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MECHANICAL AND ENVIRONMENTAL EVALUATION OF LIME-BRICK DUST MODIFIED ASPHALT FOR FLEXIBLE PAVEMENTS

Esra OZKAYNAK [1,*], Kürşat YILDIZ [2]

[1] *Gazi University, Graduate School of Natural and Applied Sciences, Ankara, Türkiye*

[2] *Gazi University, Civil Engineering Department, Ankara, Türkiye*

*** Corresponding Author:** esraozkaynak777@gmail.com, esra.ozkaynak@gazi.edu.tr

ABSTRACT

This research explores the feasibility of incorporating a 1:3 lime and brick dust blend—derived from the core components of traditional Khorasan mortar—as a modifier in hot mix asphalt (HMA). The additive was introduced into the conventional aggregate-bitumen mixture by replacing fine and filler aggregates at a rate of 2% of the total aggregate mass. Its influence on the performance of the wearing course in road pavements was analyzed through a comprehensive set of laboratory experiments. These tests assessed key parameters, including air void content (P_a), optimum bitumen ratio, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), bulk specific gravity (G_{mb}), Marshall stability and flow, indirect tensile strength, and wheel rutting depth, to evaluate durability, flexibility, and resistance to deformation. The findings indicated that the modified mixture outperformed conventional blends, significantly improving the long-term durability of the pavement surface. Furthermore, considering the reuse potential of industrial waste bricks, the lime-brick dust mixture emerged as an environmentally sustainable and viable additive for road pavement applications.

Keywords: Lime, Brick dust, Hot mix asphalt, Wearing course, Mixture modification, Sustainable materials.

1 INTRODUCTION

Binding-based materials such as lime, gypsum, and cement, when combined with natural (e.g., tuff, pumice) or artificial (e.g., brick, tile, and other fired materials) pozzolans and aggregates, are referred to as mortars. These materials are commonly used in the construction industry for applications such as joint filling and plastering. Before the discovery and widespread use of cement, lime-based mortars were frequently employed in construction. One such material is Khorasan mortar, which has been used for centuries to enhance the durability and service life of structures. It is particularly notable for its high tensile strength, resistance to water, and lightweight properties. Although there is no standardized formulation for Khorasan mortar, it is fundamentally composed of a mixture of lime and pozzolans. The mix may include either slaked or unslaked lime in varying proportions, depending on specific requirements. The pozzolanic properties of fired clay materials, such as crushed brick, tile, or ceramic, are determined by the degree of firing, and these materials are typically ground into a fine powder before being used in the mixture. Academic studies focusing on historical structures have sought to identify the original composition of existing Khorasan mortars and to evaluate whether the mixture ratios should be adjusted when restoration is required. Findings from these studies indicate that the lime content, as a percentage of the total mixture, varies between 18% and 60%, with the most common range being around 25% to 30% [1]-[9].

As is well known, road pavements are categorized into three main types: flexible, rigid, and semi-rigid pavements. Flexible pavements consist of a surfacing course placed over a series of base and subbase layers, which are laid unbound on the subgrade (pavement foundation). These pavements are designed to distribute traffic-induced stresses to the subgrade by allowing limited vertical deformations. The bituminous surfacing course, which is designed based on various factors such as traffic load, material properties, design life, and subgrade bearing capacity, consists of multiple layers of varying thicknesses. It is further classified into surface treatment and mixture-type surfacing. Mixture-type surfacing is subdivided into hot mix asphalt, warm mix asphalt, and cold mix asphalt. Hot mix asphalt (HMA), in its simplest form, represents a homogeneous mixture of aggregate with a bituminous binder that possesses adequate viscosity [10].

The performance of HMA is evaluated based on several key criteria, including: stability, fatigue resistance, flexibility, impermeability, durability, skid resistance, and workability. To enhance pavement performance and reduce maintenance costs during service life, modifying HMA with natural or artificial additives has been widely considered. This method has been successfully applied in transportation engineering for many years through the integration of various materials. The literature indicates that the incorporation of polymers (SBS, SBR, EVA), rubber, nanomaterials, and other materials (e.g., natural or waste vegetable oils, bio-based additives, industrial by-products, and reclaimed asphalt pavements) improves the mechanical and chemical properties of HMA. Polymer additives have been shown to enhance the cracking resistance of asphalt mixtures, with SBS demonstrating superior performance in terms of aging and oxidation resistance. SBR has been reported to improve the viscosity and temperature resistance of asphalt. Rubber additives positively influence the physical, chemical, and thermal properties of asphalt pavements, although high temperatures and prolonged mixing times may reduce modification efficiency. Nanomaterials, on the other hand, primarily contribute to mechanical strength improvements but exhibit limited effectiveness against moisture damage. Moreover, studies on composite modification methods, where different additives (polymer-polymer, polymer-rubber, polymer-nanomaterial) are used together, indicate significant improvements in rheological and mechanical properties. These combinations have also been found to positively impact high- and low-temperature performance [11]-[26].

Hydrated lime and brick dust are significant additives with the potential to enhance the mechanical strength, durability, and environmental sustainability of asphalt mixtures. Hydrated lime improves bonding, increases stability, mitigates aging effects, and reduces moisture sensitivity, thereby enhancing long-term performance. Brick dust, on the other hand, provides advantages in reducing permanent deformation and fatigue cracking in flexible pavements. The literature indicates that using hydrated lime as a filler enhances stability, indirect tensile strength, and resistance to moisture damage while improving low-temperature performance. The recommended dosage typically ranges between 1% and 2%, with an optimum level around 2.5%. Furthermore, hydrated lime contributes to environmental sustainability by reducing energy consumption and greenhouse gas emissions. The use of brick dust as a filler or aggregate in asphalt mixtures has been reported to improve Marshall stability and flow values, while reducing permeability and indirect tensile strength at certain levels. An optimal content of 4–5% has been found to produce the best results, whereas higher proportions negatively affect mixture performance. Replacing lime filler with brick dust significantly impacts volumetric properties, and at high replacement rates, it may lead to reduced resistance to moisture and freeze-thaw cycles. Overall, optimizing the use of hydrated lime and brick dust in asphalt mixtures not only enhances technical performance but also enables a cost-effective and sustainable pavement design [27]-[49].

In this manuscript, reference tests were conducted on a conventional HMA design for the wearing course, which forms the top layer of the pavement. The conventional mixture was prepared using limestone and/or basalt aggregates and B50/70 penetration-grade bitumen. In addition to this conventional mix, a new alternative mixture was developed by adding a combination of lime and brick dust, amounting to 2% of the total aggregate weight. These materials, which are key components of Khorasan mortar, were incorporated into the mixture, and performance tests were conducted to evaluate its mechanical and durability properties. Laboratory testing was carried out in accordance with the Highway Technical Specification (KTŞ) prepared by General Directorate of Highways (KGM), Section 407, which defines quality control criteria for the wearing course. These criteria include air void percentage, bitumen content, voids filled with asphalt (VFA), voids in mineral aggregate (VMA), Marshall stability and flow, filler-bitumen ratio, indirect tensile strength, tensile strength ratio, and wheel tracking depth (rutting). Through these laboratory experiments, the effects of lime and brick dust modification on pavement service life and performance were thoroughly examined, contributing to the existing body of literature.

In an era where sustainable infrastructure is no longer a choice but a necessity, the integration of industrial waste materials into asphalt mixtures emerges as a game-changing innovation. This study redefines conventional pavement engineering by introducing lime-brick dust, an additive that not only enhances the mechanical performance of asphalt but also contributes to a greener, more cost-effective, and durable road network. By leveraging the untapped potential of industrial by-products, this research paves the way for a new generation of asphalt design—one that balances engineering excellence, environmental responsibility, and economic viability.

2 MATERIAL AND METHOD

2.1 Aggregate

In the laboratory studies, aggregates were sourced from the Malıköy quarry, known for its limestone-based material, and the Yakupabdal quarry, which provides basalt-based material.

The lower and upper limits for the standard sieve series recommended for the wearing course in KTŞ Section 407, along with the gradation details of the mixture prepared for this study based on these limits, are presented in Table 1. Additionally, the gradation curve is visualized in Figure 1 [28].

Table 1. Gradation limits for the wearing course according to KTŞ and the gradation of the mixture used in this study.

Sieve Size		KTŞ Gradation Limits [28]		Gradation of the Mixture Used in This Study
		Lower Limit	Upper Limit	
mm	**inch**	**% passing**		**% passing**
19	3/4"	100.0	100.0	100.0
12.5	1/2"	88.0	100.0	91.0
9.5	3/8"	72.0	90.0	82.0
4.75	No.4	42.0	52.0	47.0
2.00	No.10	25.0	35.0	28.0
0.425	No.40	10.0	20.0	13.5
0.180	No.80	7.0	14.0	9.5
0.075	No.200	3.0	8.0	4.5

It can be clearly seen from Table 1 that the mixture gradation used in the study complies with the upper and lower gradation limits specified in KTŞ, and consists of 53% coarse, 42.5% fine, and 4.5% filler aggregate by fraction.

