differentiation of production emissions and lifecycle emissions is very important in this analysis. The
550 production emissions (Table 8) refer to the direct CO₂ emissions that occur during the production
551 process of the modified asphalt binder due to energy use during heating and mixing processes. This
552 is done based on the electricity emission factor for Iran (0.67 kg CO₂/kWh). Lifecycle emissions,
553 however, refer to production emissions and the environmental credit gained by avoiding the
554 incineration or disposal of the tires in landfills. Tire recycling emits a negative emission and hence
555 reduces the lifecycle emissions. Therefore:

$$\text{Lifecycle Emissions} = \text{Production-Phase Emissions} - \text{Tire Recycling Credit} \quad (12)$$

556 The point is vital to keep in mind since, despite the fact that the combination of 3% NF and 5% CR
557 results in low emissions during the manufacturing process (2.8%), the significant amount of emissions
558 resulting from tire recycling (-135 kg CO₂ per ton of binder) brings about overall negative emissions
559 (-93.9 kg CO₂ per ton).

560 **3.3.2. Tire Recycling Carbon Credit and Waste Management Benefits**

561 The use of crumb rubber provides additional environmental benefits through waste tire diversion.
562 Based on the emission factors of Gaḡol et al. (2015) and Lyu et al. (2024), each ton of recycled tire
563 rubber avoids approximately 2,700 kg of CO_{2e} emissions compared to incineration or landfilling. For
564 the 3%NF+5%CR blend (containing 5% crumb rubber by weight of binder).

565 The expression “net negative emissions” in this case means that the total lifecycle CO₂ emissions
566 after considering the environmental credits derived from avoiding incineration of the waste tires are
567 less than zero. The phrase does not mean that the binder captures CO₂ while being in use; it only
568 means that the emissions avoided due to diversion of the waste tires are higher than the emissions of
569 producing the binder.

$$\text{Net emissions} = 41.1 - (0.05 \times 2700) = -93.9 \text{ kg CO}_{2e}/\text{ton}$$

571 It amounts to a net saving of 136.2 kg CO₂ for each ton compared to the base binder (releasing 42.3
572 kg CO₂ for each ton), equating to an improvement of 322%. The net negative value indicates that the
573 modified binder captures or saves more CO₂ throughout its lifespan than it emits, mostly due to the

recycling of waste tires. Even for the 8% CR sample ($\text{Net emissions} = 43.9 - (0.08 \times 2700) = -172.1$ kg CO_{2e}/ton). This shows a decrease of 214.4 kg CO₂ per ton as opposed to the amount emitted by the base binder (or a relative improvement of 507%). However, the production of this particular sample also consumes more energy. The energy requirement during the production of the 8% CR sample is higher than usual.

Beyond the carbon emission, there is an approach of using crumb rubber to deal with the challenge of waste tire management in Iran. It is estimated that there are about 250,000 tons of waste tires produced in Iran annually (Environmental Protection Organization of Iran, 2022). Considering the 5% crumb rubber composition in the 3% NF + 5% CR mixture and the production of 1.75 million tons/yr of asphalt binder in Iran (Financial Tribune, 2017):

Annual tire diversion potential (100% adoption) = $1,750,000 \text{ tons} \times 0.05 = 87,500$ tons of waste tires
 It accounts for about 35% of the yearly volume of Iran's tire waste (250,000 tons), with other advantages, including: Landfill space saved: About 875,000 m³ annually (assuming 10 m³ per ton of tires), Toxic leachate prevented: About 438 tons of toxic substances, Vector breeding grounds prevented: Decreased risk of mosquito-transmitted diseases. The estimated Gross Domestic Product (GDP) of Iran in 2030 stands at \$349.53 billion (in nominal terms). Environmental advantages of crumb rubber-modified binders were confirmed with the help of TOPSIS multi-criteria analysis (Fig. 8).

