Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 11(4): 1068-1080 (2023)

The Statistical Analysis on Physical and Rheological Properties of the Bitumen Modified with CR+SBS+Sasobit

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Article Info

Research article
Received: 25/01/2023
Revision: 25/07/2023
Accepted: 25/07/2023

Keywords

Bitumen
Crumb Rubber
SBS
Sasobit
Statistics

Makale Bilgisi

Araştırma makalesi
Başvuru: 25/01/2023
Düzeltme: 25/07/2023
Kabul: 25/07/2023

Anahtar Kelimeler

Bitüm
Öğütülmüş Araç Lastiği
SBS
Sasobit
İstatistik

Graphical/Tabular Abstract (Grafik Özet)

The variation of the experimental results with the additive ratios in the three additived binders was statistically analyzed. Significant correlations were found between additive ratios and experimental results. / Üç katkılı bağlayıcılarda deney sonuçlarının katkı oranlarıyla değişimi istatiksel olarak analiz edilmiştir. Katkı oranları ve deney sonuçları arasında önemli ilişkiler olduğu tespit edilmiştir.

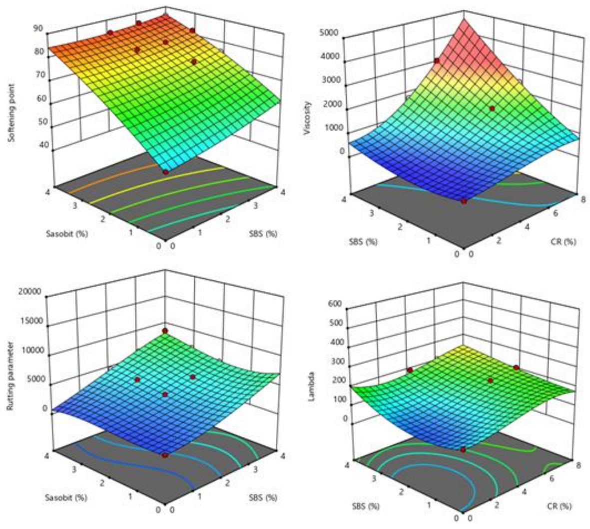

Figure A*: Effect of additive ratios on experiments /* ***Şekil A:****. Katkı oranlarının deneyler üzerindeki etkisi*

Highlights (Önemli noktalar)

- *Sasobit increased the workability of the binder and decreased its temperature sensitivity./Sasobit bağlayıcıların işlenebilirliğini artırdı ve sıcaklık hassasiyetini azalttı.*
- *SBS has increased the rutting resistance of the binders./SBSbağlayıcıların tekerlek izi direncini artırdı.*
- *CR contributed to the low temperature performance of the binders./CR baplayıcıların düşük sıcaklıkperformansına katkı sundu.*

Aim (Amaç): *The aim of this study is to make a statistical evaluation of bituminous binders modified with CR, SBS and Sasobit./ Bu çalışmanın amacı, CR, SBS ve Sasobit ile modifiye edilmiş bitümlü bağlayıcıların istatistiksel bir değerlendirmesini yapmaktır.*

Originality (Özgünlük): *The effectiveness of the additives used in bitumen modification was statistically and experimentally consistent./ Bitüm modifikasyonunda kullanılan katkıların etkinliği istatiksel ve deneysel olarak örtüşmüştür.*

Results (Bulgular): *The relationship between softening point-lambda and viscosity-rutting parameter was very important./ Yumuşama noktası-lambda ve viskozite-rutting parametresi arasındaki ilişki çok önemliydi.*

Conclusion (Sonuç): *Significant relationships were found between additive percentages and softening point, viscosity, rutting parameter and lambda values. The p value was 0.001 in all models./ Katkı yüzdeleri ile yumuşama noktası, viskozite, tekerlek izi parametresi ve lambda değerleri arasında anlamlı ilişkiler bulunmuştur. Tüm modellerde p değeri 0.001'dir.*

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DOI: 10.29109/gujsc.1242136

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Abstract

In this study, crumb rubber (CR), styrene-butadiene-styrene (SBS) and FT-Paraffin (Sasobit) additives modified bitumen binders were statistically investigated. The data set consisting of 32 binders modified by pure, CR, SBS, Sasobit and CR+SBS+Sasobit was studied. While additive ratios were defined as independent variables, results obtained from softening point, viscosity, dynamic shear rheometer and bending beam rheometer experiments were defined as dependent variables. Experiment results were analyzed individually and collectively using response surface methodology and pearson correlation methods. When the experiments were evaluated, very important relationships were found between additives rates and all experimental results. Actual values and estimated values obtained as a result of statistical analysis overlapped. It was determined that there were strong relationships between all experimental results when the pearson correlation between the experimental results was examined. Optimization was made according to the test results where the viscosity of 3000 cP (suitable workability), softening point and dynamic shear rheometer test results were maximum (superior high temperature performance) and the test data of bending beam rheometer was minimum (superior low temperature performance). According to this, CR, SBS and Sasobit rates were determined as 5.6%, 4% and 1%, respectively.

CR+SBS+Sasobit ile Modifiye Edilmiş Bitümün Fiziksel ve Reolojik Özellikleri Üzerine İstatistiksel Analiz

Makale Bilgisi

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Öz

Bu çalışmada, kırıntı kauçuk (CR), stiren-bütadien-stiren (SBS) ve parafin (Sasobit) katkıları ile modifiye edilmiş bitümlü bağlayıcılar istatistiksel olarak incelenmiştir. Saf, CR, SBS, Sasobit ve CR+SBS+Sasobit ile modifiye edilmiş 32 bağlayıcıdan oluşan veri seti incelenmiştir. Katkı oranları bağımsız değişkenler olarak tanımlanırken, yumuşama noktası, viskozite, dinamik kesme reometresi ve eğilme kirişi reometresi deneylerinden elde edilen sonuçlar bağımlı değişkenler olarak tanımlanmıştır. Deney sonuçları, yanıt yüzeyi metodolojisi ve pearson korelasyon yöntemleri kullanılarak tek tek ve toplu olarak analiz edilmiştir. Deneyler değerlendirildiğinde, katkı oranları ile tüm deneysel sonuçlar arasında çok önemli ilişkiler bulunmuştur. Gerçek değerler ile istatistiksel analiz sonucunda elde edilen tahmini değerler örtüşmüştür. Deney sonuçları arasındaki pearson korelasyonu incelendiğinde tüm deney sonuçları arasında güçlü ilişkiler olduğu tespit edildi. Viskozite 3000 cP (uygun işlenebilirlik), yumuşama noktası ve dinamik kayma reometresi test sonuçlarının maksimum (üstün yüksek sıcaklık performansı) ve eğilme kirişi reometresi test sonucunun minimum (üstün düşük sıcaklık performansı) olduğu test verilerine göre optimizasyon yapılmıştır. Buna göre CR, SBS ve Sasobit oranları sırasıyla %5.6, %4 ve %1 olarak belirlenmiştir.