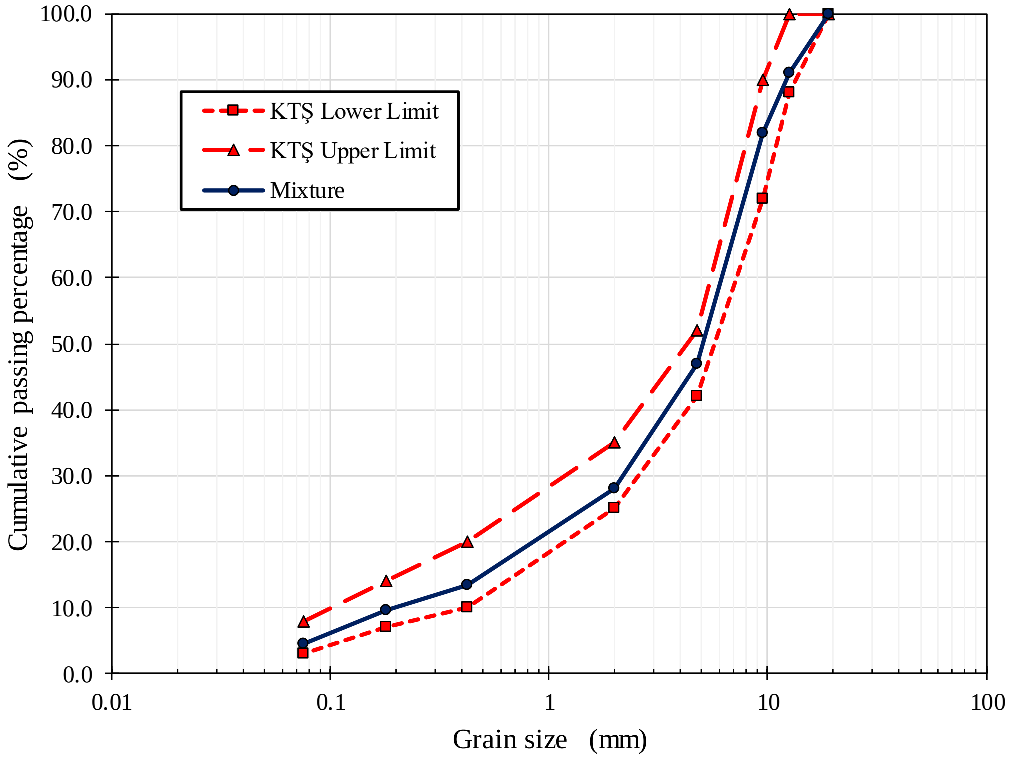

Figure 1. Granulometry curves of KTŞ limits and mixture gradation.

2.2 Asphalt Binder

In this study, a material referred to as Bitumen 50/70, sourced from the Kırıkkale refinery, was used. This material is semi-solid in physical form and contains a minimum of 5% sulfur by weight. The technical properties of this product are presented in Table 2. This bitumen grade selected for this study is one of the most commonly used in Türkiye.

Table 2. Technical properties of the bitumen used in this study.

Properties	Unit	Value	Limit Values	Limit
Penetration (25°C, 100 g, 5 s)	0.1 mm	5.7 mm (57)	50 - 70	-
Softening Point	°C	53	46 - 54	-
Resistance to Hardening (163°C)*				
• **Mass Change**	%	- 0.25	± 0.5	Max.
• **Retained Penetration**	%	53	50	Min.
• **Increase in Softening Point**	°C	6.2	9	Max.
Flash Point	°C	> 290	230	Min.
Solubility	% by weight	99.9	99	Min.

** Only the Rolling Thin Film Oven Test (RTFOT) method should be used as a reference*

2.3 Lime and Brick Dust Mixture

The lime and brick dust mixture used in this study consists of CL 80-S type 100% hydrated lime and brick dust obtained by crushing and grinding broken bricks collected from a brick manufacturing facility in a laboratory environment. Based on insights from the literature, the mix design was formulated using 25% hydrated lime and 75% brick dust. A visual representation of the prepared mixture is provided in Figure 2, which shows the dry blend of hydrated lime and brick dust prior to any binder addition. The physical and chemical properties of the hydrated lime, as reported by the supplier, are presented in Table 3.

The selection of the 25% hydrated lime and 75% brick dust ratio in this study was inspired by the traditional composition of Khorasan mortar, a historical building material known for its durability. Literature on restoration and analysis of historical structures frequently reports lime-to-total-mixture ratios of approximately 1:4 (25%) or 1:3 (~30%) in original Khorasan mortars. Therefore, this proportion was adopted to preserve the material authenticity while aligning with the performance goals of modern asphalt mixtures.

Figure 2. Lime-brick dust mixture prepared for use in this study.

Table 3. Physical and chemical properties of the slaked lime used in this study.

Properties	Unit	Value	Limit
Physical State (20°C)	-	Solid	-
Appearance	-	Powder	-
Color	-	White	-
Odor	-	Odorless	-
Density (20°C)	kg/m^3	2240	-
Bulk Density (20°C)	-	2.24	-
pH (saturated solution)	-	12.5	-
Solubility in Water (20°C)	g/l	1.65	-
Decomposition Temperature	°C	580	-
Melting Point	°C	55	-
Residue on 90-micron Sieve	%	7	Max.
Residue on 200-micron Sieve	%	2	Max.
CO_2 content	%	7	Max.
CaO + MgO	%	80	Min.
SO_3 content	%	2	Max.
MgO content	%	5	Max.
Free Lime	%	65	Min.
Free Water Content	%	2	Max.

2.4 Hot Mix Asphalt

The mixtures prepared in the laboratory consisted of aggregate and bitumen for reference tests, whereas for performance tests, the mixtures were modified by incorporating lime and brick dust in addition to aggregate and bitumen. Furthermore, to analyze the individual effects of the materials on performance, alternative mixtures were also prepared by adding only lime or only brick dust.

Although the combined use of hydrated lime and brick dust in asphalt mixtures has not been previously studied, their individual effects have been widely investigated. Prior studies suggest that the optimum lime content is generally around 2.5%, while the ideal brick dust content ranges between 4% and 5%. Moreover, North American guidelines recommend a lime content between 1% and 2%, and the KTŞ Section 411 specify a recommended range of 0.7% to 2% for hydrated lime. Based on these findings and specifications, a total additive content of 2% was selected for the lime-brick dust mixture in this study. In the prepared mixtures, 2% of the total aggregate weight was replaced with lime and brick dust, while the remaining portion consisted of limestone and/or basalt aggregates sourced from Malıköy and Yakupabdal quarries. The quantities and proportions of the aggregate, lime, and brick dust in these mixtures are detailed in Table 4 and the prepared mixtures are presented in Figure 3.

Figure 3. Mixtures prepared for use in a) reference and b) performance tests.

Table 4. Mixture designs prepared for use in the study.

Quarry Name	Mixture Gradation	Additive Condition	Aggregate Weight in the Mixture (g)	Aggregate Weight (g)	Aggregate Ratio (%)	Lime Weight (g)	Lime Ratio (%)	Brick Dust Weight (g)	Brick Dust Ratio (%)
Malıköy	General Mixture Gradation	No Additive	1150	1150	100	-	-	-	-
Yakupabdal	General Mixture Gradation	No Additive	1150	1150	100	-	-	-	-
		Brick Dust Added	1100	1078	98	-	-	22	2
		Lime Added	1150	1127	98	23	2	-	-
Yakupabdal	Alternative Mixture Gradation	No Additive	1100	1100	100	-	-	-	-
		Brick Dust Added	1100	1078	98	-	-	22	2
		Lime Added	1100	1078	98	22	2	-	-
Malıköy & Yakupabdal	General Mixture Gradation	No Additive	1100	1100	100	-	-	-	-
		Brick Dust Added	1100	1078	98	-	-	22	2
		Lime-Brick Dust Added	1100	1078	98	5.5	0.5	16.5	1.5

As seen in Table 4, the same gradation was predominantly used for aggregates sourced from two different quarries, except for Yakupabdal quarry, where an alternative mixture gradation was also tested. In addition to the conventional mixture consisting of aggregate and bitumen, modified mixtures incorporating lime, brick dust, and a lime-brick dust blend were also studied.

2.5 Design of Mixture-Type Pavements

HMA is produced by mixing heated bitumen with hot, dried aggregates. Achieving optimal pavement performance requires a well-designed mix and accurate material property assessment. According to the MS-2 (Asphalt Mix Design Methods) manual by the Asphalt Institute, Marshall, Hveem, and Superpave are the main HMA design methods. This study adopts the Marshall method to determine the optimal bitumen binder content for pavement design [50].

2.6 Laboratory Tests

The experiments were conducted in accordance with the standards detailed in Table 5.

Table 5. Laboratory experiments and standards.

Experiment Name	Test Standard
Materials Finer Than No.200 Sieve in Mineral Aggregates by Washing [51]	AASHTO T11-22
Relative Density (Specific Gravity) and Absorption of Coarse Aggregate [53]	ASTM C127-24
Relative Density (Specific Gravity) and Absorption of Fine Aggregate [54]	ASTM C128-22
Determination of the Particle Density of Filler-Pyknometer Method [55]	TS EN 1097-7
Theoretical Maximum Specific Gravity and Density of Asphalt Mixtures [56]	AASHTO T209-22
Bulk Specific Gravity and Density of Non-Absorptive Compacted Asphalt Mixtures [57]	ASTM D2726M-21
Preparation of Asphalt Mixture Specimens Using Marshall Apparatus [52]	ASTM D6926-20
Marshall Stability and Flow of Asphalt Mixtures [58]	ASTM D6927-22
Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage [60]	AASHTO T283-22
Wheel Tracking [61]	TS EN 12697-22+A1

3 RESULTS AND DISCUSSION

The evaluation of experimental data was conducted by categorizing the aggregates based on their source quarries into three main groups. During this evaluation, the following test results were utilized: specimen preparation using the Marshall apparatus, Marshall stability and flow, resistance to moisture-induced damage (indirect tensile strength), and wheel tracking (rutting) performance.

3.1 Mixtures Prepared Using Malıköy Quarry

In this section, limestone-based aggregates sourced from the Malıköy quarry were used. Marshall specimens were prepared using asphalt mixtures with five different bitumen contents, and stability and flow tests were performed on these specimens. Considering the ideal air void percentage recommended in KTŞ Section 407 for the wearing course, the optimum bitumen content was determined, and other design parameters (VMA, VFA, G_{mb}, stability, and flow) were calculated based on this optimum bitumen content. Subsequently, indirect tensile strength and, consequently, tensile strength ratios were determined for conditioned and unconditioned specimens prepared according to the optimum bitumen content.

