POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)

Self-healing potential of porous asphalt concrete containing different aggregates and metal wastes through microwave heating

Farklı agregalar ve metal atıkları içeren poroz asfalt betonunun mikrodalga ısıtması ile kendini iyileştirme potansiyeli

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Bu makaleye şu şekilde atıfta bulunabilirsiniz(To cite to this article): Atakan M. ve Yıldız K., "Self-healing potential of porous asphalt concrete containing different aggregates and metal wastes through microwave heating", ***Politeknik Dergisi***, 25(2): 623-631, (2022).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: **10.2339/politeknik.810673**

Self-Healing Potential of Porous Asphalt Concrete Containing Different Aggregates and Metal Wastes Through Microwave Heating

Highlights

- *Basalt aggregate is almost three times more microwave absorber than limestone aggregate.*
- *Basalt aggregate provided better microwave healing performance compared to limestone.*
- *Aluminum shavings may be a better option than steel shavings to enhance microwave healing.*

Graphical Abstract

This paper evaluates the microwave healing potential of asphalt concrete (AC) that contains metal wastes such as aluminum and steel shavings. Besides, the use of basalt and limestone aggregate (BA and LA) in AC were evaluated.

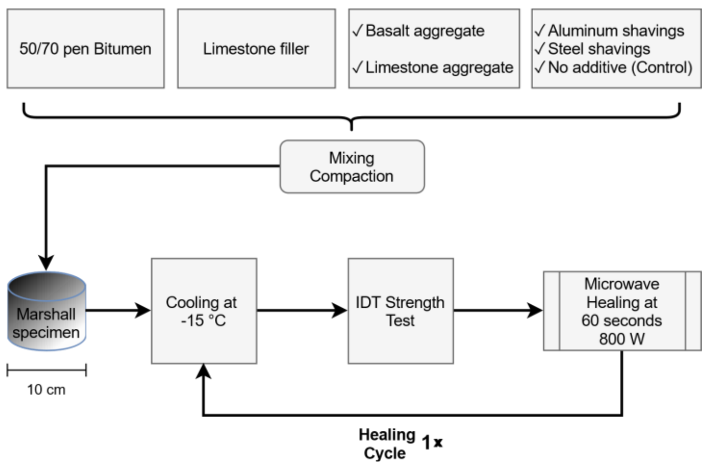

Figure Flow chart of the experimental process

Aim

The aim of the paper is to research the microwave healing potential of the porous AC containing different metal wastes and aggregates.

Design & Methodology

Firstly, microwave absorption capabilities of BA and LA were determined. In the second step of the study, porous AC specimens were prepared, and they were damaged by the indirect tensile (IDT) strength test at low temperatures. After that, damaged specimens were healed via microwave heating, and they were damaged again by the IDT strength test. In the end, the healing index of the specimens was determined as the proportion of healed specimen's strength to the original

Originality

Although there is a growing body of literature that recognizes using steel fibers in microwave healing AC, aluminum shavings and BA were used for the first time to improve microwave healing of AC.

Findings

It has been found that BA is almost three times more microwave absorber material than LA, and asphalt specimens containing BA showed better healing performance Besides, specimens with aluminum shavings showed better healing performance.

Conclusion

It has been demonstrated for the first time that aluminum shavings might be a better option than steel shavings to accelerate microwave healing. It is also concluded that, BA could be used to improve microwave healing of AC.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission

Self-Healing Potential of Porous Asphalt Concrete Containing Different Aggregates and Metal Wastes Through Microwave Heating

Araştırma Makalesi / Research Article

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(Geliş/Received : 14.10.2020 ; Kabul/Accepted : 16.12.2020 ; Erken Görünüm/Early View : 21.12.2020)

ABSTRACT

Asphalt is known as a self-healing material due to its temperature-related flow behavior. When damage occurs in asphalt concrete, bitumen can flow into cracks with heat and provide recovering by filling the cracks. Much of the current literature on self-healing pays particular attention to artificially heat asphalt concrete by several methods, including microwave heating. Although there is a growing body of literature that recognizes using steel fibers in microwave healing asphalt, there are no data on the use of aluminum fibers to improve microwave healing. This paper evaluates the microwave healing potential of asphalt concrete that contains metal wastes such as aluminum and steel shavings. Besides, the use of basalt and limestone aggregate (BA and LA) in asphalt concrete were evaluated. To achieve this, firstly, microwave absorption capabilities of BA and LA were determined. In the second step of the study, porous asphalt concrete specimens were prepared, and they were damaged by the indirect tensile (IDT) strength test at low temperatures. After that, damaged specimens were healed via microwave heating, and they were damaged again by the IDT strength test. In the end, the healing index of the specimens was determined as the proportion of healed specimen's strength to the original. It has been found that BA is almost three times more microwave absorber material than LA, and asphalt specimens containing BA showed better healing performance. It has also been demonstrated for the first time that aluminum shavings might be a better option than steel shavings to accelerate microwave healing.

