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# OPTIMIZATION OF THE TEMPERATURE SUSCEPTIBILITY OF BITUMEN MODIFIED WITH WASTE TIRE RUBBER BY TAGUCHI METHOD

# ATIK ARABA LASTİĞİ İLE MODİFİYE EDİLMİŞ BİTÜMLERİN SICAKLIĞA DUYARLILIĞININ TAGUCHI YÖNTEMİ İLE OPTİMİZASYONU

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## ABSTRACT

The purpose of this study is to optimize the temperature susceptibility of the bitumen modified with the tire rubber. For this purpose, 2, 5 and 10 % waste tire rubber (by weight of bitumen) is mixed into 70-100 penetration bitumen at mixing temperatures of 150, 160 and 170$^{o}$C for mixing time of 30, 60 and 120 minute and mixing speed of 250, 350 and 450 rpm. Taguchi method is used as design of experiment method. The temperature susceptibility of the binders is evaluated by the penetration index (PI). It is found that the order of the importance of variables affecting the temperature susceptibility of binders is tire rubber content, mixing speed, mixing temperature and mixing time, respectively. Optimum conditions for the maximum PI of 3.72 are obtained at the mixing temperature of 150$^{o}$C, mixing time of 120 minute tire rubber content of 10% and mixing speed of 250 rpm. As a result, this new binder is produced by fewer experiments using Taguchi method compared to the other experimental methods. Thus, using the Taguchi method could save time and energy. Moreover, it is seen that tire rubber modified bituminous binders can provide better resistance against permanent deformations due to the lower temperature susceptibility in hot climate regions.

***Keywords*** **:** Tire Rubber, Temperature susceptibility, Bitumen, Taguchi method.

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**ÖZET**

Bu çalışmanın amacı, atık araba lastiği ile modifiye edilmiş bitümün sıcaklığa karşı duyarlılığını optimize etmektir. Bu amaç için, bitüm ağırlığının %2, 5 ve 10 oranlarında atık araba lastiği, 70-100 penetrasyon asfaltı ile150, 160 ve 170°C' de 30, 60 ve 120 dakika süreleri ile 250, 350 ve 450 rpm hızlarında karıştırılmıştır Deney tasarım yöntemi olarak Taguchi yöntemi kullanılmıştır. Bağlayıcıların sıcaklığa duyarlılıkları, Penetrasyon İndeksi (Pİ) ile değerlendirilmiştir. Bağlayıcıların sıcaklığa duyarlılıklarına etki eden değişkenlerin önem sırasının; araba lastiği oranı, karıştırma hızı, karıştırma sıcaklığı ve karıştırma süresinin olduğu bulunmuştur. 3.75 ile maksimum Pİ değeri için optimum şartlar %10 araba lastiği oranı, 250 rpm karıştırma hızı, 120 dakika karıştırma süresi ve 150°C karıştırma sıcaklığında elde edilmiştir. Sonuç olarak bu yeni bağlayıcı, Taguchi deney tasarım yöntemi kullanılarak, klasik deney tasarım yöntemlerine kıyasla daha az sayıda deney yapılarak üretilmiştir. Böylece Taguchi yöntemi kullanılarak zaman ve enerji tasarruf edilmiştir. Ayrıca, araba lastiği ile modifiye edilmiş bitümlü bağlayıcıların daha düşük sıcaklığa duyarlılıklarından dolayı, sıcak bölgelerdeki kalıcı deformasyonlara karşı daha iyi direnç sağlanabileceği görülmüştür.

**Anahtar kelimeler:** Araba lastiği, Bitüm, Sıcaklığa Duyarlılık, Taguchi Yöntemi.

## 1. INTRODUCTION

Conventional bituminous materials have tended to perform satisfactorily in most highway pavement and airfield runway applications. However, in recent years, increased traffic levels, larger and heavier trucks, new axle designs and increased tire pressures have increased the interest to the highway system. This has resulted in the need to enhance the properties of existing bitumen material. Bitumen modification offers one solution to overcome the deficiencies of bitumen and thereby improve the performance of bitumen mixtures. (Gordon, 2002; Brule et al., 1988; Brown et al., 1990; Isacsson and Lu, 1995).The best known form of modification is by means of polymer modification, traditionally used to improve the temperature susceptibility of bitumen by increasing binder stiffness at high service temperatures and reducing stiffness at low service temperatures (Brule et al., Collins et al., 1991; Goodrich , 1991; King et al., 1993).