The experimental results were compared with the KTŞ Section 407 quality control criteria for the wearing course, confirming that the limestone-based mixture meets all specified requirements. However, during the planning phase of the study, it was intended to evaluate how the performance would be affected by using lime, brick dust, and lime-brick dust in mixtures prepared with aggregates from different rock types. At this stage, however, adding additives to the mixture and conducting the related tests does not appear to be particularly effective. This is because all design parameters obtained using the conventional mixture fall within the optimal ranges prescribed by the specifications, eliminating the need for modifying the conventional mixture.

3.2 Mixtures Prepared Using Yakupabdal Quarry

In this section, basalt-based aggregates sourced from the Yakupabdal quarry were used. Marshall specimens were prepared using asphalt mixtures with five different bitumen contents, and stability and flow tests were conducted on these specimens. The results revealed that compacting mixtures prepared with basalt-based aggregates is significantly challenging. Specifically, the Marshall acceptance criterion requires the specimen height to fall within the range of 63.5 ± 2.5 mm. However, the heights of the specimens were found to be far above this upper limit, indicating difficulties during the compaction stage. VMA values were also significantly higher than the specification limits, underscoring the porous nature of this material and suggesting that both water and bitumen absorption would be considerably high. In summary, although the use of relatively stronger rocks like basalt for the wearing course is desirable, the experimental results clearly highlight the drawbacks of this material.

Given these challenges, it becomes essential to evaluate the performance of aggregates from this quarry when combined with additional additives. To this end, 2% by weight of brick dust and lime were individually added to the basalt-based aggregates. The results showed that the Marshall specimen heights were closer to the standard limits compared to the traditional mixture. While a slight decrease in VMA values was observed, they were still significantly above the specification limits. Furthermore, compared to the mixture without additives, water and bitumen absorption were adversely affected by both brick dust and lime additives.

As an alternative, the mixture gradation was modified while adhering to the boundary values recommended in KTŞ Section 407. Based on this adjustment, mixtures were prepared using aggregates from the Yakupabdal quarry with 2% by weight of either brick dust or lime added. The experimental results for these mixtures similarly indicated that VMA values remained far above the specification limits, leading to similar conclusions.

In conclusion, it was determined that adding brick dust and lime mixture, to aggregates from the Yakupabdal quarry does not provide any significant benefit. Because even lime, a commercial product frequently preferred for mixture modification, failed to meet the specification limits when added to the mixture at the same ratio. When the effects of brick dust and lime on mixture performance were evaluated, similar results were observed. Considering the recycling potential of waste bricks, which are ground into brick dust, it was decided to use only brick dust as an additive in subsequent stages of the study.

3.3 Mixtures Prepared Using from both Yakupabdal and Malıköy Quarries

In this section, basalt and limestone aggregates sourced from the Yakupabdal and Malıköy quarries, respectively, were used together. Considering the relative durability of basalt aggregates for wearing courses, the compaction difficulties associated with their use, and insights from previous trial mixtures, it was decided to source coarse aggregates from the Yakupabdal quarry and fine aggregates and fillers from the Malıköy quarry for the new mixtures. To evaluate the performance of modified mixtures, lime-brick dust was added to the traditional mix recipe consisting of aggregates and bitumen to create next-generation mixtures. For additional comparison, brick dust was also added at the same ratio.

Marshall specimens were prepared for all alternative mixtures at five different bitumen contents, and stability and flow tests were conducted on these specimens. Details of the Marshall specimens and related test results are provided in Table 6, Table 7, and Table 8. Data on air void percentage (P_a), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), bulk specific gravity (G_{mb}), Marshall stability, and flow for each bitumen content are presented as graphs in Figure 4, Figure 5, and Figure 6. Using these graphs, the optimum bitumen content corresponding to the ideal air void percentage for the wearing course, as recommended in KTŞ Section 407, was determined, along with other design parameters (VMA, VFA, G_{mb}, stability, and flow) based on this optimum bitumen content. Subsequently, indirect tensile strengths and tensile strength ratios were determined for conditioned and unconditioned specimens prepared at the optimum bitumen content. These results are detailed in Table 9 through Table 14. Additionally, wheel tracking tests were conducted on specimens prepared at the optimum bitumen content. The results are visualized in Figure 7, Figure 8, and Figure 9, and summarized in Table 15, Table 16, and Table 17.

Table 6. Details and test results of Marshall specimens prepared with B50/70 bitumen and aggregates from Yakupabdal & Malıköy quarries.

Bitumen Content by Weight (%) - Sample No	Average Specimen Height (mm)	Specimen Air-Dry Weight (g)	Specimen Submerged Weight (g)	Specimen Saturated Surface-Dry Weight (g)	Specimen Volume (cm^3)	Bulk Specific Gravity, G_{mb}	Theoretical Max. Specific Gravity, G_{mm}	Air Void Percentage, P_a (%)	Voids in Mineral Aggregate, VMA (%)	Voids Filled with Asphalt, VFA (%)	Marshall Flow (mm)	Marshall Stability (kgf)	Corrected Marshall Stability (kgf)
4.00 - A	64.1	1126.9	641.0	1141.1	500.1	2.253					2.90	1057	1042
4.00 - B	64.3	1130.1	645.3	1145.1	499.8	2.261					3.50	1084	1063
4.00 - C	64.2	1123.2	640.0	1139.4	499.4	2.249					3.00	1084	1066
AVERAGE						2.255	2.477	9.0	16.6	45.8	3.13		1057
4.50 - A	63.3	1136.4	645.7	1143.9	498.2	2.281					3.20	1205	1209
4.50 - B	63.6	1132.9	642.3	1139.2	496.9	2.280					3.10	1064	1061
4.50 - C	63.6	1131.0	642.8	1138.2	495.4	2.283					3.60	1140	1137
AVERAGE						2.281	2.461	7.3	16.0	54.4	3.30		1135
5.00 - A	62.2	1132.7	646.8	1136.6	489.8	2.313					3.60	1195	1230
5.00 - B	62.9	1136.2	647.9	1139.2	491.3	2.313					3.60	1185	1199
5.00 - C	63.0	1134.4	646.5	1138.8	492.3	2.304					3.80	1155	1167
AVERAGE						2.310	2.445	5.5	15.4	64.0	3.67		1198
5.50 - A	62.9	1136.4	646.3	1140.5	494.2	2.299*					4.00	1005	1017
5.50 - B	62.9	1146.7	655.0	1148.9	493.9	2.322					4.80	1238	1253
5.50 - C	62.7	1142.1	650.4	1144.5	494.1	2.311					4.20	1216	1237
AVERAGE						2.317	2.430	4.7	15.5	70.0	4.33		1245
6.00 - A	62.2	1149.7	659.0	1151.6	492.6	2.334					3.50	1090	1122
6.00 - B	62.4	1143.1	654.3	1145.4	491.1	2.328					4.90	1129	1156
6.00 - C	62.4	1144.9	657.9	1147.0	489.1	2.341					5.20	1243	1273
AVERAGE						2.334	2.414	3.3	15.3	78.3	4.53		1184

*$G_{sb(coarse)}$=2.513; $G_{sa(coarse)}$=2.596; Water absorption$_{(coarse)}$=1.27; $G_{sb(fine)}$=2.695; $G_{sa(fine)}$=2.752; Water absorption$_{(fine)}$=0.77; $G_{sa(filler)}$=2.779; $G_{sb(aggregate)}$=2.599; $G_{sa(aggregate)}$=2.668; $G_{mm(mixture)}$=2.622; $G_{se(aggregate)}$=2.622; G_b=1.040; P_{ba}=0.36; Aggregate weight in the specimen=1100 g; Specimen mix temperature=150°C; *:Discarded specimen*

Table 7. Details and test results of Marshall specimens prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and 2% brick dust additive.

Bitumen Content by Weight (%) - Sample No	Average Specimen Height (mm)	Specimen Air-Dry Weight (g)	Specimen Submerged Weight (g)	Specimen Saturated Surface-Dry Weight (g)	Specimen Volume (cm^3)	Bulk Specific Gravity, G_{mb}	Theoretical Max. Specific Gravity, G_{mm}	Air Void Percentage, P_a (%)	Voids in Mineral Aggregate, VMA (%)	Voids Filled with Asphalt, VFA (%)	Marshall Flow (mm)	Marshall Stability (kgf)	Corrected Marshall Stability (kgf)
4.00 - A	64.2	1129.1	644.1	1145.8	501.7	2.251					2.70	1292	1270
4.00 - B	64.6	1132.3	649.9	1150.2	500.3	2.263					3.30	1192	1162
4.00 - C	64.5	1127.6	643.3	1146.7	503.4	2.240					3.30	1272	1243
AVERAGE						2.251	2.478	9.2	16.7	45.2	3.10		1225
4.50 - A	63.9	1138.9	648.9	1145.5	496.6	2.293					4.30	1265	1252
4.50 - B	63.9	1126.0	645.3	1145.0	499.7	2.253*					3.70	1278	1265
4.50 - C	64.2	1137.1	645.7	1147.3	501.6	2.267					4.40	1252	1231
AVERAGE						2.280	2.462	7.4	16.0	54.0	4.13		1242
5.00 - A	62.4	1130.1	644.0	1135.1	491.1	2.301					3.50	1265	1295
5.00 - B	63.6	1137.5	649.0	1141.7	492.7	2.309					3.40	1249	1245
5.00 - C	64.6	1138.4	648.6	1143.3	494.7	2.301					3.80	1138	1110
AVERAGE						2.304	2.446	5.8	15.6	62.7	3.57		1217
5.50 - A	62.0	1139.0	654.0	1141.6	487.6	2.336					4.10	1260	1303
5.50 - B	62.1	1147.2	659.6	1149.6	490.0	2.341					3.60	1205	1242
5.50 - C	61.8	1131.7	646.8	1134.8	488.0	2.319*					3.60	1225	1273
AVERAGE						2.339	2.430	3.8	14.7	74.4	3.77		1273
6.00 - A	62.7	1153.6	664.7	1155.7	491.0	2.349					4.00	1137	1156
6.00 - B	62.2	1149.9	661.5	1152.2	490.7	2.343					4.70	1154	1187
6.00 - C	62.2	1148.1	658.4	1150.3	491.9	2.334					6.00	1292	1329
AVERAGE						2.342	2.415	3.0	15.0	79.9	4.90		1224

*$G_{sb(coarse)}$=2.513; $G_{sa(coarse)}$=2.596; Water absorption$_{(coarse)}$=1.27; $G_{sb(fine)}$=2.695; $G_{sa(fine)}$=2.755; Water absorption$_{(fine)}$=0.81; $G_{sa(filler)}$=2.776; $G_{sb(aggregate)}$=2.599; $G_{sa(aggregate)}$=2.669; $G_{mm(mixture)}$=2.623; $G_{se(aggregate)}$=2.623; G_b=1.040; P_{ba}=0.37; Aggregate weight in the specimen=1100 g; Specimen mix temperature=150°C; *:Discarded specimen*

Table 8. Details and test results of Marshall specimens prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and a 2% lime-brick dust additive.