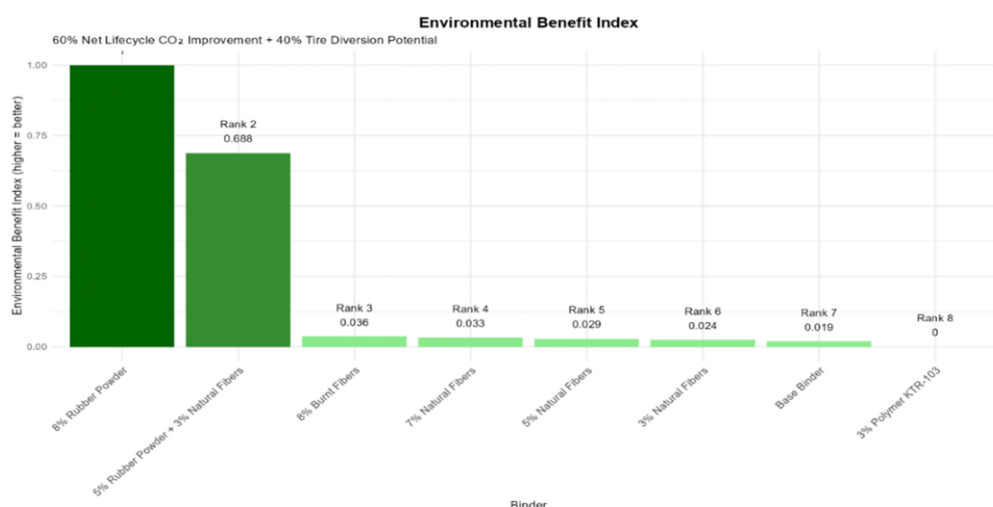


Fig. 8. Environmental Benefit Index and net lifecycle CO₂ improvement (60%) and tire diversion potential (40%).

594

595 The highest environmental benefit index was received for the 8% Rubber Powder binder (0.95),
 596 whereas the 5% Rubber Powder + 3% Natural Fibers binder had almost the same index (0.85). Such
 597 high index values indicate the great environmental benefit of tire recycling because the 8% Rubber
 598 Powder binder demonstrates an additional lifecycle CO₂ reduction of 214.39 kg/ton and annually
 599 diverts 70,000 tons of waste tires, whereas the 5% Rubber + 3% NF binder gives an improvement of
 600 136.18 kg/ton and annually diverts 52,500 tons. On the other hand, the KTR-103 polymer binder had
 601 the lowest value of environmental benefit index (-0.05).

602

603 **Table 9.** Scenario Analysis for Modified Binder Adoption in Iran (2030)

Scenario	Adoption Rate (%)	CR Consumption (tons/yr)	Tire Diversion (%)	Net Lifecycle CO ₂ Improvement (Tons/yr)	GDP Impact (10 ⁶ USD)
Baseline	0	0	0	0	\$0
Conservative	20	17,500	7.0	47,670	\$5.59
Moderate	40	35,000	14.0	95,340	\$11.18
Aggressive	60	52,500	21.0	143,010	\$16.77
Maximum	80	70,000	28.0	190,680	\$22.36

604 † CR Consumption = 1,750,000 tons binder/yr × 5% CR content × Adoption Rate. Tire Diversion = CR Consumption /
 605 250,000 tons/yr (Iran's annual tire waste; Environmental Protection Organization of Iran, 2022). Net Lifecycle CO₂
 606 Improvement = Annual binder consumption × Adoption Rate × 136.2 kg CO₂/ton binder (322% improvement over neat
 607 binder; see Section 3.3.2).

608 ‡ GDP Impact calculated using Equations 3 and 4: $\Delta GDP/GDP_{base} = 0.658 \times \Delta CE/CE_{base}$; CR =
 609 $GDP_{scenario}/GDP_{base} - 1$. GDP_{base} for Iran's transportation sector = \$31.04 billion (Statistical Center of Iran,
 610 2020). GDP projections for 2030 from IMF World Economic Outlook (2024).

611

612 The sensitivity analysis of TOPSIS rankings for various weighting strategies is provided in Fig. 9. As
 613 shown from the scenario analysis, even modest usage of the optimal modified binder can lead to
 614 tangible environmental and economic benefits. Based on the aggressive scenario (60% usage of the
 615 optimal modified binder), about 143,010 tons of CO₂ equivalent emissions could be prevented
 616 annually on a life cycle basis (taking into account the effect of tire recycling), which would result in
 617 GDP savings of \$16.77 million and prevention of 52,500 tons of waste tires going into landfills each
 618 year. With maximum usage of the optimal modified binder (80%), up to 190,680 tons of CO₂

emissions could be avoided annually. With regard to intermediate adoption rates, the moderate case will realize 95,340 tons of CO₂ per year reduction and \$11.18 million GDP effect, while the conservative case will result in 47,670 tons of CO₂ per year reduction and \$5.59 million GDP effect.