Rubber is one of the polymers used in hot mix asphalt (HMA) concrete. A large amount of tire rubber is used in HMA. In recent years, the use of waste tire rubber in bituminous mixtures has increased because of large availability of used rubber tires and the disposing problems. In addition to these applications, many studies have been made on the tire rubber modified bitumen mixtures (Soon-Jae et al., 2008a, 2008b, 2008c; Cheuk and Wing, 2007; Çelik and Atiş, 2007; Piti and Chalermphol, 2006). Generally, two processes such as wet process and dry process, tire rubber is used in HMA. In the dry process, tire rubber is mixed with bituminous mixture to replace some of the aggregates in the mixture and in the wet process; tire rubber is added to the bitumen to modify the physical and chemical properties of the bitumen. When the tire rubber is added to the bitumen by means of wet process, temperature susceptibility of the bitumen improves. In wet process, tire rubber content, mixing temperature, mixing time and mixing speed have important effect on the temperature susceptibility of the resulting binder (Freddy et al., 1991; Pfeiffer, 1950; Pfeiffer and Doormaal., 1936). Pfeiffer and van Doormaal (1936) expressed the temperature susceptibility quantitatively by a term designated as "penetration index" (PI). PI is determined by using both softening point (ring and ball test) and penetration at 77°F, and assuming that the penetration of bitumen cement at its softening point is 800. The PI values range from about -3 for highly temperature susceptible bitumens to about +7 for highly blown low temperature susceptible (high PI) bitumens (Shell Bitumen Handbook, 1990). The advantages of using rubber in bitumen are to reduce the number of waste tires, to obtain more flexible pavements under heavy loads, which results in fewer cracking and durability problems, and to increase the resistance cold weather cracking and to warm weather rutting.

The digestion of the rubber into hot bitumen affects the performance of the bituminous mixtures. Mixing temperature, mixing time (Green and Tolonen, 1977) and tire rubber content have considerable influence on the properties of digestion of the rubber into hot bitumen. The purpose of the present study is to find the optimum conditions for the maximum temperature susceptibility of tire rubber modified bitumen. The experimental study was so designed that the experiments gave the optimum working conditions of the parameters affecting the temperature susceptibility using Taguchi method. One of the advantages of the Taguchi method (Kackar, 1985; Roy, 1990; and Phadke, 1983) over the conventional experimental design methods, in addition to keeping the experimental cost at the minimum level, is that it minimizes the variability around the target when bringing the performance value to the target value. Its other advantage is that the optimum working conditions determined from the laboratory work can also be reproduced in the real production environment (Bilen et al., 2001).

## 2. MATERIAL AND METHOD

The bitumen used in this study was provided by Batman Oil Refinery in Turkey. This bitumen, 70/100 penetration, was subjected to typical standard laboratory tests. The results of these tests are incorporated in Table 1. The PI of the base bitumen was determined to be 2 from the Nomograph in Shell 1990 (Shell Bitumen Handbook, 1990). After reviewing the work of earlier investigators on the evaluation of the effect of rubber on bitumen and bituminous mixtures, the rubber concentration were selected as 2, 5 and 10% by weight of bitumen. The tire rubber was used in the powder form. The gradation of tire rubber used is given in Table 2.