1. INTRODUCTION (GİRİŞ)

Bitumen is extensively used as a binder in road pavements owing to its favorable physical and rheological properties. By transferring these properties of bitumen to asphalt mixtures, it enables safe, economical and comfortable road construction. Although bitumen and hot bituminous mixtures are frequently used in asphalt road construction, they are destroyed before completing their service life due to heavy vehicle traffic and climatic reasons. In order to prevent this situation, bitumen and asphalt are modified with various additives. These additives can be selected from

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artificial, natural, recycling and waste materials. The criteria sought here are to rise the performance of bitumen and asphalt, to contribute to the natural environment and to be economical. But most of the time, it is not possible to meet all of these criteria with a single additive. In this case, besides the individual use of the additives, their multiple uses have started to be the subject of studies. Undoubtedly, styrene-butadiene-styrene (SBS) comes first among these additives. While SBS increases softening point, viscosity, rutting parameter, creep stiffness values of bituminous binders, it decreases penetration values. SBS modified asphalt mixtures improve permanent deformation at high temperature, moisture, aging and crack resistance at low temperature [1-6]. However, with the use of high rates of SBS, the cost increases and the workability decreases [7]. Therefore, the additives that can be used with SBS have been the subject of study. Crumb rubber (CR) obtained from ground vehicle tires have been used alternatively as a material. CR provides benefits in waste management in terms of environmental benefits and lowering the cost of bitumen. CR increases softening point, viscosity, rutting parameter values of bituminous binders whereas it decreases penetration and creep stiffness values. Moreover, CR additived bitumen show close thermal and aging sensitivity with SBS additived bitumen, whereas showing less moisture sensitivity than SBS additived bitumen [8-12]. As a result of the use of CR and SBS, workability problems occur with increasing viscosity. To prevent this situation, warm mix additives are used. At the beginning of these contributions is FT-paraffin (Sasobit). Sasobit not only reduces the viscosity, but also increases the softening point and rutting parameter values [13-16]. Considering the individual and combined use of Sasobit and SBS additives in bitumen modification, Sasobit provides superior properties to bituminous binders in terms of temperature sensitivity, while SBS provides superior properties to bitumen in terms of rutting parameter. The combined use of additives not only reduced the viscosity, but also increased the performance of the bituminous binder. [17]. When the rheological properties of Sasobit+CR modified bituminous binders are examined, the use of additives improves the low temperature performance of the binder. In addition, the resistance of the binder against permanent deformations at high temperatures increases [18]. The new investigation implicates studies of bitumen and asphalt using the Response Surface Method (RSM). RSM is a statistical approach that uses quantitative information from appropriate tests to construct many regression equations that correlate the determinants with the empirical results. It is a set of methods used to develop a variety of experimental designs and to determine the connections between the empirical factors and the responses. The optimal conditions are then calculated from these relationships. It is especially useful for evaluating data with many inputs and outputs, as in this study. With this method, the experiments are evaluated not only individually but also together and optimum conditions are determined. Therefore, it helps to obtain multifunctional binders, not just single-purpose binders.

The aim of this study is to make a statistical evaluation of bituminous binders modified with CR, SBS and Sasobit. In this context, using response surface methodology (RSM), the relationship between additive ratios and test results is examined and optimization is made. In addition, the relationship between different experimental results is determined with the help of the Pearson correlation method.

2.MATERIALS AND METHODS (MATERYAL VE METOD)

B 160/220 penetration class pure bitumen was used in the study. As additive material, crumb rubber obtained from ground vehicle tires, Kraton D-1101® type styrene-butadiene-styrene (SBS) and FT-Paraffin (Sasobit®), which is preferred in warm mixtures (Figure 1), were used. The rate of CR was %4, %6, %8, SBS and Sasobit was %2, %3, %4 by weight of bitumen in the single and triple usage. Softening point (ASTM D36 standard), viscosity (ASTM D4402 standard), dynamic shear rheometer (AASHTO T315 standard) and bending beam rheometer (AASHTO T313 standard) tests were applied to the binders. While evaluating the rutting parameter ($G^*/\sin\delta$) data in the dynamic shear rheometer experiment at 64 ºC, lambda (λ) data, which is the m-value ratio of the creep stiffness, was taken into account in the bending beam rheometer experiment at -10 ºC. Softening point test are used to determine the consistency and temperature sensitivity of bitumen. Viscosity is the resistance to movement, that is, to rotation. Viscosity test is done to determine the workability of binders. Viscosities of the binders at 135 ºC are expected not to exceed 3000 cP in terms of suitable workability. With the help of this test, the mixing and compaction temperatures of the asphalt are determined. The medium and high temperature performance of the binders is determined by the dynamic shear rheometer test, while the low temperature performance is determined by the beam bending rheometer test.