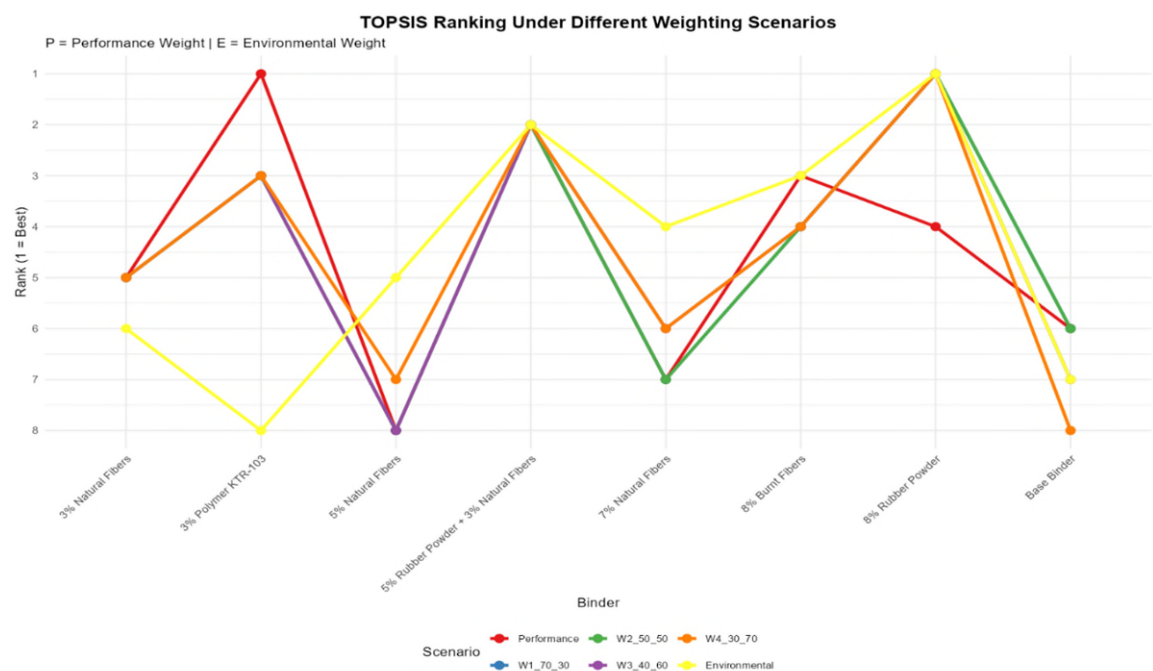


Fig. 9. Sensitivity analysis of TOPSIS rankings under different weighting scenarios (P = Performance weight, E = Environmental weight).

The ranking for 5% Rubber Powder + 3% Natural Fibers mixture is consistent (Rank #2) regardless of scenario, which validates its strong resilience as a viable solution. The 8% Rubber Powder binder exhibits increased ranking with increasing weight of environmental variables, whereas the KTR-103 polymer displays decreased ranking as the weight of environmental variables increases. Scenario analysis reveals that the choice of the best binder is based on the relative weights given to performance versus environmental variables. However, it is significant to state that these lifecycle advantages are much higher than production phase cost savings (\$0.24 million at same adoption rates) since the credit for tire recycling shifts small production phase savings into overall negative emissions in the lifecycle. These lifecycle advantages can only be realized if the waste tires are kept out of incineration and landfill disposal. If the waste tires are recycled for some other reason (for example, energy production and civil engineering applications), then these advantages will not be realized.

637 3.3.3. Comparative Environmental Performance

638 Table 10 provides a comparative summary of the environmental performance of all tested samples
639 relative to the neat binder.

640

641 **Table 10.** Summary of Environmental Performance Metrics

Sample	Energy Reduction (%)	CO ₂ Reduction (%)	Tire Diversion Credit (kg CO ₂ /ton)*	CO ₂ Reduction (kg/ton)	Net Lifecycle CO ₂ Improvement (kg/ton)†
3% Natural Fibers	4.5	4.5	0	1.90	1.90
5% Natural Fibers	8.5	8.5	0	3.60	3.60
7% Natural Fibers	12.0	12.1	0	5.12	5.12
8% Crumb Rubber	-4.0	-3.8	216	-1.61	214.39
8% Goat hair ash	14.6	14.7	0	6.22	6.22
3% NF + 5% CR	2.8	2.8	135	1.18	136.18
KTR-103 Polymer	-16.7	-16.8	0	-7.11	-7.11

642 *Calculated as: CR content (%) × 2,700 kg CO₂/ton (tire recycling credit; Gagol et al., 2015; Lyu et al., 2024)

643 †Calculated as: (42.3 kg/ton × CO₂ Reduction %) + Tire Diversion Credit. Negative values indicate increased emissions
644 relative to neat binder. Note: The 3%NF+5%CR blend shows a production-phase reduction of 2.8% but a lifecycle
645 improvement of 136.18 kg CO₂/ton (322% relative improvement over neat binder) when the tire recycling credit is
646 included.