**Table 1.** Physical properties of bitumen cement used in this study

| | | |
|---|---|---|
| Penetration, 25°C, 100 gr, 5s (1/10mm) | ASTM D5 | 85 |
| Specific Gravity (gr/cm$^3$) | ASTM D70 | 1.047 |
| Flash Point (°C) | ASTM D92 | 215 |
| Ductility, 25°C, 5 cm/min | ASTM D113 | +100 |
| Softening Point (°C) | ASTM D36 | 57 |

**Table 2.** The Gradation of Waste Tire Rubber

| Sieve Size | Percent Passing |
|---|---|
| No.10 (2 mm) | 100 |
| No.40 (0.42 mm) | 77 |
| No.80 (0.18mm) | 0 |

A speed adjustable vertical shaft mixer with a capacity of 2 liters was used to mix the tire rubber and bitumen. Temperature control during mixing was achieved by using thermostat running with a thermocouple attached to the mixer. The machine was operated at 250-350 and 450 rpm for mixing. Mixing temperatures are selected 150-160 and 170°C. The mixing time affects the homogeneity of tire rubber into the hot bitumen and therefore mixing was carried out for a duration of 30, 60 and 120 minute to asses the effect of mixing time on the properties of the tire rubber modified bitumen. Penetration and Softening Point (Ring and Ball) tests were conducted on all tire rubber modified bitumen and base bitumen. All tests were carried out in accordance with the ASTM standards. In order to evaluate the temperature susceptibility of binders, the penetration index of all mixes were determined by Nomograph in Shell 1990 (The Shell Bitumen Handbook, 1990) using both penetration and softening point values obtained from the study by Hinislioglu and Bayrak (2000).

### *2.1. Experimentation approach*

In the traditional approach of experimentation, while one factor is kept varying, all the other factors are kept constant. The optimum conditions arrived in the conventional approach may not be a true optimum if the interactions between the factors are present. To study the factors and its interactions, factorial experiments and response surface designs are available. In the case of a full factorial design, the number of experiments is numerous, and it is practically not possible to carry out the experiments in most of the cases. Therefore, the fractional factorial experiments using orthogonal array was investigated by Taguchi (Roy, 1990) which can substantially decrease the number of experiments and feasible to study the effect of factors and its interactions. The linear graph developed by Taguchi (Taguchi, 1962; Peace, 1993) is useful to scientists and engineers to design and analyze the experimental data without having basic knowledge of factorial design.

### *2.2. Taguchi Analytical Methodology*

The Taguchi method is a powerful tool for the design of a high quality system. It provides not an efficient, but a systematic approach to optimize designs for performance and quality. Further, Taguchi parameter design can optimize the performance through the settings of design parameters and reduce the sensitivity of system performance to source of variation (Taguchi, 1962; Peace, 1993).

### *2.3. Orthogonal Array*

The experiments were designed based on orthogonal array technique. Factors and their levels affecting the PI of the binders were determined based on the brainstorming session and literature review on the subject. Four factors with three levels have been taken for experimentation. In the orthogonal array technique, the minimum number of experiments for four factors with three levels (Table 3) are 9, therefore, $L_9(3^4)$ orthogonal array was used. The order of the experiments was obtained by inserting parameters into columns of orthogonal array, $L_9(3^4)$, chosen as experimental plans given in Table 4. But the order of experiments was randomly made to avoid noise sources which had not been considered initially and which could take place during an experiment and affect results in a negative way.

**Table 3.** Factors and their levels studied in the experiments.

| | Factors | Levels | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| A | Mixing temperature (°C) | 150 | 160 | 170 |
| B | Mixing time (minute) | 30 | 60 | 120 |
| C | The content of waste tire rubber (% by weight of bitumen) | 2 | 5 | 10 |
| D | The mixing speed (rpm) | 250 | 350 | 450 |

**Table 4.** $L_9(3^4)$ experimental plan used in the study

| Experiment No | Factors | | | | S/N |
|---|---|---|---|---|---|
| | A | B | C | D | |
| 1 | 1 | 1 | 1 | 1 | 6.02 |
| 2 | 1 | 2 | 2 | 2 | 5.15 |
| 3 | 1 | 3 | 3 | 3 | 7.96 |
| 4 | 2 | 1 | 2 | 3 | 1.66 |
| 5 | 2 | 2 | 3 | 1 | 8.69 |
| 6 | 2 | 3 | 1 | 2 | 4.56 |
| 7 | 3 | 1 | 3 | 2 | 7.75 |
| 8 | 3 | 2 | 1 | 3 | 2.54 |
| 9 | 3 | 3 | 2 | 1 | 7.16 |
| | | | | Average | 5.72 |