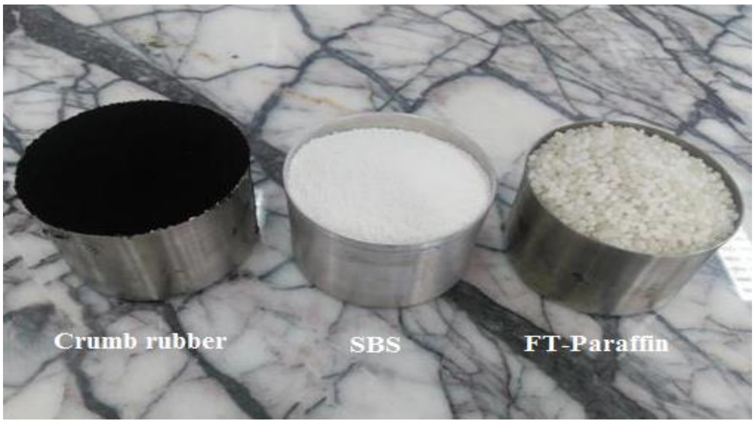

Figure 1. Materials utilized in the research. (Çalışmada kullanılan deneyler)

In the research, an empirical plan was designed considering statistical regression using the response surface methodology (RSM) method, and optimal states were assessed by response functions. In empirical design, it is necessary to decide the effective parameters to obtain optimum results with less number of tests. In the RSM method, results are achieved economically, in a short time, with maximum efficiency and with less effort. With this method, the effects of the independent variables on the response functions are evaluated and optimization is made [19–22]. In this study, the additive rates were taken as the independent variable while the experimental results were taken into account as response functions in the RSM method.

3.THE STATISTICAL ANALYSIS RESULTS (İSTATİKSEL ANALİZ SONUÇLARI)

RSM was used to study the effects of the additive on softening point, viscosity at 135°C, rutting parameter and lambda and to study the combined effects of three factors; percentage of additives as independent variables. To study the impact of the factors, 32 experimental results (Table 1) were run in a design matrix using the CCD (Central Composite Design) method. Design Expert 12 software was used to design the tests in this study. As seen in Table 1, the ratios of binders with single additive material used in the study were chosen to be compatible with triple modifications. Almost all of the three additives binders in the table gave better results than the 5% SBS modified binder, which is frequently used in practice and laboratory. In triple modifications, better results were also obtained than the 7% SBS modification, which is the maximum that can be used due to the viscosity limit [23].

Table 1. Test data of binder (Bağlayicilarin test dataları)

CR (%)	SBS (%)	Sasobit (%)	Softening point (ºC)	Viscosity at 135 ºC (cP)	Rutting parameter (G*/sinδ)	Lambda (λ)
0	0	0	42.1	262	539	62.6
4	0	0	51.2	525	1384	63.3
6	0	0	53.1	612.5	2030	60.3
8	0	0	55.4	862.5	2295	58.4
0	2	0	46.65	562.5	1098	75.7
0	3	0	51.7	794	1717	93.7
0	4	0	54.4	1125	2662	112.8
0	0	2	62.9	250	1213	113.4
0	0	3	68.7	237.5	1668	161.9
0	0	4	78.5	212.5	2137	196.8
4	2	2	69.1	875	3471	124.3
4	2	3	80.1	834	4344	180.7
4	2	4	84.2	787	4564	209.5
4	3	2	75	1275	4817	134.5
4	3	3	80.1	1200	5420	193.1
4	3	4	85.4	1150	6226	238.0
4	4	2	76	1750	5955	191.2
4	4	3	82.1	1700	6933	250.3

4	4	4	85.9	1625	8642	276.1
6	2	2	72.5	1688	5935	183.4
6	2	3	80.7	1613	6877	232.6
6	2	4	84.5	1488	7872	251.1
6	3	2	75.3	2250	8574	190.0
6	3	3	80.8	2163	10129	235.2
6	3	4	85.7	2100	12227	277.7
6	4	2	77.8	3063	10786	207.9
6	4	3	82.9	2925	13320	277.7
6	4	4	86.7	2713	14429	299.7
8	2	2	73.3	2463	7678	205.8
8	2	3	80.8	2275	9728	239.9
8	2	4	85.4	2150	10777	256.1
8	3	4	86.8	3075	15825	268.5

3.1. The Statistical Result of Softening Point Test (Yumuşama Noktası Deneyinin İstatiksel Sonuçları)

The CR, SBS and Sasobit ratios were used as independent variables and softening point test data as response function in the design made with the RSM method as seen in Figure 2. Statistical results obtained from the softening point test data were given in Table 2. The significance of the model was represented by the high F-value and low P-value (<0.05) for F and P, showing that the factor and corresponding factors agree very well. The R2 value > 0.80 showed that the prepared model fits well and has good significant agreement between the responses (actual and predicted). In addition, the standard deviation (Std. Dev.) for the coefficient of variance (C.V.%) after analysis for all models considered was far less than the obtained mean values, which also indicates the adequacy of the analysis of variance. The lower value of the generated model's standard deviation compared to its mean indicates its variance with respect to the test data. The experimental data therefore led to fewer ambiguities for the generated model. The P-value as low as 0.0001 indicated that the model was very important. Strong relationships were found between the additive ratio and the softening point. Quadratic model was used in the analysis. R2 (0.996) value close to 1 showed that the values obtained with the real results and the established model are very close. The standard deviation (1.01) and coefficient of variance (1.38) proved that the error margin of the model in the study was low. The changes in the softening point depending on the Sasobit and SBS ratios were given in Figure 3. Sasobit was the most influential on the softening point experimental results.

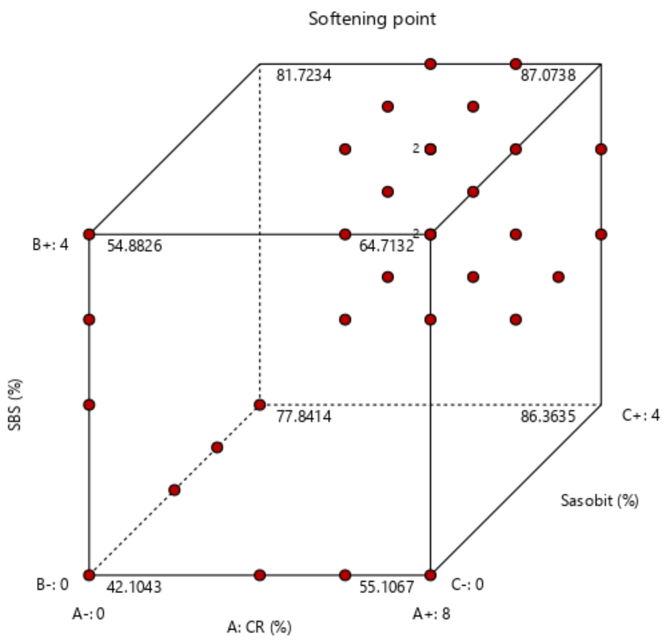

Figure 2. The cube design according to the softening point data (Yumuşama noktası verileri küp tasarımı)