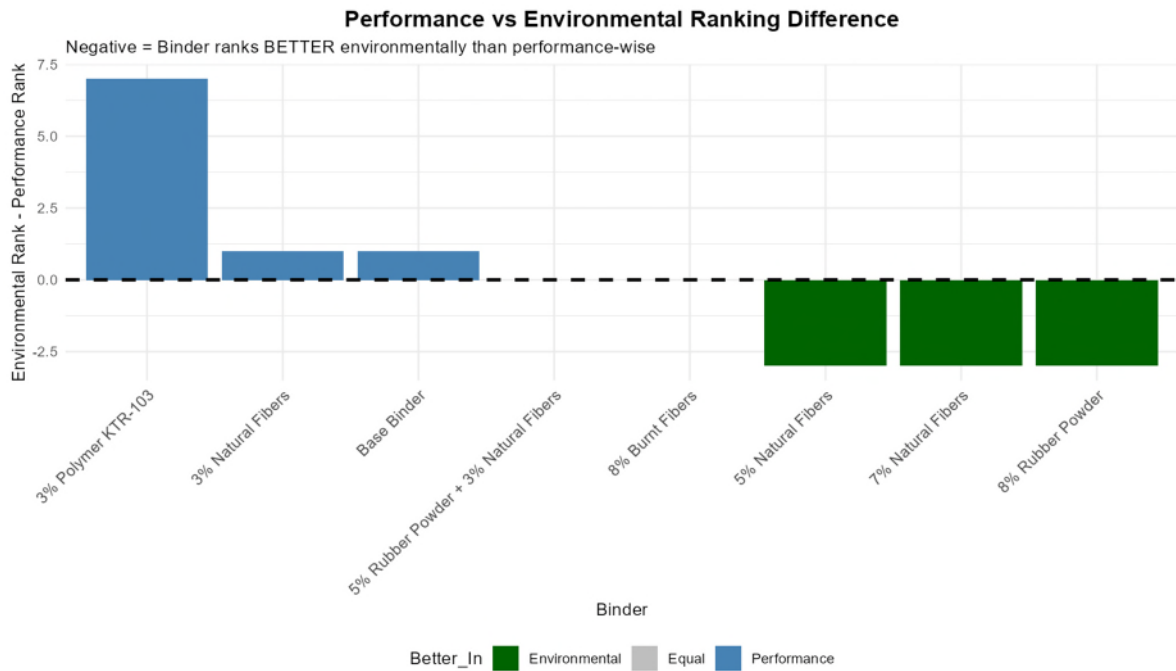
647

648 3.4. Overall Performance Trade-offs

649 The results obtained in the rheological studies reveal a significant trade-off. Indeed, KTR-103
650 polymer displayed the highest resistance to rutting and stiffness compared to the other samples. Thus,
651 its efficiency in acting as a high-temperature modifier is confirmed. However, such an improvement
652 in performance was linked to the higher energy usage, higher CO₂ emissions, and reduced fatigue
653 resistance compared to some of the sustainable blends. In turn, the best sustainable blend
654 (3%NF+5%CR) demonstrated good results in terms of performance and reduced environmental
655 footprint. This trade-off reflects the challenge in achieving a balance between good performance and
656 sustainability when using petroleum-derived additives. This trade-off highlights the importance of
657 sustainable alternatives that can provide good performance in all aspects.

658 To assess this tradeoff quantitatively, the decision analysis method using TOPSIS technique, which
659 involves a combination of eight mechanical performance criteria with the Environmental Benefit

660 Index (combining CO₂ improvement and tire diversion possibilities) was performed. Redundancy was
661 checked in environmental criteria to ensure that there is no double-counting. Energy Reduction (%)
662 and CO₂ Reduction (%) are calculated from the same measured energy consumption data (see Table
663 8). CO₂ emissions were estimated based on the grid emission factor of Iran (0.67 kg CO₂/kWh).
664 Hence, these two criteria are physically redundant because they measure the same impact during the
665 production phase but in different units. Using them together means that there will be double counting
666 of the impact of the production phase. Therefore, only Net Lifecycle CO₂ Improvement was
667 considered as the sole production phase criterion. Tire Diversion Potential was added separately to
668 account for the solid waste aspect. Thus, there were nine criteria in total, eight mechanical criteria
669 plus Net Lifecycle CO₂ Improvement and Tire Diversion Potential. The difference in ranking between
670 environmental performance and mechanical performance is presented in Fig. 10. From the analysis
671 on the difference in ranking, a distinct tradeoff between mechanical and environmental performance
672 is evident. The 8% Rubber Powder binder has a negative difference of -3 ranks, which means that it
673 has excellent environmental performance but weak mechanical performance. On the other hand, the
674 3% Polymer KTR-103 binder has a positive difference of +6 ranks.



675

676

677

Fig. 10. Performance vs environmental ranking difference for modified asphalt binders.