Keywords: Basalt aggregate, IDT strength, metal waste, microwave heating, self-healing asphalt.

Farklı Agregalar ve Metal Atıkları İçeren Poroz Asfalt Betonunun Mikrodalga Isıtması ile Kendini İyileştirme Potansiyeli

ÖZ

Asfalt, sıcaklığa bağlı akış davranışı nedeniyle kendi kendini iyileştiren bir malzeme olarak bilinir. Asfalt betonunda hasar oluştuğunda, bitüm ısı ile çatlaklara akabilir ve çatlakları doldurarak iyileşme sağlayabilir. Kendi kendini iyileştirme ile ilgili mevcut literatürde çoğunlukla, çeşitli yöntemlerle asfalt betonunun yapay olarak ısıtılmasına önem verilmektedir ve mikrodalga ısıtması bu yöntemlerden biridir. Literatürde, mikrodalgayla iyileşen asfaltta çelik liflerinin kullanımını kabul eden çalışmalarda bir artış olmasına rağmen, mikrodalga iyileştirmeyi artırmak için alüminyum liflerin kullanımına ilişkin veri yoktur. Bu makale, alüminyum ve çelik talaşı gibi metal atıklarını içeren asfalt betonunun mikrodalgayla iyileşme potansiyelini değerlendirmektedir. Ayrıca asfalt betonunda bazalt ve kalker agregası (BA ve KA) kullanımı değerlendirilmiştir. Bu amaçla, öncelikle BA ve KA'nın mikrodalga emiş kabiliyetleri belirlendi. Çalışmanın ikinci aşamasında poroz asfalt betonu numuneleri hazırlanmış ve düşük sıcaklıklarda endirekt çekme (IDT) dayanım testi ile hasar verilmiştir. Bundan sonra, hasarlı numuneler mikrodalga ısıtması ile iyileştirildi ve IDT dayanım testi ile tekrar hasar verildi. Sonunda, numunelerin iyileştirme indeksi, iyileştirilmiş numunenin dayanımının ilk haline oranı olarak belirlendi. Sonuçta, BA'nın KA'dan neredeyse üç kat daha fazla mikrodalga emici malzeme olduğu ve BA içeren asfalt numunelerinin daha iyi iyileşme performansı gösterdiği bulunmuştur. Ayrıca, mikrodalga iyileşmesini hızlandırmak için alüminyum talaşlarının çelik talaştan daha iyi bir seçenek olabileceği de ilk defa bu çalışmada ortaya konmuştur.

Anahtar Kelimeler: Bazalt agregası, IDT dayanımı, metal atıkları, mikrodalga ısıtması, kendini iyileştiren asfalt.

1. INTRODUCTION

The porous asphalt pavement is widely used due to its advantages, such as noise reduction and water drainage ability [1]. However, the porous asphalt pavement is less durable and has shorter service life than dense asphalt pavements because of its high air void content around 20%, which promotes water and air to penetrate the surface course [1–5]. Therefore, porous asphalt pavements are required more frequent maintenance than dense asphalt pavements, and this brings about an increase in both life cycle costs and traffic restriction during maintenance [5, 6].

Previous researches demonstrated that asphalt pavement can be self-healed, and the service life of porous asphalt pavement can be extended by self-healing [6–10]. Besides, since the self-healing procedure can be

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accomplished in a short time compared with conventional maintenance, long-lasting traffic restrictions can be prevented, which can be seen in conventional maintenance techniques [5]. The self-healing of the asphalt phenomenon was found out by Bazin in 1967 [11]. After that, it has become a research topic. Since the viscosity of bitumen drops with heat, it tends to flow into cracks, and damages can be healed in a certain threshold of temperatures (i.e., 30-70 °C) depending bitumen type [12, 13]. Asphalt cracks can also be healed by itself in the ambient temperature unless being exposed to traffic loads. But the healing process may take a long time, namely several days, in low temperatures. Since it is not possible to close the road to traffic such a long time in practice, it is necessary to heat the pavement artificially and accelerate the healing process [13].

In recent years, there has been an increasing amount of literature on self-healing asphalt via induction and microwave heating. The induction heating method, which involves adding electrically conductive material in asphalt concrete and expose it electromagnetic field in order to provide heating, was used for the self-healing of asphalt for the first time in 2009 by Garcia et al. by using conductive fibers and filler, i.e., steel wool and graphite [14]. Since then, much research on induction healing of asphalt has been done [15–20]. Nowadays, it is also known microwave heating can be used to accelerate healing in the asphalt concrete by adding microwave-absorbers in it [21]. Some of the researchers have even argued that microwave heating could be more advantageous than induction heating [22–24]. The microwave healing technique was used for the first time in 2013 by Gallego et al. [23]. It has become a research topic since then, and many studies have been done on microwave healing of asphalt concrete [2, 8, 28–37, 16, 38, 39, 19, 21, 22, 24–27].