In the optimization, two samples were prepared for each mix. Since the PI is bigger the temperature susceptibility is lower, Performance statistic, which is called Signal to Noise ratio (S/N), values were calculated based on the quality characteristic of "the bigger the better" using Eq. (1):

$$S/N = -10Log\left[\frac{1}{n}\sum_{1}^{n}\frac{1}{Y_i^2}\right] \quad (1)$$

where S/N is performance statistics, defined as the signal to noise ratio (S/N unit: dB), n number of repetition done for an experimental combination, and $Y_i$ performance value of i*th* experiment. The levels of parameters that maximize the S/N were determined as optimum conditions. However, in Taguchi method the experiment corresponding to optimum working conditions might not have been done during the whole period of the experimental stage. In such cases, the performance value corresponding to optimum working conditions can be predicted by utilizing the balanced characteristic of orthogonal array using Eq. (2) (Peace, 1993):

$$Y_i = \mu + X_i + e_i \quad (2)$$

where μ is the overall mean of performance value, $X_i$ the fixed effect of the parameter level combination used in i*th* experiment, and $e_i$ the random error in i*th* experiment.

## 3. RESULTS AND DISCUSSION

### 3.1. The effects of the factors on S/N

Fig. 1 shows the effect of the mixing temperature, mixing time, tire rubber content and mixing speed on the PI. It is seen that maximum PI was reached at the mixing temperature of 150°C. As the mixing time and the content of the tire rubber increase the PI also increases. PI decreases with increasing the mixing speed. It is seen from Figure 1. Those optimum conditions are mixing temperature of 150°C, mixing time of 120 min., tire rubber content of 10% (by weight of bitumen) and mixing speed of 250 rpm.