678 Negative figures denote binders which perform better environmentally but not in terms of
679 performance. The 8% Rubber powder and 7% Natural fiber binders exhibit the greatest environmental
680 benefit, whereas the KTR-103 Polymer binder is environmentally disadvantageous although it
681 performs well. The findings show that whereas use of natural fibers on their own is relatively
682 environmentally friendly by reducing production phase energy (4.5%-12.1% CO₂ reduction), the use
683 of a combination of natural fibers and crumb rubber gives high environmental benefits from the
684 diversion of waste tires. The 8% goat hair ash sample represents the greatest reduction in energy in
685 the non-crumb rubber samples (14.6%), but the 3%NF + 5%CR sample gives the most balanced
686 solution. In addition to the above, this analysis reveals another important trade-off between
687 performance and sustainability. Although the KTR-103 polymer performed better in terms of rutting,
688 it required the greatest amount of energy and emitted the greatest amount of CO₂ (16.8% more than
689 the neat binder). Conversely, the 3%NF+5%CR mixture showed similar or better performance with
690 regard to fatigue and thermal cracking resistances while emitting net negative life-cycle CO₂
691 emissions (-93.9 kg CO₂/ton) once the tire recycling benefit was taken into account. This corresponds
692 to an improvement of 136.2 kg CO₂/ton compared to the neat binder (42.3 kg CO₂/ton) or an
693 improvement of 322%.

694 The differentiation between production-phase and lifecycle emissions must be made in this case
695 study. The CO₂ reduction of production phase for the 3%NF+5%CR formulation is 2.8% (1.18 kg
696 CO₂ per ton), whereas the lifecycle CO₂ reduction of 136.2 kg CO₂ per ton is possible owing to the
697 joint efforts of production-phase savings and tire recycling benefit (135 kg CO₂ per ton as a result of
698 diversion of 5% waste tires from landfilling or burning). It becomes evident that sustainable modifiers
699 can provide balance in performance and at the same time greatly reduce their environmental impact
700 in comparison with oil-derived additives. As seen in Figure 11, despite the fact that the KTR-103
701 polymer showed better mechanical performance (Rank #1), it showed lower environmental
702 performance (Rank #7) and thus was rated #3 overall. On the other hand, the 8% Rubber Powder
703 additive showed average performance (Rank 4) but still had the best ranking (Rank 1) because of its

substantial environmental benefits (improvement by 214.39 kg CO₂ per ton and 70,000 tons of diverted tires per year). The mixture made up of 5% Rubber Powder and 3% Natural Fibers reached close to optimal balance (Rank 2 for performance and for environmental aspects) and, therefore, justified its choice as the most sustainable material.

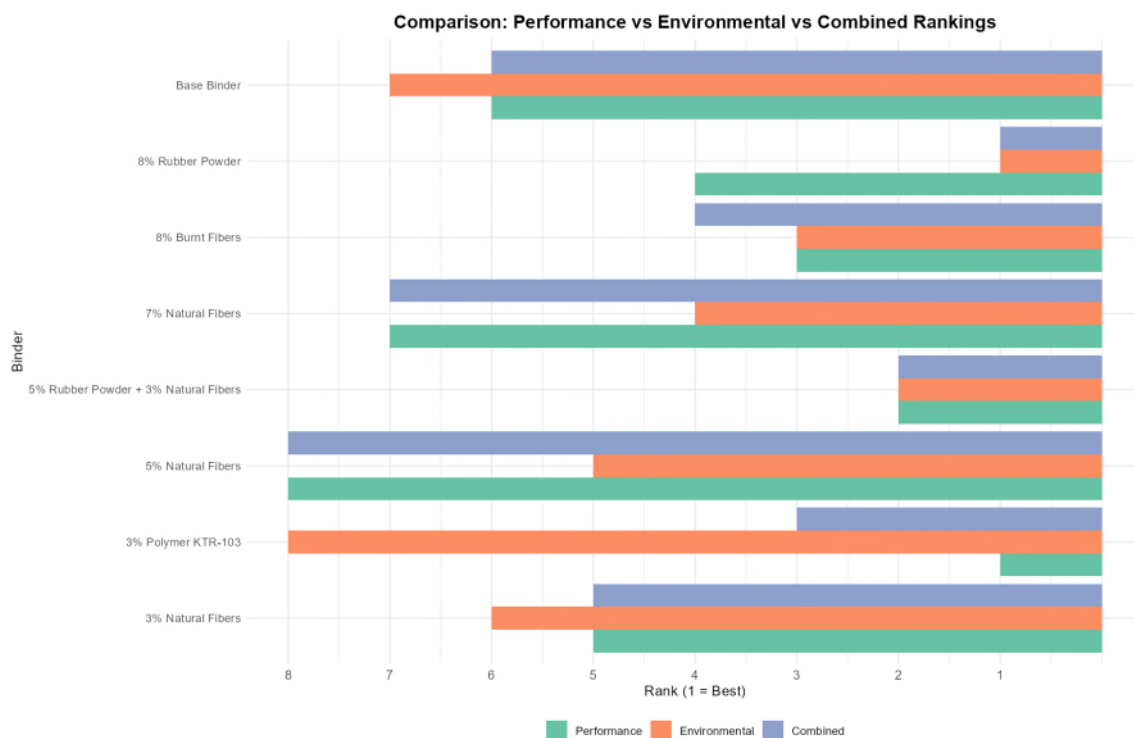


Fig. 11. Comparison of TOPSIS rankings for performance-only, environmental-only, and combined (60% performance + 40% environment) scenarios.