Bitumen Content by Weight (%) - Sample No	Average Specimen Height (mm)	Specimen Air-Dry Weight (g)	Specimen Submerged Weight (g)	Specimen Saturated Surface-Dry Weight (g)	Specimen Volume (cm^3)	Bulk Specific Gravity, G_{mb}	Theoretical Max. Specific Gravity, G_{mm}	Air Void Percentage, P_a (%)	Voids in Mineral Aggregate, VMA (%)	Voids Filled with Asphalt, VFA (%)	Marshall Flow (mm)	Marshall Stability (kgf)	Corrected Marshall Stability (kgf)
4.00 - A	63.7	1126.4	642.8	1137.7	494.9	2.276					3.00	1296	1288
4.00 - B	63.4	1126.9	643.8	1140.1	496.3	2.271					3.00	1249	1250
4.00 - C	63.7	1126.2	642.9	1139.5	496.6	2.268					2.46	1343	1335
AVERAGE						2.271	2.481	8.5	15.7	46.3	2.82		1291
4.50 - A	62.7	1136.2	648.8	1141.8	493.0	2.305					2.90	1338	1361
4.50 - B	62.3	1133.4	645.8	1136.9	491.1	2.308					3.10	1312	1346
4.50 - C	62.9	1133.8	647.8	1138.7	490.9	2.310					3.00	1254	1269
AVERAGE						2.307	2.465	6.4	14.8	56.9	3.00		1325
5.00 - A	62.5	1139.2	651.8	1142.8	491.0	2.320					3.10	1204	1230
5.00 - B	61.8	1141.2	655.0	1143.9	488.9	2.334					3.20	1336	1388
5.00 - C	61.7	1133.6	649.5	1137.0	487.5	2.325					2.80	1223	1273
AVERAGE						2.327	2.449	5.0	14.5	65.6	3.03		1297
5.50 - A	62.1	1140.0	654.9	1142.7	487.8	2.337					4.20	1198	1235
5.50 - B	61.6	1143.8	659.1	1146.1	487.0	2.349					3.40	1163	1214
5.50 - C	61.0	1138.9	658.5	1141.0	482.5	2.360					3.60	1283	1359
AVERAGE						2.349	2.433	3.5	14.1	75.4	3.73		1269
6.00 - A	61.2	1144.0	661.4	1145.6	484.2	2.363					4.60	1210	1275
6.00 - B	61.2	1139.0	657.2	1141.0	483.8	2.354					4.70	1014	1069
6.00 - C	61.4	1138.8	657.8	1141.4	483.6	2.355					4.00	1089	1142
AVERAGE						2.357	2.418	2.5	14.2	82.3	4.43		1162

$G_{sb(coarse)}$=2.513; $G_{sa(coarse)}$=2.596; Water absorption$_{(coarse)}$=1.27; $G_{sb(fine)}$=2.682; $G_{sa(fine)}$=2.740; Water absorption$_{(fine)}$=0.79; $G_{sa(filler)}$=2.737; $G_{sb(aggregate)}$=2.592; $G_{sa(aggregate)}$=2.662; $G_{mm(mixture)}$=2.615; $G_{se(aggregate)}$=2.627; G_b=1.040; P_{ba}=0.53; Aggregate weight in the specimen=1100 g; Specimen mix temperature=150°C

As indicated in the footnotes of Tables 6, 7, and 8, aggregates were separated in accordance with the mix gradation required by the Marshall design method. The bulk and apparent specific gravities and water absorption percentages were determined for coarse, fine, and filler aggregates. Based on these values, the overall apparent and bulk specific gravities of the aggregate blend were calculated. In addition, the effective specific gravity of the aggregate was determined using the theoretical maximum specific gravity of the loose mix and the specific gravity of the bitumen.

For each of the five selected bitumen content levels, three Marshall specimens were prepared. By measuring the height and weight of the specimens under various conditions, their bulk specific gravities were calculated, and average values were determined for each bitumen content. For each level, the theoretical maximum specific gravity, air void content, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) were also calculated. Finally, Marshall stability and flow tests were performed on all specimens in accordance with the relevant standard, and stability values were corrected based on specimen heights.

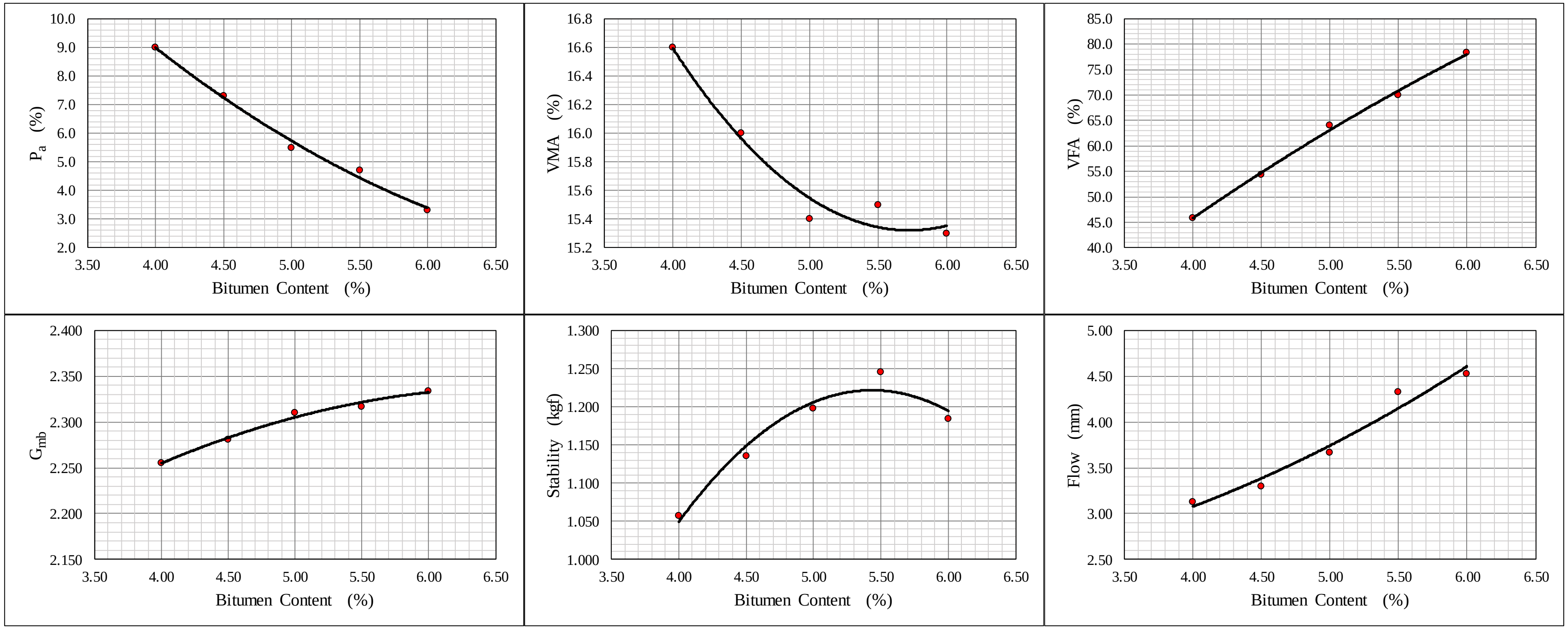

Figure 4. Test curves used to determine the design parameters of the conventional mixture prepared with B50/70 bitumen and aggregates from Yakupabdal & Malıköy quarries.