A great deal of previous research into microwave healing has focused on using steel fibers in asphalt concrete to accelerate microwave healing [2, 16, 22–24, 30, 33–35]. Aluminum fibers, on the other hand, have been used only in induction heating [40]. In other words, the effect of aluminum wastes on microwave healing has not been studied before. The basalt aggregate (BA) and the limestone aggregates (LA) are commonly used in the asphalt-mix [25], and BA has the potential to accelerate microwave heating of asphalt concrete [41]. Therefore, the effect of using BA and LA in asphalt concrete to self-healing asphalt was also aimed to research. The experimental methodology of this study involves respectively damaging the specimens by indirect tensile (IDT) strength test, applying microwave heating to heal specimens, damaging the specimens again by IDT, and determining the healing performance of the specimens. Besides, the microwave heating rate of the aggregates was determined and compared.

2. MATERIALS AND METHODS

2.1. Metal Wastes

Two kinds of metal wastes were used in the asphalt specimens: steel shavings and aluminum shavings (Fig 1). Metal shavings had a rectangular cross-section, and their sizes are listed in Table 1. Also, there were very long spiral pieces in steel shavings, and these pieces were not used in the mixture to prevent regional clustering.

Metal waste additives were added to the mixture at certain amounts. These additive amounts were 1 and 2 grams for each specimen that is equal to 2.17 % and 4.34 % by weight of the bitumen, respectively. Besides, control specimens were made without additives (Table 4).

Table 1. Sizes of the metal shavings

Metal Waste	Thickness, mm	Width, mm	Length Distribution
Steel shavings	0.008	0.028	About 75% 3-5 mm About 25% 5-10 mm
Aluminum shavings	0.019	0.065	All of them about 10 mm

Figure 1. Metal wastes used in asphalt specimens

2.2. Bitumen

In this study, 50/70 pen bitumen was utilized, which was supplied from Kırıkkale Oil Refinery. The properties of the bitumen are shown in Table 2.

2.3. Aggregates

Both BA and LA were supplied from the quarries in Ankara. LA was supplied from Yakup Abdal-2 quarry, and BA was supplied from Soğulcak quarry. The physical characteristics of aggregates are shown in Table 3. Aggregate gradation used in asphalt mixture was selected according to a previous study [1], which was based on the Dutch Standard. This gradation was used for both BA and LA (Table 5). However, as filler material (i.e., grain size <0.075 mm) limestone dust was used in all specimens.

Table 2. Properties of 50/70 pen bitumen [42]

Parameters	Value
Penetration (0.1 mm)	50/70
Softening Point (°C)	46-54
Flash Point (°C)	230 (Min)
Solubility (%)	99 (Min)
Softening point rise (°C)	9 (Max)
Resistance to hardening (a) at 163 °C	
Loss on heating (%)	0.5 (Max)
Penetration after heating (%)	50 (Min)
Softening point after heating (° C)	48 (Min)

Table 3. Physical characteristics of the aggregates

	Grain size (mm)					
	Limestone Aggregate			Basalt Aggregate		
Property	0-4.75	4.75-13.2	13.2-19	0-4.75	4.75-13.2	13.2-19
Dry unit weight (g/cm^3)	2.64	2.69	2.7	2.73	2.64	2.58
Saturated surface dry unit weight (g/cm^3)	2.67	2.71	2.71	2.75	2.66	2.60
Bulk specific gravity (g/cm^3)	2.73	2.73	2.72	2.79	2.69	2.63
Water absorption rate (%)	1.37	0.43	0.26	0.88	0.67	0.63

2.4. Microwave Oven

The microwave oven used in the experiments was a standard household type working at 2.45 GHz frequency. In addition, it had 800 W output power, and 100% power option were adopted in all heating processes.

2.5. Determining Microwave Heating Rate of Aggregates

The microwave heating rate of BA and LA were determined before using in the asphalt mixture. To achieve this, 80 g fine aggregate (0.5-2.0 mm) were taken in a 50-ml beaker and heated in the microwave oven. Then its temperature was measured every 30 s via an infrared thermometer (Fig 2). The experiment was finalized when 120 s heating time was completed. The test was carried out for three separate samples of BA and LA.

Figure 2. Measuring the temperature of the aggregate sample

2.6. Preparation of The Marshall Specimens

Asphalt mixtures used in the study consist of bitumen, limestone filler, two types of aggregate, and two kinds of metal waste. Generated specimen groups are shown in Table 4. For each specimen group, 3 specimens were produced. There were 30 specimens in total.