The obtained data show that high environmental benefits brought about by the process of tires recycling due to CO₂ emissions reduction (214.39 kg per ton of material) and a high volume of waste utilization (70,000 tons of tires per year) outweigh slight performance drawbacks.

3.5. Economic Impact Assessment

Based on Equation 3, for the period 2010-2022 using World Bank data, Iran experienced a GDP growth rate of 2.5% per year and a carbon emission growth rate of 3.8% per year. Therefore using equation 3 we have 0.658 for P, which indicates that a 1% change in emissions is in tandem with 0.658% change in GDP for the case of Iran.

720 According to figures from the Iran Road Maintenance and Transportation Organization (RMTO),
721 asphalt consumption at domestic level is 35 million tonnes per annum (consisting of 25 million tonnes
722 of road maintenance and 10 million tonnes of municipal use), whereas the country's production
723 capacity stands at more than 150 million tonnes per annum from about 900 producers (Financial
724 Tribune, 2017). Considering an average binder ratio of 5% per weight of asphalt pavement mix, this
725 means a consumption of about 1.75 million tonnes of asphalt binder per annum in Iran. Using the
726 above figure of binder consumption and the production phase CO₂ reduction obtained for
727 3%NF+5%CR blend (2.8%, which is equal to 1.18kg CO₂ per tonne of asphalt binder), the annual
728 production phase CO₂ reduction can be calculated as:

729
$$\text{Annual CO}_2 \text{ reduction} = 1,750,000 \text{ tons} \times 42.3 \text{ kg/ton} \times 0.028 = 2,073 \text{ tons CO}_2/\text{year}$$

730 The calculation above is for savings during the production phase only. For translating the production
731 phase saving into economic savings for the transportation industry of Iran:

732
$$\text{GDP Impact (Production-Phase)} = (2,073 \text{ tons} / 175,000,000 \text{ tons}) \times 0.658 \times \$31.04 \text{ billion} \approx \$0.24$$

733 million

734 The number 175,000,000 tons stands for Iran's estimated annual emissions of CO₂ in the
735 transportation sector (IEA, 2022); 0.658 is the economic effect coefficient, which is calculated using
736 Equation 3; and \$31.04 billion is Iran's GDP in the transportation sector (Statistical Center of Iran,
737 2020). Even without the benefits from end-of-life tire recycling, the adoption of the improved binder
738 results in certain economic gains through decreased emissions during the production phase. However,
739 the total economic advantage, including the savings from waste disposal, increased life of the
740 pavement, and end-of-life tire recycling, will still be higher.

741 GDP percentage change for transportation industry in each scenario (CR) has been determined using
742 Equation 4. Under Aggressive scenario, a lifecycle net CO₂ benefit of 143,010 tons/year translates to
743 a GDP percentage change of 0.0548%, which means that the GDP impact is \$16.77 million. The
744 results of all the scenarios are given in Table 9 below.

745 **3.6. Limitations and Assumptions**

746 Assumptions made for the environmental assessment include the following:

- 747 1. Grid emission factor: Iran's grid emission factor (0.67 kg CO₂/kWh) was based on data from
748 2020 and varies by region.
- 749 2. Tire recycling credit: It was assumed that tires would be incinerated or landfilled instead of
750 recycled.
- 751 3. Scale of production: Laboratory energy generation results were scaled up to industrial
752 production.
- 753 4. Transportation effects: The effects of transporting materials and the emissions generated by
754 construction machinery were ignored.
- 755 5. End of life: Modified binders were assumed to have the same end-of-life processing
756 requirements as regular asphalt.
- 757 6. Service life: Service life improvements were not accounted for in the assessment.

758 These findings align with those obtained from the research conducted by Gilfillan & Marland (2021),
759 where the case is Iran, which is among the main emitters in the Middle East region, where energy
760 intensity acts as the main driver in contributing to increased emissions in line with increased
761 population and wealth levels. These positive contributions towards the environment highlighted in
762 the current research can help significantly in reducing carbon footprints in the transportation
763 infrastructure industry in Iran.

764 This study involves the following processes: (1) asphalt binder manufacturing process (including
765 heating and mixing), (2) processing of the materials (fiber manufacturing, rubber grinding), and (3)
766 credits for waste tire diversion.