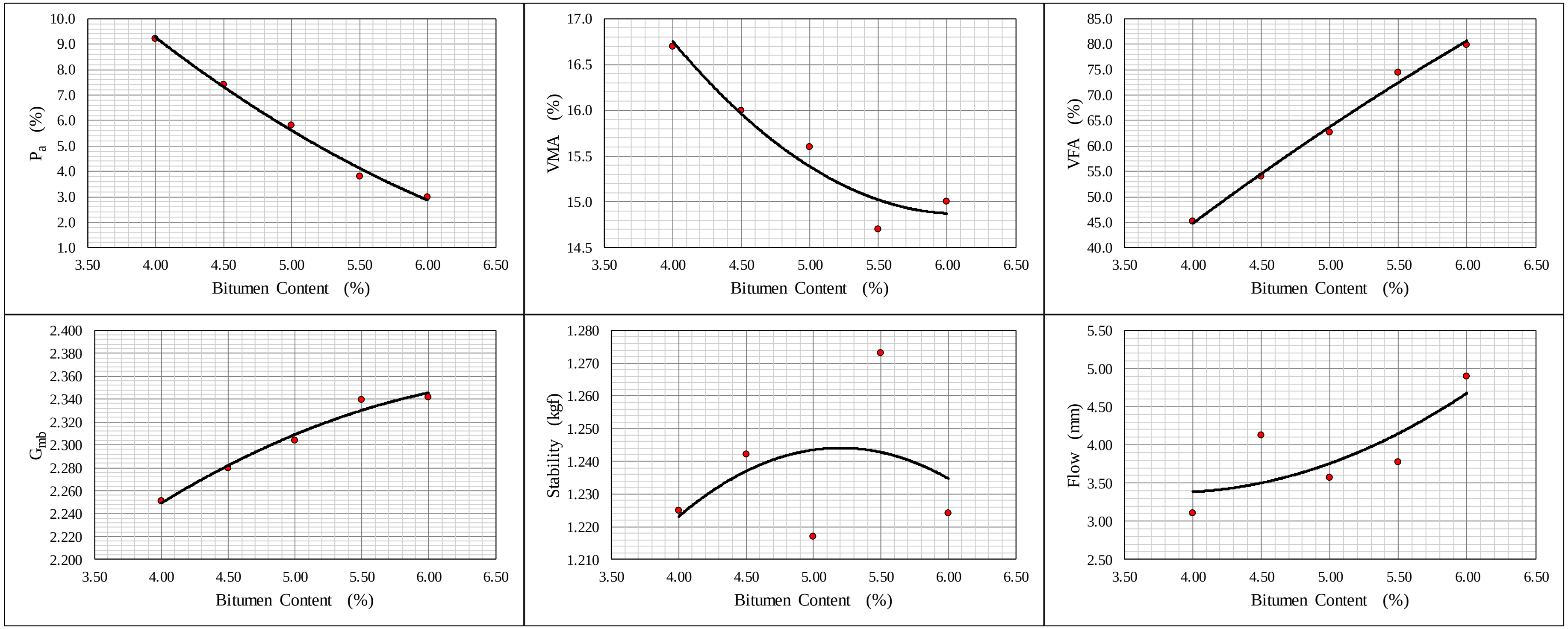

Figure 5. Test curves used to determine the design parameters of the modified mixture prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and 2% brick dust additive.

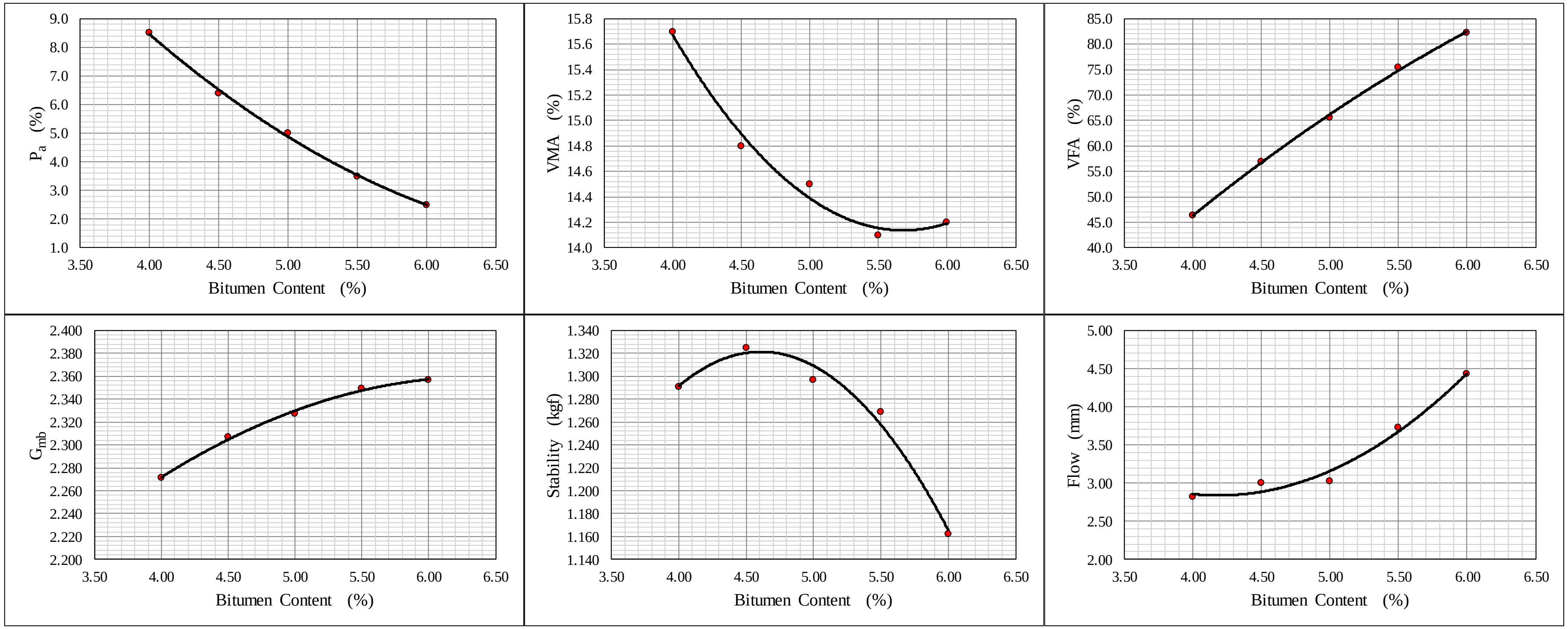

Figure 6. Test curves used to determine the design parameters of the modified mixture prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and a 2% lime-brick dust additive.

In accordance with the MS-2 (Asphalt Mix Design Methods) manual published by the Asphalt Institute, the graphs in Figures 4, 5, and 6 were constructed using polynomial fitting rather than a linear approach, as the relationships between variables are better represented in this form. Using these graphs and considering the acceptable range for the wearing course specified in KTŞ Section 407, the optimum bitumen content was determined based on the selected target air void content, and subsequently, other design parameters—including VMA, VFA, G_{mb}, stability, and flow—were derived accordingly.

Although an initial target of 4% air voids was assumed, it was essential that all other parameters associated with the corresponding optimum bitumen content also fell within the optimum range defined by the specification. As a result, air void values were selected as 4.2%, 4.5%, and 4.3%, corresponding to optimum bitumen contents of 5.6%, 5.35%, and 5.2%, respectively. Based on these optimum bitumen contents, the respective values of VMA, VFA, G_{mb}, Marshall stability, and flow were determined.

Table 9. Details and test results of conditioned specimens prepared with B50/70 bitumen and aggregates from Yakupabdal & Malıköy quarries (Optimum bitumen content=5.6%; Gmm(mixtures)=2.425; Average specimen diameter=101.6 mm).

Sample No	Average Specimen Height (mm)	Specimen Air-Dry Weight (g)	Specimen Submerged Weight (g)	Specimen Saturated Surface-Dry Weight (g)	Specimen Volume (cm^3)	Bulk Specific Gravity, G_{mb}	Air Void Percentage, P_a (%)	Air Void Volume (cm^3)	Vacuum Saturated Specimen Air-Dry Weight (g)	Specimen Saturation Percentage (%)	Specimen Ultimate Load (kgf)	Specimen Indirect Tensile Strength (kgf/cm^2)
1	62.3	1143.4	655.5	1147.6	492.1	2.324	4.2	20.6	1159.8	79.6	1248	12.6
2	62.9	1144.1	653.6	1147.4	493.8	2.317	4.5	22.0	1160.1	72.7	1208	12.0
5	62.9	1144.9	655.7	1147.1	491.4	2.330	3.9	19.3	1159.0	73.1	1168	11.6
7	62.5	1145.2	657.0	1147.6	490.6	2.334	3.7	18.4	1159.1	75.7	1229	12.3
AVERAGE						2.326	4.1					12.1

Table 10. Details and test results of unconditioned specimens prepared with B50/70 bitumen and aggregates from Yakupabdal & Malıköy quarries (Optimum bitumen content=5.6%; Gmm(mixtures)=2.425; Average specimen diameter=101.6 mm).

Sample No	Average Specimen Height (mm)	Specimen Air-Dry Weight (g)	Specimen Submerged Weight (g)	Specimen Saturated Surface-Dry Weight (g)	Specimen Volume (cm^3)	Bulk Specific Gravity, G_{mb}	Air Void Percentage, P_a (%)	Specimen Ultimate Load (kgf)	Specimen Indirect Tensile Strength (kgf/cm^2)
3	62.7	1141.1	651.9	1143.9	492.0	2.319	4.4	1441	14.4
4	62.6	1143.8	655.0	1145.8	490.8	2.330	3.9	1119	11.2
6	63.0	1146.0	655.8	1147.9	492.1	2.329	4.0	1331	13.3
8	62.1	1137.4	650.9	1139.8	488.9	2.326	4.1	1255	12.6
AVERAGE						2.326	4.1		12.9

Table 11. Details and test results of conditioned specimens prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and 2% brick dust additive (Optimum bitumen content=5.35%; Gmm(mixtures)=2.432; Average specimen diameter=101.6 mm).

Sample No	Average Specimen Height (mm)	Specimen Air-Dry Weight (g)	Specimen Submerged Weight (g)	Specimen Saturated Surface-Dry Weight (g)	Specimen Volume (cm^3)	Bulk Specific Gravity, G_{mb}	Air Void Percentage, P_a (%)	Air Void Volume (cm^3)	Vacuum Saturated Specimen Air-Dry Weight (g)	Specimen Saturation Percentage (%)	Specimen Ultimate Load (kgf)	Specimen Indirect Tensile Strength (kgf/cm^2)
1	62.4	1136.7	651.3	1140.1	488.8	2.325	4.4	21.4	1149.0	57.5	920	9.2
3	62.8	1140.1	652.3	1142.8	490.5	2.324	4.4	21.7	1158.0	82.5	900	9.0
4	63.3	1140.6	654.9	1144.0	489.1	2.332	4.1	20.1	1154.5	69.1	883	8.7
7	62.3	1140.3	655.0	1142.8	487.8	2.338	3.9	18.9	1155.2	78.7	957	9.6
AVERAGE						2.330	4.2					9.1

Table 12. Details and test results of unconditioned specimens prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and 2% brick dust additive (Optimum bitumen content=5.35%; Gmm(mixtures)=2.432; Average specimen diameter=101.6 mm).