Table 2. Statistical results of softening point test data (Yumuşana noktasıyla verileri istatiksel sonuçları)

Transform	Source	P-value	F-value	Std. Dev.	R^2	C.V.%
Power	Quadratic	0.0001	604.53	1.01	0.9960	1.38

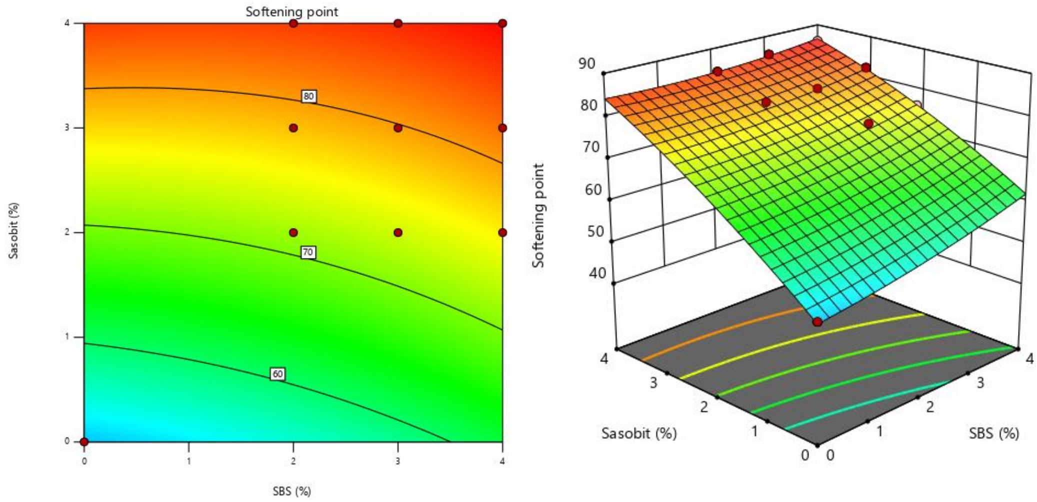

Figure 3. Change of softening point with Sasobit and SBS ratio (Sasobit ve SBS oranları ile yumuşama noktası değişimi)

Figure 4 shows not only the fit but also the distribution of the differences between the actual and the predicted data. As can be seen in the figure, the actual and estimated values are very close to each other. This has proven the close relationship between the factors and the suitability of the established model. In addition, an equation (Formula 1) was determined for the viscosity estimation based on the additive ratios. Here, A: CR ratio, B: SBS ratio, and C: Sasobit ratio.

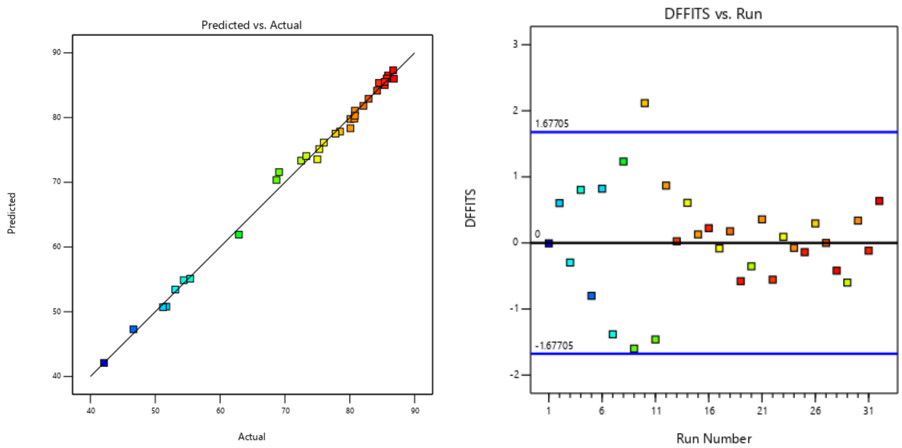

Figure 4. The diagnostic plots according softening point (Yumuşama noktasına göre diagnostik grafikler)

Softening point = 42.1 + 2.68 * A + 1.99 * B + 10.88 * C - 0.1 * AB - 0.14 * AC - 0.56 * BC - 0.13 * A^2 + 0.29 * B^2 - 0.49 * C^2 (1)

3.2. The Statistical Result of Viscosity Test
(Yumuşama Noktası Deneyinin İstatiksel Sonuçları)

The CR, SBS and Sasobit ratios were used as independent variables and viscosity test data as response function in the design made with the RSM method as seen in Figure 5. Statistical results obtained from the viscosity test data were given in Table 3. The P-value as low as 0.0001 indicated that the regression model was very important. Strong relationships were found between the ratio of additive and the viscosity. Cubic model was used in the analysis. R2 (0.9987) value close to 1 showed that the values obtained with the real results and the established model are very close. The standard deviation (49.63) and coefficient of variance (3.41) proved that the error margin of the model in the study was low. The changes in the viscosity depending on the CR and SBS ratios were given in Figure 6. SBS was the most influential additive on the viscosity experimental results.