767 **Recommendations for Future Research**

768 According to the results and limitations found from this research work, it is recommended that future
769 works include:

- 770 1. Field validation: Pilot plant tests and test sections for a prolonged period of time (more than 5
771 years) need to be conducted to prove the results found from the laboratory studies.
- 772 2. Aging effect: Long term aging effect (after 5-10 year of PAV simulation) needs to be studied to
773 determine the longevity of fiber modified binder using goats' hair fibers.
- 774 3. Moisture sensitivity: Moisture sensitivity of the mixture containing goats' hair fibers needs to be
775 tested since the natural fibers have a tendency to take moisture.
- 776 4. Optimization of modifier: The modification process can be further optimized by changing the
777 parameters of fiber-rubber mixture (length of fiber, rubber particle size).
- 778 5. Other fibers from animals: Research into other fibers available locally from animals (e.g.,
779 camel fiber, cattle hair) as asphalt modifiers that are sustainable and environment-friendly.
- 780 6. Life cycle costing: A full life cycle costing evaluation including cost savings during
781 maintenance, extended life of the product and benefits at the end of the life of recycling would give
782 a more accurate economic analysis.
- 783 7. Applicability in other regions: The environmental analysis needs to be done in other regions
784 with different energy sources and waste management techniques.
- 785 8. Multi-criteria decision-making framework enhancement: The TOPSIS approach presented in
786 this research should be expanded to take into account additional criteria like cost, feasibility of
787 construction, and field performance data.

788 **Practical Implications**

789 Implications of the study include the following for the pavement industry:

- 790 1. Immediate implementation: The modified 3%NF+5%CR mix can be implemented through
791 current asphalt plants with few changes since the mixing temperature, duration, and speed fall within
792 the traditional boundaries.

- 793 2. Circular economy: The application of goat hair fibers, which is an agricultural by-product,
794 together with crumb rubber from used tires is a way to recycle two waste streams at once.
- 795 3. Viable financially: At the production phase, the GDP gain is expected to reach \$0.24 million,
796 while the potential economic savings amount to \$16.77 million when 60% of the roads will use the
797 modified binder.
- 798 4. Environmental requirements compliance: The net negative lifecycle emission of -93.9 kg CO₂
799 per ton makes the binder a potentially viable solution for transportation departments who need to
800 reduce the carbon footprint of their construction.
- 801 5. The potential in other regions: Taking into account the availability of goat hair fibers in
802 Middle Eastern countries and the wide prevalence of used tires worldwide, this technology may
803 become useful for both developing and developed countries.
- 804 6. Better performance: Better resistance to rutting, fatigue, and thermal cracking results in
805 increased pavement life and less frequent maintenance procedures.
- 806 7. Evidence-based material selection: The TOPSIS methodology is a quantitative method for
807 making the selection of materials that are based on both the performance and sustainability metrics.
808 For projects which emphasize on sustainability, the best material is 8% Rubber Powder with
809 Closeness index equal to 0.95. For balanced projects, the 5% Rubber Powder + 3% Natural Fibers is
810 the optimal blend with Closeness = 0.73. The KTR-103 polymer is superior mechanically, but its
811 Closeness index equals to 0.22 only.

812 **4. Conclusion**

813 The joint application of natural fibers and crumb rubber from discarded tires provides a sustainable
814 and high-performance replacement for asphalt binders. Optimal mixture (3% natural fibers + 5%
815 crumb rubber) provided improved resistance to rutting, fatigue cracking, and thermal cracking, as
816 well as:

- 817 • CO₂ emissions reduction at the production stage: 2.8% (equivalent to 1.18 kg CO₂ per ton of
818 binder)

819 • Negative emissions lifecycle: -93.9 kg CO₂/ton (or 136.2 kg CO₂/ton improvement compared
820 to neat binder that emitted 42.3 kg CO₂/ton, which equals to 322% relative improvement)

821 • National annual benefits (based on 1.75 million tons of asphalt binder utilization in Iran):

822 o Reduction of CO₂ emissions at the production stage: 2,073 tons/year

823 o Lifecycle CO₂ emission improvement (with tires' contribution): 238,350 tons/year

824 o Annually diverting tires from landfills: 87,500 tons/year (35% of annual tire waste of Iran)

825 o Contribution to GDP (60% lifecycle: \$16.77 million)

826 An important observation from this study is that of the performance-sustainability trade-off associated
827 with the KTR-103 polymer reference blend. KTR-103 was found to have the best resistance against
828 rutting and stiffness, making it an efficient high temperature modifier; however, it was also found to
829 consume more energy, emit more CO₂, and be less resistant to fatigue than many of the sustainable
830 blends.

831 In addition to technical advantages, this research provides a contribution to several Sustainable
832 Development Goals of the United Nations. The reuse of waste tire rubber and goat hair fibers is
833 aligned with SDG 12 (Responsible Consumption and Production) . Improved pavement durability
834 contributes to SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and
835 Communities) due to less maintenance and noise abatement. Finally, negative lifetime greenhouse
836 gas emissions (-93.9 kg CO₂/ton, 322% better than neat binder) contribute to SDG 13 (Climate
837 Action).