Sample No	Average Specimen Height (mm)	Specimen Air-Dry Weight (g)	Specimen Submerged Weight (g)	Specimen Saturated Surface-Dry Weight (g)	Specimen Volume (cm^3)	Bulk Specific Gravity, G_{mb}	Air Void Percentage, P_a (%)	Specimen Ultimate Load (kgf)	Specimen Indirect Tensile Strength (kgf/cm^2)
2	63.1	1137.8	650.4	1140.7	490.3	2.321	4.6	1065	10.6
5	62.4	1133.8	649.8	1136.2	486.4	2.331	4.2	1046	10.5
6	62.4	1142.1	656.3	1144.7	488.4	2.338	3.9	1082	10.9
8	62.6	1138.7	653.3	1142.2	488.9	2.329	4.2	1072	10.7
AVERAGE						2.330	4.2		10.7

Table 13. Details and test results of conditioned specimens prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and a 2% lime-brick dust additive (Optimum bitumen content=5.2%; Gmm(mixtures)=2.443; Average specimen diameter=101.6 mm).

Sample No	Average Specimen Height (mm)	Specimen Air-Dry Weight (g)	Specimen Submerged Weight (g)	Specimen Saturated Surface-Dry Weight (g)	Specimen Volume (cm^3)	Bulk Specific Gravity, G_{mb}	Air Void Percentage, P_a (%)	Air Void Volume (cm^3)	Vacuum Saturated Specimen Air-Dry Weight (g)	Specimen Saturation Percentage (%)	Specimen Ultimate Load (kgf)	Specimen Indirect Tensile Strength (kgf/cm^2)
1	62.1	1098.9	630.7	1101.7	471.0	2.333	4.5	21.2	1114.2	72.2	980	9.9
3	62.3	1142.3	658.2	1144.7	486.5	2.348	3.9	18.9	1153.6	59.7	1109	11.2
4	60.1	1137.8	652.5	1140.3	487.8	2.333	4.5	22.1	1151.5	62.1	1004	10.5
8	62.9	1140.5	654.6	1143.3	488.7	2.334	4.5	21.9	1154.8	65.4	1187	11.8
10	62.8	1141.5	657.6	1144.7	487.1	2.343	4.1	19.9	1153.3	59.5	1181	11.8
AVERAGE						2.338	4.3					11.0

Table 14. Details and test results of unconditioned specimens prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and a 2% lime-brick dust additive (Optimum bitumen content=5.2%; Gmm(mixtures)=2.443; Average specimen diameter=101.6 mm).

Sample No	Average Specimen Height (mm)	Specimen Air-Dry Weight (g)	Specimen Submerged Weight (g)	Specimen Saturated Surface-Dry Weight (g)	Specimen Volume (cm^3)	Bulk Specific Gravity, G_{mb}	Air Void Percentage, P_a (%)	Specimen Ultimate Load (kgf)	Specimen Indirect Tensile Strength (kgf/cm^2)
2	62.7	1142.1	654.6	1144.8	490.2	2.330	4.6	1139	11.4
5	62.3	1142.3	657.0	1144.9	487.9	2.341	4.2	1010	10.2
6	62.9	1141.9	657.4	1145.0	487.6	2.342	4.1	1282	12.8
7	62.6	1145.9	658.2	1148.7	490.5	2.336	4.4	1251	12.5
9	62.1	1141.3	657.6	1144.7	487.1	2.343	4.1	1212	12.2
AVERAGE						2.338	4.3		11.8

The specimens prepared at optimum bitumen content were divided into two equal groups, with those listed in Tables 9, 11, and 13 subjected to conditioning before undergoing the indirect tensile strength (ITS) test, while those in Tables 10, 12, and 14 were tested in dry (unconditioned) state. When dividing the Marshall specimens into two subgroups, care was taken to ensure that their average bulk specific gravities or average air void percentages were equal or closely matched. As shown in the tables, the individual ITS values of both conditioned and unconditioned specimens exceed 5 kgf/cm^2, meeting the KTŞ specification criteria. Moreover, the tensile strength ratios (TSR)—calculated as the ratio of the average ITS of conditioned specimens to that of unconditioned ones—were also found to be above the 80% threshold, in compliance with the standard.

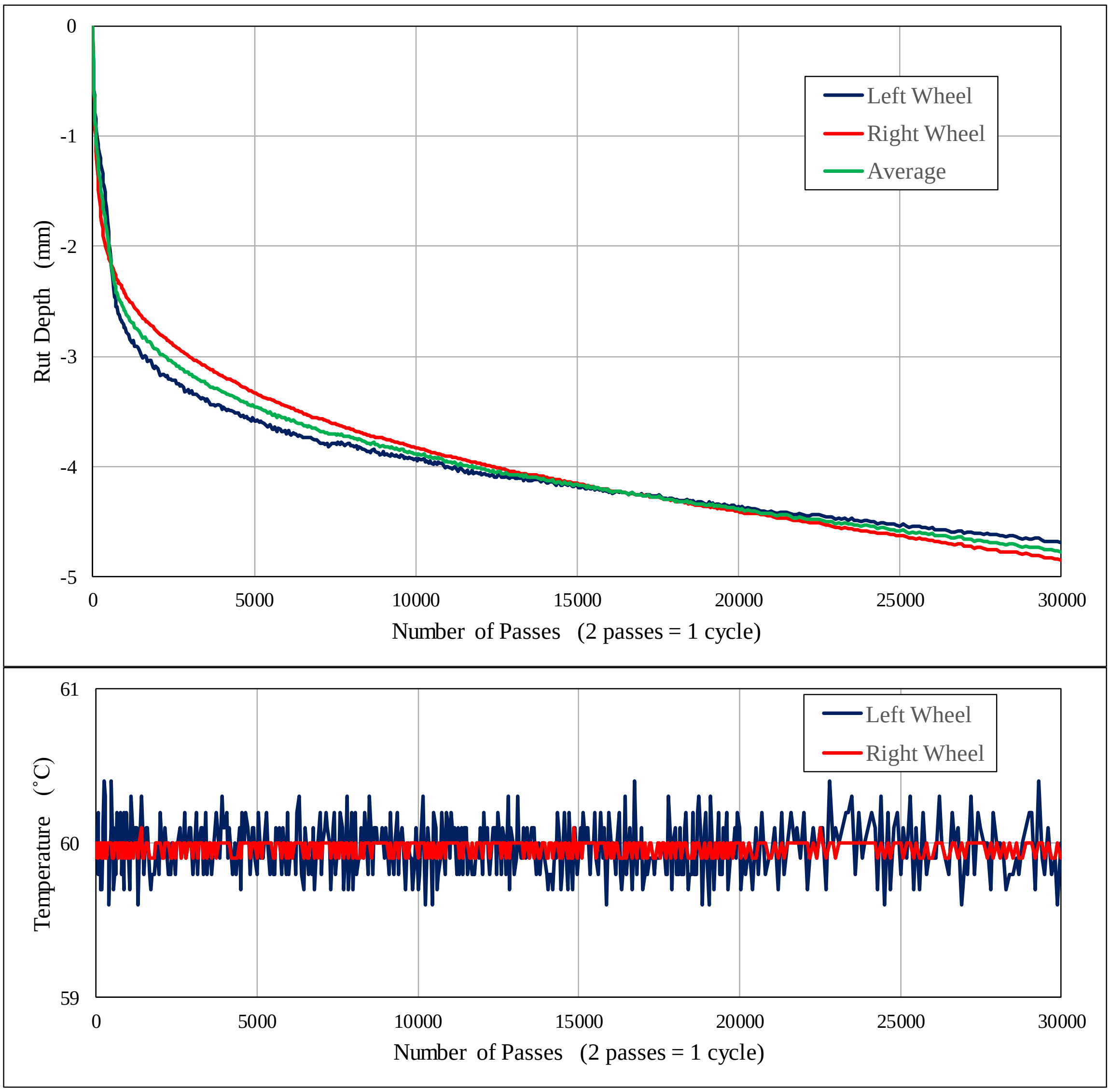

Figure 7. Wheel tracking test results of the conventional mixture prepared with B50/70 bitumen and aggregates from Yakupabdal & Malıköy quarries.