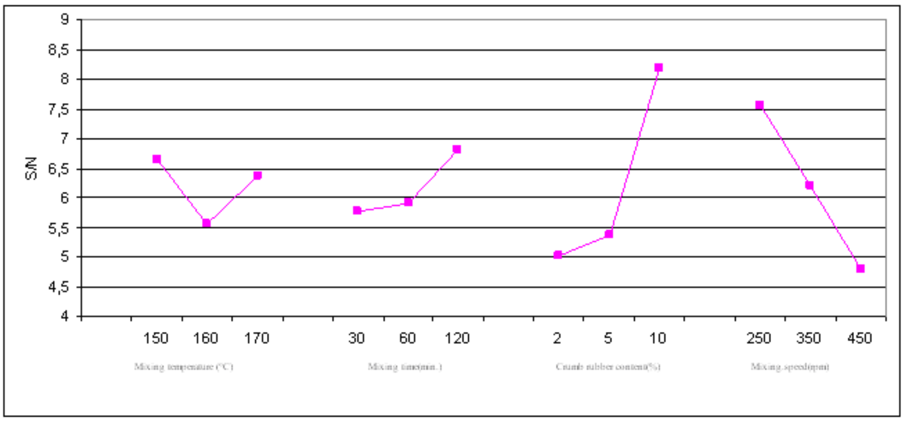


**Figure 1.** Average effects of the factors

**3.2. Statistical evaluation of the test results**

ANOVA is an important statistical analysis and diagnostic tool which helps us to reduce the error variance and quantifies the dominance of a control factor. The column under the p% gives an idea about the degree of contribution of the factors to the measured response. If the p% is high, the contribution of the factors to that particular response is more. Likewise, if the p% is low, the contribution of the factors to that particular response is less. (Srinivasan et al., 2003). Results of ANOVA before pooling showed that (Table 5), both tire rubber content and mixing speed played significant role on PI. Moreover, because of the effect of the mixing temperature and the mixing time was negligible, they were pooled (Table 6). The contribution of the parameters to maximum PI was given in Table 6. Parameter values given in Table 8 are the optimum conditions that maximize the PI. The numerical value of the maximum point in each graph marks the best value of that particular parameter. The maximum values for each parameter are given in Table 7. In addition, if the experimental plan given in Table 4 is studied carefully, it can be seen that an experiment corresponding to the optimum conditions (A:1 B:3 C:3 D:1) was not performed during the experimental work. When the optimum is not one of the trial runs already completed, this projection should be verified by running a confirmation test(s). Confirmation testing is a necessary and important step in the Taguchi method as it is direct proof of the methodology. Thus, it should be noted that the S/N value of 11.2 given in Table 7 is the predicted result by using equation 2. In order to test the predicted result, confirmation experiments were conducted twice at the optimum working conditions. From average of the confirmation test results, S/N value was obtained as 11.4.As it is seen the confirmation test result was obtained very closer to the predicted PI. Therefore, it can be said that the interactive effects of the factors are negligible for the PI of the binders and also prove that the Taguchi Method can successfully be applied to the PI experiments, with a very limited number of experiment and in a shorter time.

**Table 5.** The results of ANOVA before pooling

| Factors | Pooling | Degree of freedom | Sum of Squares | Variance | F | Pure Sum of Squares | Contribution (%) |
|---|---|---|---|---|---|---|---|
| Mixing temp.(°C) | N | 2 | 3.02 | 1.51 | - | 3.02 | 6.24 |
| Mixing time (min.) | N | 2 | 3.312 | 1.656 | - | 3.312 | 6.843 |
| Tire rubber content (%) | N | 2 | 26.298 | 13.149 | - | 26.298 | 54.332 |
| Mixing speed(rpm) | N | 2 | 15.771 | 7.885 | - | 15.771 | 32.583 |
| Error | | 0 | | | - | | |
| Total | | 8 | 48.402 | | | | 100 |

**Table 6.** The results of ANOVA after pooling

| Factors | Pooling | Degree of freedom | Sum of Squares | Variance | F | Pure Sum of Squares | Contribution (%) |
|---|---|---|---|---|---|---|---|
| Mixing temp.(°C) | Y | (2) | (3.02) | | | | |
| Mixing time (min.) | Y | (2) | (3.312) | | | | |
| Tire rubber content (%) | N | 2 | 26.298 | 13.149 | 8.305 | 23.131 | 47.79 |
| Mixing speed(rpm) | N | 2 | 15.771 | 7.885 | 4.98 | 12.604 | 26.04 |
| Error | | 4 | 6.332 | | | | 26.17 |
| Total | | 8 | 48.402 | | | | 100 |

**Table 7.** Performance statistic at optimum conditions

| Factors | Levels | Contribution (S/N) |
|---|---|---|
| Mixing temperature (°C) | 1 (150°C) | 0.656 |
| Mixing time (min.) | 3 (120min.) | 0.837 |
| Tire rubber content (%) | 3 (10%) | 2.411 |
| Mixing speed (rpm) | 1 (250rpm) | 1.569 |
| Total Contribution from all factors | | 5.47 |
| Average of performance | | 5.72 |
| Expected performance (S/N) | | 11.2 |
| Confirmation test result (S/N) | | 11.4 |
| Confirmation test result for PI | | 3.72 |

## 4. CONCLUSIONS

The following conclusions can be drawn from this study:

- According to ANOVA table, the most significant parameter affecting the temperature susceptibility is the tire rubber content.
- Optimum conditions maximizing the PI are: mixing temperature of 150°C, mixing time of 120 min., tire rubber content of 10% (by weight of bitumen) and mixing speed of 250 rpm.
- Approximately 86% improvement was provided in the temperature susceptibility of the binder obtained at the optimum conditions.
- It is seen that the results of the confirmation tests are about the same with the result predicted from the Taguchi optimization. This is the power of Taguchi method and hence the results are the cost effective.
- It is shown that Taguchi method can be used in such experimental studies as an alternative to the more expensive conventional design of experiment methods.

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