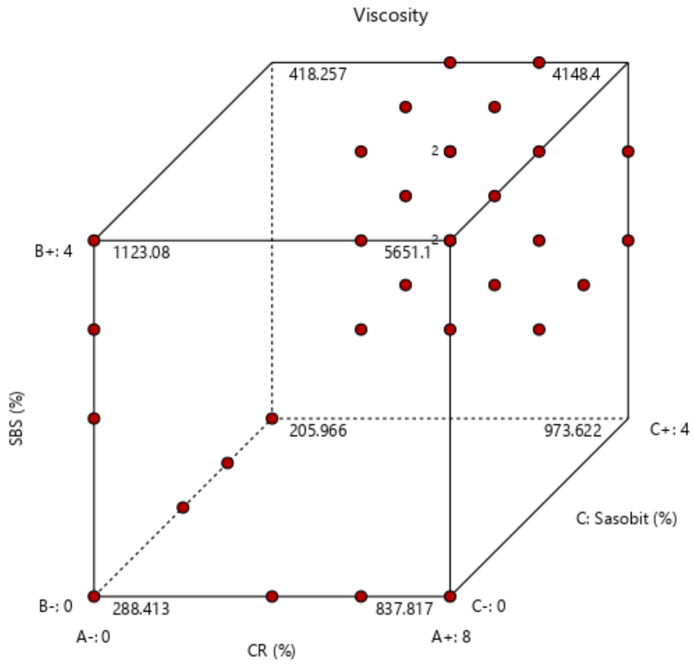

Figure 5. The cube design according to the viscosity data (Viskozite verileri küp tasarımı)

Table 3. Statistical results of viscosity test data (Viskozite verileri istatiksel sonuçları)

Transform	Source	P-value	F-value	Std. Dev.	R^2	C.V.%
Power	Cubic	0.0001	500.69	49.63	0.9987	3.41

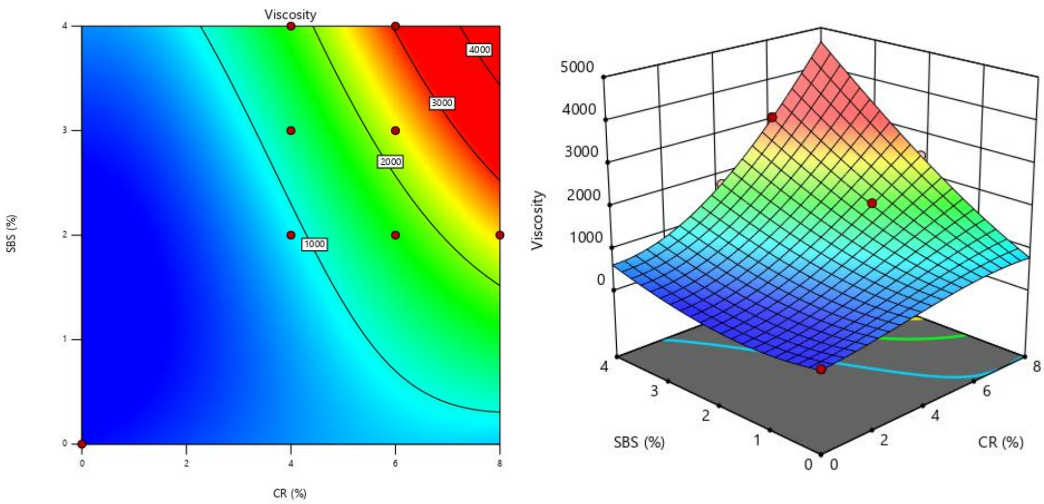

Figure 6. Change of viscosity with Sasobit and SBS ratio (Sasobit ve SBS oranları ile viskozite değişimi)

Figure 7 shows not only the fit but also the distribution of the differences between the actual and the predicted data. As can be seen in the figure, the actual and estimated values are very close to each other. This has proven the close relationship between the factors and the suitability of the established model. In addition, an equation (Formula 2) was determined for the viscosity estimation based on the additive ratios. Here, A: CR ratio, B: SBS ratio, and C: Sasobit ratio.

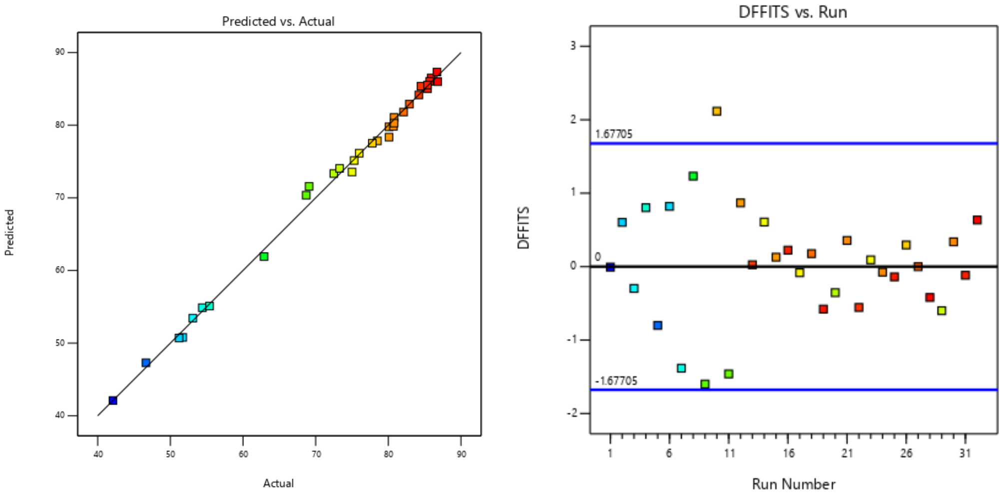

Figure 7. The diagnostic plots according viscosity (Viskoziteye göre diagnostik grafikler)

Viscosity = 288.41 - 54.09 * A - 22.88 * B - 158.09 * C + 11.38 * AB + 46.02 * AC - 151.05 * BC + 33.88 * A^2 + 88.53 * B^2 + 92.64 * C^2 - 7.94 * ABC + 15.22 * A^2B - 6.36 * A^2C - 2.2 * AB^2 + 2.93 * AC^2 + 19.46 * B^2C + 8.58 * BC^2 - 2.32 * A^3 - 7.66 * B^3 - 14.57 * C^3 (2)

3.3. The Statistical Result of Dynamic Shear Rheometer Test (Dinamik Kesme Reometresi Deneyinin İstatiksel Sonuçları)

The CR, SBS and Sasobit ratios were used as independent variables and dynamic shear rheometer test data (rutting parameter) as response function in the design made with the RSM method as seen in Figure 8. Statistical results obtained from the rutting parameter data were given in Table 4. A P-value as low as 0.0001 indicated that the regression model was very important. Strong relationships were found between the ratio of additive and the rutting parameter. Cubic model was used in the analysis. R2 (0.997) value close to 1 showed that the values obtained with the real results and the established model are very close. The standard deviation (371.05) and coefficient of variance (5.9) proved that the error margin of the model in the study was low. The changes in the rutting parameter depending on the Sasobit and SBS ratios were given in Figure 9. SBS was the most influential additive on the rutting parameter experimental results.