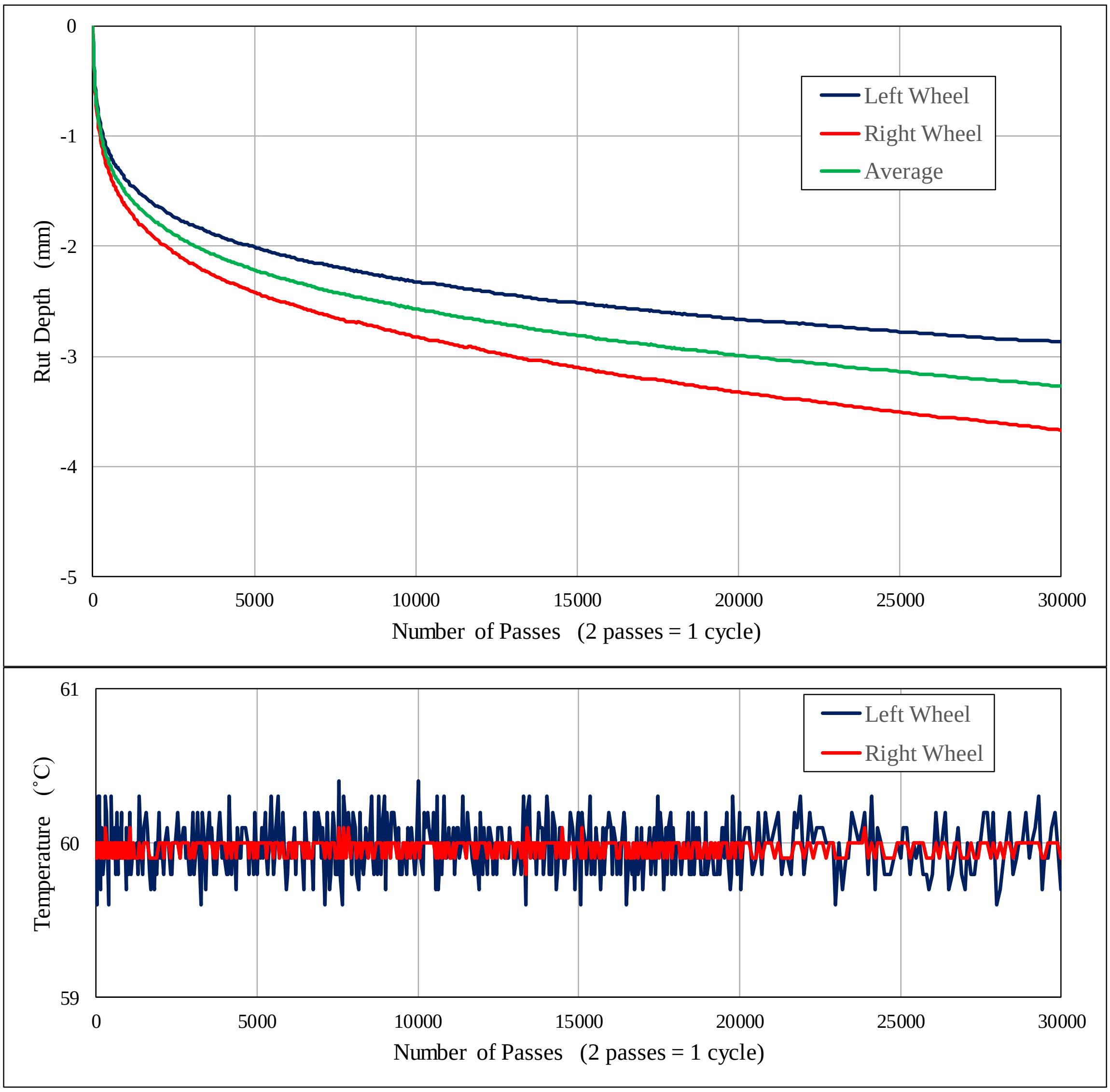

Figure 8. Wheel tracking test results of the modified mixture prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and 2% brick dust additive.

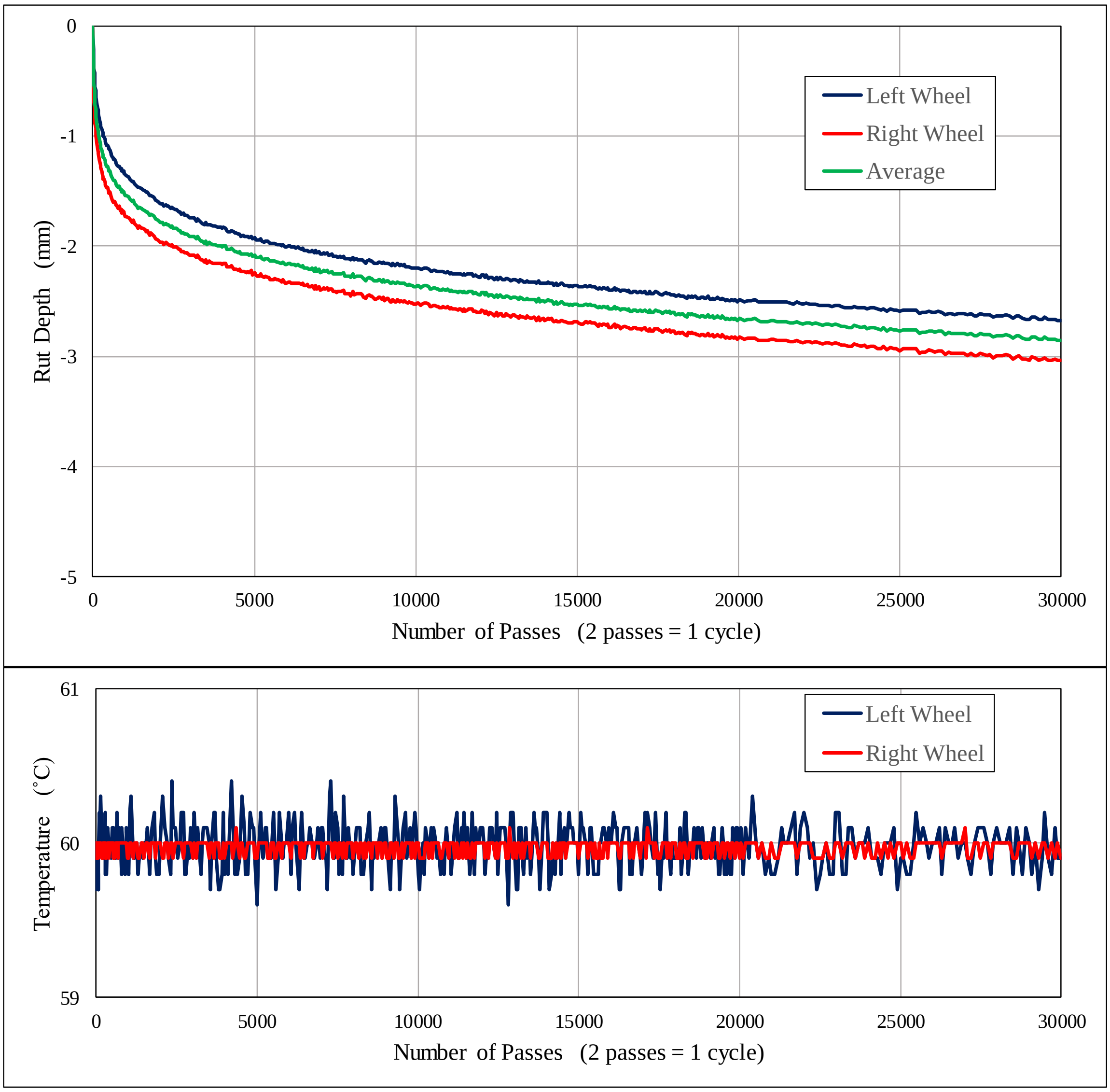

Figure 9. Wheel tracking test results of the modified mixture prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and a 2% lime-brick dust additive.

Figures 7, 8, and 9 show the wheel tracking depth as a function of the number of passes during the wheel tracking test, including results for both wheels and their average values. The specimen temperature was monitored to maintain the standard-prescribed 60 ± 1°C. Per the standard, the test should end at 20 mm wheel tracking depth or 10,000 cycles, but it was extended to 30,000 passes (15,000 cycles) to prevent data loss from potential sudden deformations due to voids. The graphs provide wheel tracking depth, proportional depth, and slope values. The results indicate a notable reduction in wheel tracking depth for modified mixtures, with lime-brick dust additive showing the best performance.

Table 15. Evaluation of wheel tracking test data for the conventional mixture prepared with B50/70 bitumen and aggregates from Yakupabdal & Malıköy quarries.

Sample	Wheel Rut Slope (mm/1,000 cycles) [cycle range]	Wheel Rut Slope - Linear Section (mm/1,000 cycles) [cycle range]	Wheel Rut Depth (mm) [cycle count]	Proportional Wheel Rut Depth (%) [cycle count]
Left Wheel	0.09 [10,000 - 5,000]	0.06 [14,300 - 12,300]	3.9 - 4.4 - 4.7 [5,000 - 10,000 - 15,000]	9.4 [15,000]
Right Wheel	0.11 [10,000 - 5,000]	0.09 [12,700 - 10,700]	3.8 - 4.4 - 4.9 [5,000 - 10,000 - 15,000]	9.7 [15,000]
Average	0.10	0.08	3.9 - 4.4 - 4.8	9.5

Table 16. Evaluation of wheel tracking test data for the modified mixture prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and 2% brick dust additive.

Sample	Wheel Rut Slope (mm/1,000 cycles) [cycle range]	Wheel Rut Slope - Linear Section (mm/1,000 cycles) [cycle range]	Wheel Rut Depth (mm) [cycle count]	Proportional Wheel Rut Depth (%) [cycle count]
Left Wheel	0.07 [10,000 - 5,000]	0.04 [13,900 - 11,900]	2.3 - 2.7 - 2.9 [5,000 - 10,000 - 15,000]	5.7 [15,000]
Right Wheel	0.10 [10,000 - 5,000]	0.08 [12,250 - 10,250]	2.8 - 3.3 - 3.7 [5,000 - 10,000 - 15,000]	7.3 [15,000]
Average	0.08	0.06	2.6 - 3.0 - 3.3	6.5

Table 17. Evaluation of wheel tracking test data for the modified mixture prepared with B50/70 bitumen, aggregates from Yakupabdal & Malıköy quarries, and a 2% lime-brick dust additive.

Sample	Wheel Rut Slope (mm/1,000 cycles) [cycle range]	Wheel Rut Slope - Linear Section (mm/1,000 cycles) [cycle range]	Wheel Rut Depth (mm) [cycle count]	Proportional Wheel Rut Depth (%) [cycle count]
Left Wheel	0.06 [10,000 - 5,000]	0.04 [12,150 - 10,150]	2.2 - 2.5 - 2.7 [5,000 - 10,000 - 15,000]	5.3 [15,000]
Right Wheel	0.06 [10,000 - 5,000]	0.04 [12,050 - 10,050]	2.5 - 2.8 - 3.0 [5,000 - 10,000 - 15,000]	6.1 [15,000]
Average	0.06	0.04	2.4 - 2.7 - 2.9	5.7

Tables 15, 16, and 17 present key parameters calculated using graphs derived from wheel tracking test data. The wheel tracking slope was determined both from 5,000–10,000 cycles, as specified in the standard, and from the linear segment covering at least 2,000 cycles. A decrease in this value for modified mixtures compared to the conventional mixture indicates improved resistance to wheel tracking deformation. A similar assessment can be made based on wheel tracking depth at specific cycle counts, with 5,000, 10,000, and 15,000 cycle depths (in mm) listed in the tables. Additionally, the proportional wheel tracking depth, which expresses material deformation as a percentage of the initial specimen height, is significantly lower in modified mixtures than in the conventional mix. Considering all performance criteria from the wheel tracking test, the lime-brick dust additive stands out as having the most significant positive effect among the modified mixtures.