838 Figure 12 illustrates the final TOPSIS score combination. TOPSIS multi-criteria analysis results
839 revealed that sustainable binders could have an advantage over traditional polymers under the
840 mechanical and environmental criteria. Among the examined binders, the 8% Rubber Powder binder
841 had the best final score (Closeness = 0.95), followed by the 5% Rubber Powder & 3% Natural Fibers
842 mixture (Closeness = 0.73). The third place belongs to the KTR-103 polymer binder, although this
843 one showed better mechanical properties (Closeness = 0.22). This means that even small reductions

in mechanical properties can be compensated with significant environmental advantages of tire recycling (214.39 kg CO₂/ton improvement, 70,000 tons/year tire diversion).

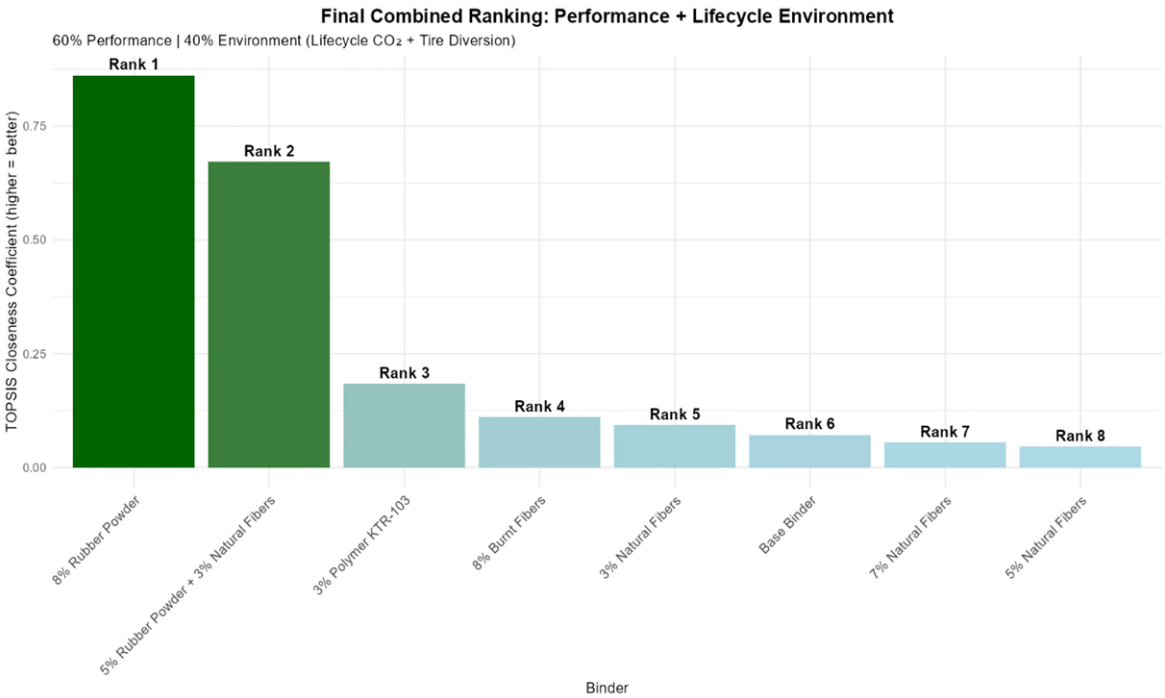


Fig. 12. Final TOPSIS ranking of asphalt binders integrating both mechanical performance and environmental benefits

According to findings, the binder for 8% rubber powder is the best in terms of the aggregate rating (Closeness = 0.95) followed by the 5% rubber powder and 3% natural fibers combination (Closeness = 0.73) despite having better mechanical properties than the KTR-103 polymer (Closeness = 0.22). Some recommendations can be made based on the results of these experiments for application in the future. It is necessary to conduct pilot production experiments to confirm the experimental findings in practice, as well as to conduct field tests with the performance monitoring of such modified binders. Moreover, a life cycle cost assessment including savings on maintenance can be conducted. However, the following limitations are noted for the current study. The current research was performed at laboratory scale with no field validation, and the environmental impact assessment is based on the local data (grid emission factor: 0.67 kg CO₂/kWh) specific to the studied region. The LCA system boundaries did not include aggregate manufacturing, materials transport, construction stage, and pavement lifetime. In addition, further examination of aging characteristics and moisture

861 sensitivity is needed for the large-scale application of the technology. Future research should perform
862 comprehensive LCA analysis with larger system boundaries and field validation.

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864 The manuscript has been edited with the help of AI-powered proofreading tools.

865 **Competing Interests**

866 The authors have no relevant financial or non-financial interests to disclose.

867 **Data Availability**

868 All data required for this manuscript are fully provided within the paper itself.

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