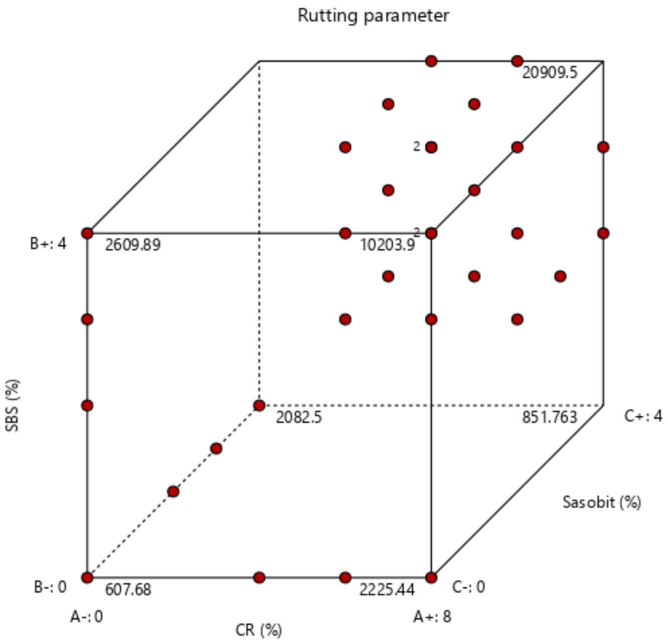

Figure 8. The cube design according to the rutting parameter data (Tekerlek izi parametresi verileri küp tasarımı)

Table 4. Statistical results of dynamic shear rheometer test data (Dinamik kesme reometresi verileri istatiksel sonuçları)

Transform	Source	P-value	F-value	Std. Dev.	R^2	C.V.%
Power	Cubic	0.0001	213.14	371.05	0.9970	5.90

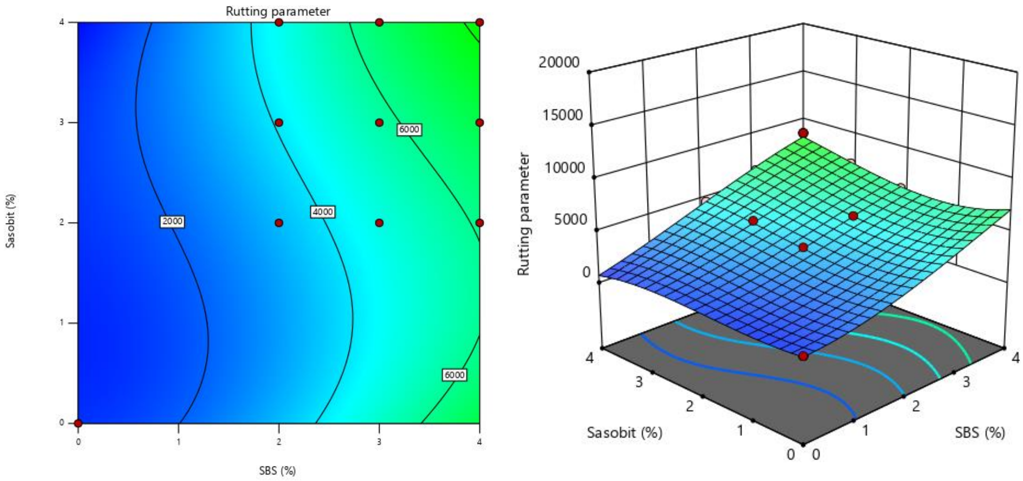

Figure 9. Change of rutting parameter with Sasobit and SBS ratio (Sasobit ve SBS oranları ile tekerlek izi parametresi değişimi)

Figure 10 shows not only the fit but also the distribution of the differences between the actual and the predicted data. As can be seen in the figure, the actual and estimated values are very close to each other. This has proven the close relationship between the factors and the suitability of the established model. In addition, an equation (Formula 3) was determined for the rutting parameter estimation based on the additive ratios. Here, A: CR ratio, B: SBS ratio, and C: Sasobit ratio.

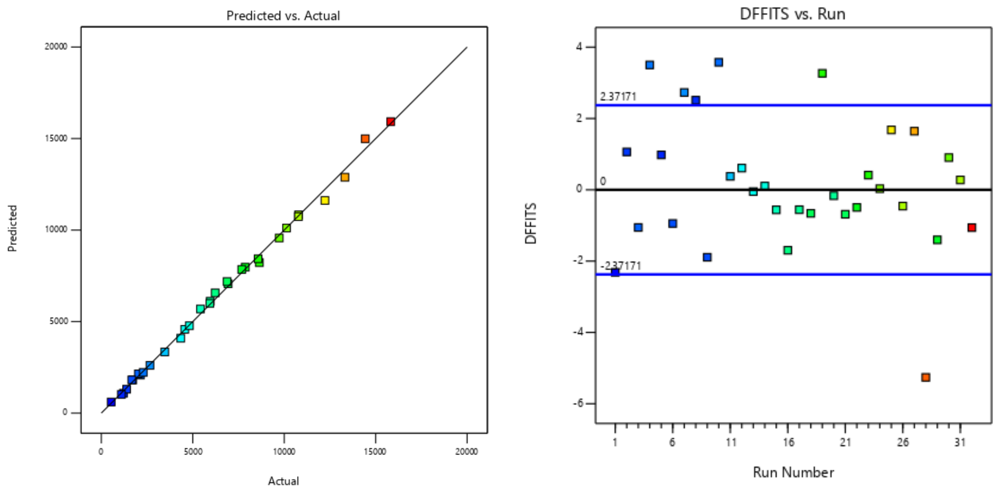

Figure 10. The diagnostic plots according rutting parameter (Tekerlek izi parametresine göre diagnostik grafikler)

Rutting parameter = 607.68 - 395.47 * A - 458.83 * B - 669.74 * C + 226.61 * AB - 31.3 * AC - 770.44 * BC + 210.22 * A^2 + 426.57 * B^2 + 650.1 * C^2 + 162.17 * ABC - 13.27 * A^2B + 10.46 * A^2C + 16.58 * AB^2 - 35.36 * AC^2 - 60.68 * B^2C + 117.68 * BC^2 - 16.94 * A^3 - 46.68 * B^3 - 97.62 * C^3 (3)

3.4. The Statistical Result of Bending Beam Rheometer Test (Kiriş Eğme Reometresi Deneyinin İstatiksel Sonuçları)

The CR, SBS and Sasobit ratios were used as independent variables and bending beam rheometer test data (lambda) as response function in the design made with the RSM method as seen in Figure 11.