Table 18 summarizes the results, comparing them with KTŞ Section 407 quality control criteria, while Figure 10 presents bar charts showing the relationships between design parameters for all mixtures.

Table 18. Comparison of design parameters and specification criteria for mixtures (conventional, 2% brick dust modified, and 2% lime-brick dust modified) prepared with B50/70 bitumen and aggregates from Yakupabdal & Malıköy quarries.

Properties	Mixture Design Parameters			Specification Criteria [28]
	Conventional	2% Brick Dust Additive	2% Lime-Brick Dust Additive	
Air Void Percentage, P_a (%)	4.2	4.5	4.3	3.0 – 5.0
Bitumen Content by Weight (%)	5.6	5.35	5.2	4.0 – 7.0
Voids in Mineral Aggregate, VMA (%)	15.30	15.10	14.26	14 - 16
Voids Filled with Asphalt, VFA (%)	72.5	70.0	69.0	65 - 75
Marshall Flow (mm)	4.23	4.02	3.32	2 - 4
Marshall Stability (kgf)	1220	1244	1292	≥ 900
Filler / Bitumen Ratio	0.80	0.84	0.87	≤ 1.5
Tensile Strength Ratio, TSR (%)	94.3	85.7	93.3	≥ 80
Indirect Tensile Strength, ITS (kg/cm^2)	≥ 11.2	≥ 8.7	≥ 9.9	≥ 5
Wheel Rutting Depth (mm) [for 10,000 cycle]	4.4	3.0	2.7	≤ 4.5

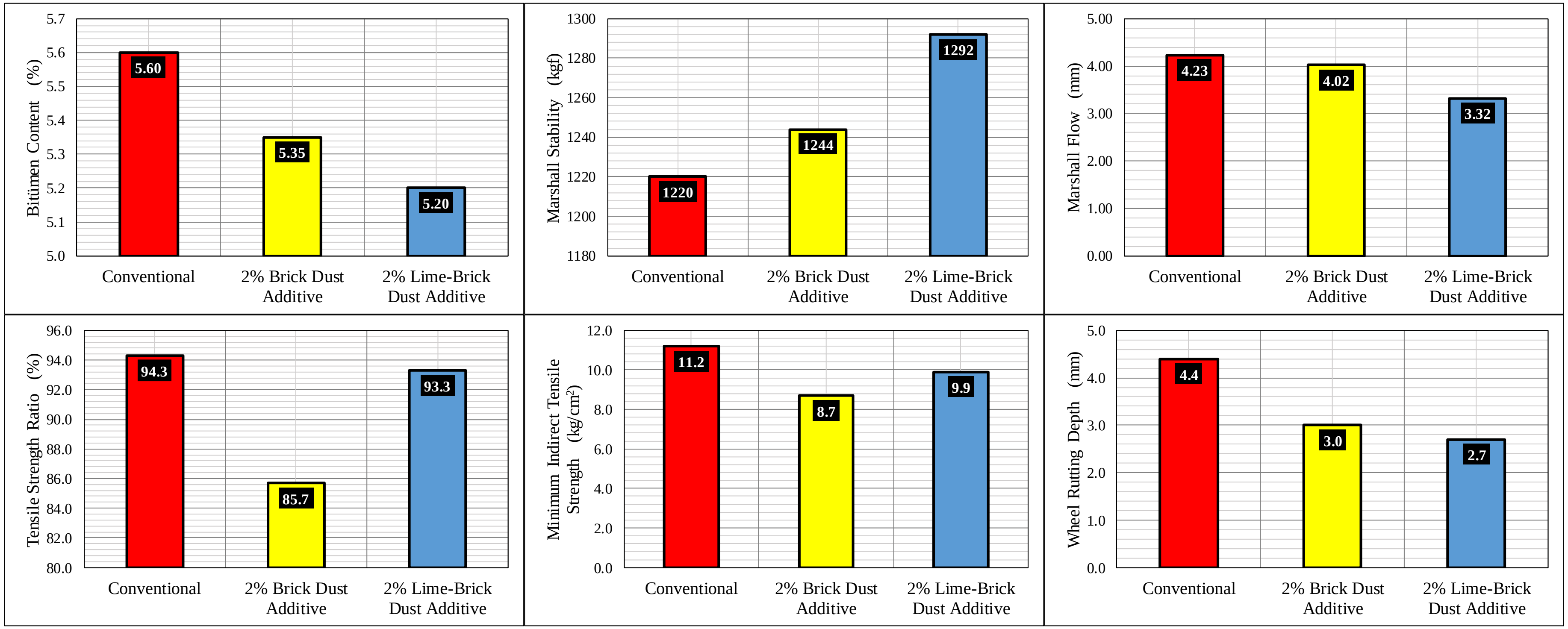

Figure 10. Comparison of design parameters for mixtures (conventional, 2% brick dust modified, and 2% lime-brick dust modified) prepared with B50/70 bitumen and aggregates from Yakupabdal & Malıköy quarries.

The results in Table 18 clearly show that all mixtures (conventional, 2% brick dust modified, and 2% lime-brick dust modified) meet the criteria specified in the standard. While the addition of 2% lime-brick dust to the conventional mixture resulted in no significant change in tensile strength, the inclusion of 2% brick dust led to a slight reduction. Compared to the conventional mixture, both modified mixtures exhibited reductions in optimum bitumen content and wheel rutting depth. Additionally, the Marshall stability values increased, while flow values decreased with additive incorporation.

As shown in Figure 10, adding brick dust reduced the optimum bitumen content by approximately 4.5% and the wheel rutting depth by around 30%, while Marshall stability increased by nearly 2%, and flow values decreased by 5%. When lime-brick dust was added, optimum bitumen content decreased by about 7%, and wheel rutting depth dropped by approximately 40%, whereas Marshall stability improved by nearly 6%, and flow values declined by 22%.

These findings support the use of hybrid aggregate gradation with basalt, a relatively more durable rock type, and demonstrate that the addition of modifiers enables bitumen content optimization, providing economic benefits. Moreover, the significant reduction in wheel rutting depths enhances long-term pavement performance, while the increase in stability values contributes to improved durability.

The performance of the mixtures was also influenced by the geological origin of the aggregates. Limestone-based aggregates from the Malıköy quarry exhibited better workability and compliance with specification limits, whereas basalt-based aggregates from the Yakupabdal quarry showed challenges in compaction and resulted in elevated VMA values. These findings highlight the significant effect of aggregate source on volumetric properties and overall mixture behavior. The combination of limestone and basalt aggregates offered a balanced solution, enabling better compaction and enhanced durability, especially when used together with additives.

Drawing from literature on the use of lime or brick dust as additives in pavement structures, it can be concluded that these modifiers have a positive effect on Marshall stability and flow values. Additionally, in certain studies, they have also improved indirect tensile strength and wheel tracking resistance. Therefore, the results obtained in this study align well with previous research aimed at similar objectives. What distinguishes this study from previous research is the simultaneous use of both hydrated lime and brick dust as a combined additive in hot mix asphalt—a combination that, to the best of our knowledge, has not been investigated before. This unique approach clearly underscores the originality and novelty of the research.

In addition to the mechanical performance improvements observed in this study, the economic and environmental impacts of using lime-brick dust as a pavement modifier are also noteworthy.

From an economic perspective, the reduction in optimum bitumen content by 7% contributes to cost savings, as bitumen is one of the most expensive components in asphalt production. Moreover, utilizing industrial waste materials such as brick dust as filler can reduce dependency on conventional filler materials, further lowering material costs. The increased durability of modified asphalt mixtures reduces maintenance and rehabilitation costs, making this approach particularly beneficial for high-traffic roads and regions with extreme weather conditions. Additionally, the reuse of brick waste decreases disposal costs, supporting more sustainable waste management practices.

From an environmental standpoint, the incorporation of lime-brick dust into asphalt mixtures presents multiple sustainability benefits. The reduction in bitumen consumption directly leads to lower carbon emissions, as bitumen production is an energy-intensive process. Furthermore, the utilization of recycled materials contributes to resource conservation, reducing the demand for virgin aggregates. The improved impermeability properties of the modified mixtures also enhance resistance to water infiltration, potentially mitigating the environmental risks associated with water damage and surface runoff contamination.

These findings suggest that lime-brick dust-modified asphalt mixtures can serve as a viable alternative for cost-effective and environmentally friendly pavement applications. Future research should further explore the long-term sustainability of this approach through life cycle assessments and real-world field applications.

4 CONCLUSION AND SUGGESTIONS

This study examined the feasibility of using a lime-brick dust blend as a modifier in flexible pavement structures and demonstrated that the modified mixtures exhibited superior performance compared to conventional asphalt mixtures.

- The optimum bitumen content decreased by approximately 7%, leading to potential cost savings.

- Wheel rutting depth was reduced by 40%, indicating enhanced resistance to permanent deformation.
- Marshall stability improved by 6%, thereby increasing the load-bearing capacity of the pavement.
- Air void and voids filled with asphalt (VFA) reached optimal levels, improving impermeability and reducing moisture-related damage.

These findings suggest that the incorporation of lime and brick dust in asphalt pavements can serve as a technically viable and environmentally sustainable solution. For future studies:

- Different bitumen grades and aggregate combinations should be explored to assess applicability under varying climatic conditions.
- The modification ratio should be further optimized by testing different additive percentages.
- Long-term field tests should be conducted to validate laboratory results under real traffic conditions.

In conclusion, this study contributes to sustainable engineering practices by demonstrating the effective utilization of industrial waste materials in pavement construction. The results provide valuable insights into improving asphalt pavement performance while promoting eco-friendly material usage.

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Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

Contributions of the Authors

Esra Ozkaynak: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.

Kürşat Yıldız: Writing – review & editing, Writing – original draft, Supervision, Project administration, Visualization, Methodology, Investigation, Conceptualization.

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