Statistical results obtained from the lambda data were given in Table 5. A P-value as low as 0.0001 indicated that the regression model was very important. Strong relationships were found between the ratio of additive and the lambda. Cubic model was used in the analysis. R2 (0.9924) value close to 1 showed that the values obtained with the real results and the established model are very close. The standard deviation (10.39) and coefficient of variance (5.61) proved that the error margin of the model in the study was low. The changes in the lambda depending on the CR and SBS ratios were given in Figure 12. CR was the most influential additive on the lambda experimental results.

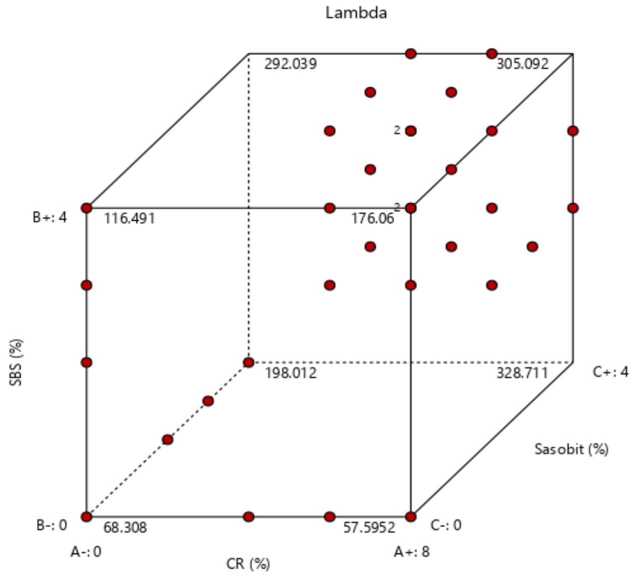

Figure 11. The cube design according to the lambda data (Lamda verileri küp tasarımı)

Table 5. Statistical results of bending beam rheometer test data (Kiriş eğme reometresi verileri istatiksel sonuçları)

Transform	Source	P-value	F-value	Std. Dev.	R^2	C.V.%
Power	Cubic	0.0001	82.59	10.39	0.9924	5.61

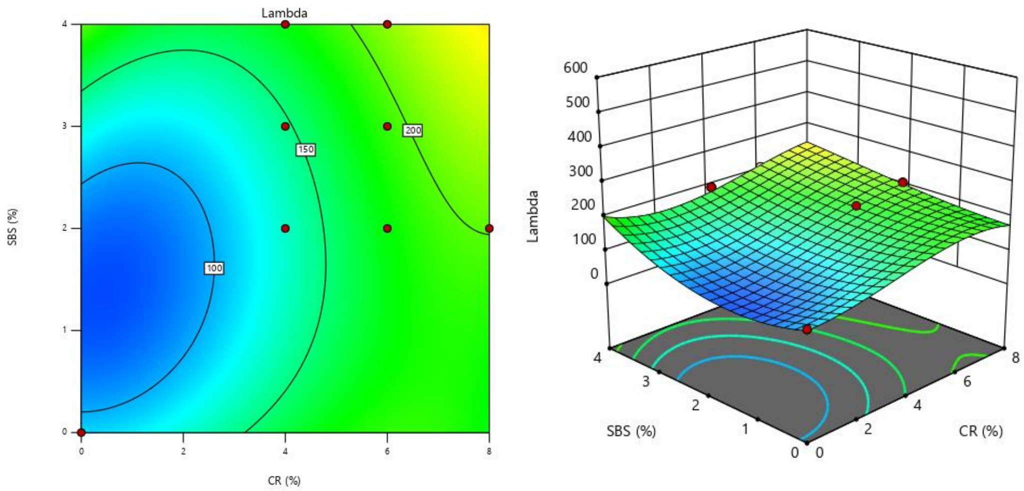

Figure 12. Change of lambda with Sasobit and SBS ratio (Sasobit ve SBS oranları ile lamda değişimi)

Figure 13 shows not only the fit but also the distribution of the differences between the actual and the predicted data. As can be seen in the figure, the actual and estimated values are very close to each other. This has proven the close relationship between the factors and the suitability of the established model. In addition, an equation (Formula 4) was determined for the lambda estimation based on the additive ratios. Here, A: CR ratio, B: SBS ratio, and C: Sasobit ratio.

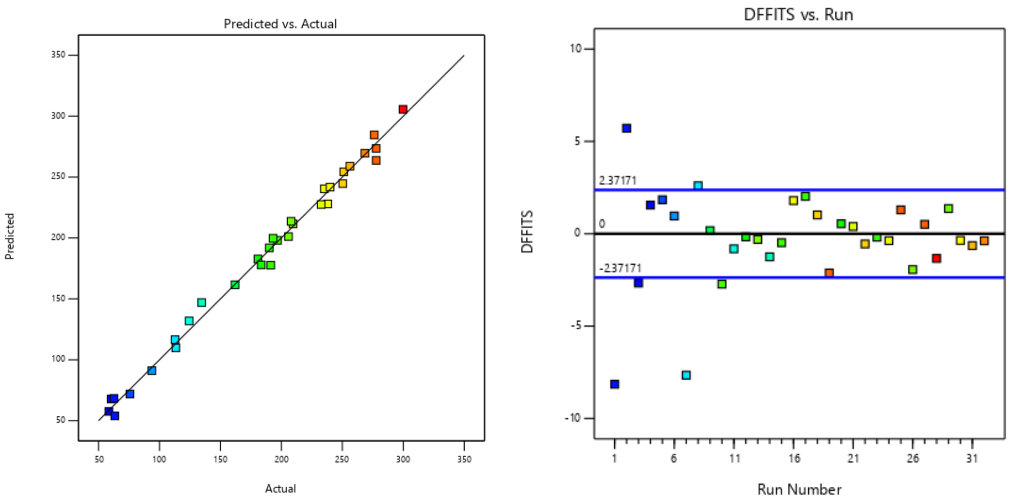

Figure 13. The diagnostic plots according lambda (Lamdaya göre diagnostik grafikler)

Lambda = 68.31 - 24.83 * A - 13.89 * B - 27.01 * C + 1.54 * AB + 12.88 * AC - 16.76 * BC + 7.69 * A^2 + 9.2 * B^2 + 32.89 * C^2 - 1.47 * ABC + 1.04 * A^2B - 0.96 * A^2C - 1.92 * AB^2 - 0.19 * AC^2 + 6.18 * B^2C - 1.28 * BC^2 - 0.59 * A^3 - 0.68 * B^3 - 4.51 * C^3 (4)

3.5. The Statistical Result of Tests Evaluated Together (Birlikte Değerlendirilen Deneylerin İstatiksel Sonuçları)

The softening point, viscosity, dynamic shear rheometry and bending beam rheometer test results of the binders were evaluated with the help of Pearson correlation method. The results obtained were given in Table 6. Highly congruent correlations were detected between the different experimental data. Moreover, it was determined that there was a very significant correlation between softening point-bending beam rheometer (0.936) and viscosity-dynamic shear rheometer (0.935). This showed that binders with high softening point, that is, low temperature sensitivity, are resistant to low temperature deformations. On the other hand, it has been revealed that binders with high viscosity will also be resistant to high temperature permanent deformations. The rutting potential of asphalt mixtures obtained with these binders will be reduced as in the literature [7,17].

Table 6. Pearson correlation between experimental results (Deney sonuçları arasındaki Pearson korelasyonu)

		Softening point	**Viscosity**	**Rutting parameter**	**Lambda**
Softening point	**Pearson Correlation**	1	0.616**	0.761**	0.936**
	Sig. (2-tailed)		0.000	0.000	0.000
	N	32	32	32	32
Viscosity	**Pearson Correlation**	0.616**	1	0.935**	0.857
	Sig. (2-tailed)	0.000		0.000	0.000
	N	32	32	32	32
Rutting parameter	**Pearson Correlation**	0.761**	0.935**	1	0.857**
	Sig. (2-tailed)	0.000	0.000		0.000

	N	32	32	32	32
Lambda	**Pearson Correlation**	0.936**	0.721**	0.857**	1
	Sig. (2-tailed)	0.000	0.000	0.000	
	N	32	32	32	32

The optimum solution to maximize the softening point, viscosity, rutting parameter values while minimize the lambda values was given in the Table 7 considering the lower and upper limits of the independent variables (additive contents) in the research. According to the data set in the study and the percentage of additives used, it was decided that effect of Sasobit on softening point, SBS on viscosity and rutting parameter, and CR additives on the lambda were more dominant

Table 7. Optimization results according to experimental data and additive rates (Deney verileri ve katkı oranlarına göre optimizasyon sonuçları)

Test values	CR (%)	SBS (%)	Sasobit (%)	Result
Softening point	6.592	3.854	3.935	86.883
Viscosity	7.135	3.944	3.763	3522.468
Rutting parameter	7.999	3.873	2.597	15797.865
Lambda	2.287	0.641	0.063	42.58

Considering the 3000 cP viscosity value at 135 ^{o}C, which was required for the workability of bituminous binders, the results in the Table 8 were obtained when all the experimental data were optimized. Here, the lambda values were taken as the minimum while the softening point and rutting parameter values were taken as the maximum for optimization. It was aimed to obtain a binder with superior performance against high and low temperatures without workability problems. Thus, suitable binder was selected for regions having large temperature differences considering low and high temperature performance together. Addition of 5.6% CR, 4% SBS and 1% Sasobit to the pure binder allowed the production of such a binder. In addition, the use of SBS additive at the maximum rate (4%) in optimization according to the additive percentages considered in the study showed that it was the most effective additive in all experimental parameters.

Table 8. Statistical results of bending beam rheometer test data (Kiriş eğme reometresi verileri istatiksel sonuçları)

CR (%)	SBS (%)	Sasobit (%)	Viscosity	Softening point	Rutting parameter	Lambda
5.600	4.000	1.002	3000.000	70.927	8799.020	143.598

4.CONCLUSIONS (SONUÇLAR)

In this study, statistical analysis of pure, CR, SBS, Sasobit and CR+SBS+Sasobit modified binders was carried out according to the RSM method, taking into account the additive ratio and the performance of the binders. In addition, the relationship between all performance criteria (softening point, viscosity, rutting parameter and lambda) was examined and optimization was made.

Significant relationships were found between additive percentages and softening point, viscosity, rutting parameter and lambda values. The p value was 0.001 in all models. This showed that the changes in the dependent factors were consistent with the changes in the independent factors. Moreover, the R2 value was approximately 0.99 in all models. In other words, the actual value and the estimated values obtained with the established model almost completely overlapped. When the experimental results were analyzed according to the Pearson correlation, significant relationships were found. The relationship between softening point-lambda and viscosity-rutting parameter was very important. Considering the most important benefits of the additives, Sasobit increased the workability of the binder and decreased its temperature sensitivity. SBS has increased the rutting resistance of the connectors. CR contributed to the low temperature performance of the binders. By using statistical analysis, the additive rates that serve the different properties of bitumen were determined. When all the test results were evaluated, the optimum additive ratio was determined as 5.6% CR, 4% SBS and 1% Sasobit. It was determined that the most effective additive material was SBS. Thanks to this analysis, the consistency of the experimental results was proven. In addition, the optimum ratios of additives that can be used in the field were determined.

ACKNOWLEDGMENTS (TEŞEKKÜR)

This study was supported by the project number 119M161 under the "TÜBITAK 1002" program. The authors would like to thank TUBITAK.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Yunus ERKUŞ**:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

Baha Vural KÖK**:** He analyzed the data and commented on the results.

Verileri analiz etmiş ve sonuçları yorumlamıştır.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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