In order to prepare specimens, first of all, 1030 grams aggregate and bitumen were kept in the oven at 150 °C for 3 hours. Next, the aggregate and 46 grams (4.5 %) bitumen were mixed in a bowl homogenously, and metal wastes were added during the mixing process. Then, the asphalt mixture was put in a Marshall mold and compacted with 50 blows to each face of the specimen via an automatic Marshall compactor. Once compaction was completed, the specimens were removed from the mold and left to cool down at room temperature. The diameters of the produced Marshall specimens were 101.6 mm, and their heights were changing between 60 mm and 70 mm. Aggregate gradation and bitumen content of the used asphalt mixture are listed in Table 5

Table 4. Specimen groups

#	Name	Aggregate	Metal Additive	Additive Amount (g)
1	B-Control	Basalt	No Additive	0
2	B- Al 1 g	Basalt	Aluminum Shavings	1
3	B- Al 2 g	Basalt	Aluminum Shavings	2
4	B- St 1 g	Basalt	Steel Shavings	1
5	B- St 2 g	Basalt	Steel Shavings	2
6	L-Control	Limestone	No Additive	0
7	L- Al 1 g	Limestone	Aluminum Shavings	1
8	L- Al 2 g	Limestone	Aluminum Shavings	2
9	L- St 1 g	Limestone	Steel Shavings	1
10	L- St 2 g	Limestone	Steel Shavings	2

Table 5. Composition of asphalt mixture

Sieve size (mm)	Weight (%)	Weight (g)
13.2 – 19	14.5	149.35
9.5 - 13.2	37	381.10
4.75 -9.5	28.75	296.125
2 - 4.75	5	51.50
0.5 – 2	4.50	46.35
0.25 - 0.5	2.50	25.75
0.075 - 0.25	3.25	33.475
0- 0.075	4.50	46.35
Total Aggregate	100	1030
Bitumen	4.5*	46
Additives	0/2.17/2.34 **	0/1/2

* by weight of the aggregate ** by weight of the bitumen

2.7. Indirect Tensile Test

IDT test was performed before and after healing in order to determine the healing index of the specimens. Marshall test apparatus was modified with two rectangular-section steel bars to measure the IDT strength of the specimen (Fig 3).

First, specimens were kept in a freezer for 24 hours approximately at -15 °C before the IDT test to provide brittle cracking. Then, specimens were loaded till they were broken. While performing the IDT test, the loading rate was 50 mm/min, according to the standard of ASTM D6931-17. When the test was ended, the maximum load was recorded. After the healing procedure, the IDT test

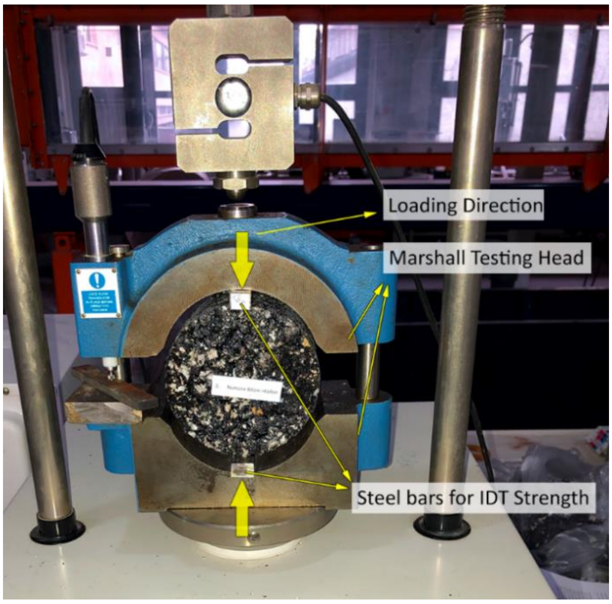

Figure 3. Experimental setup for IDT strength test with Marshall Stability Head

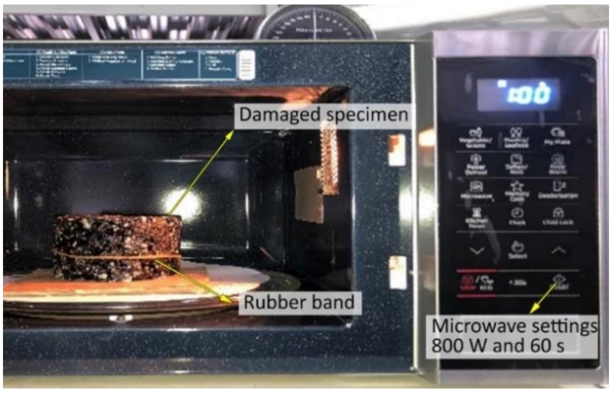

Figure. 4. Microwave healing process of damaged specimens

was applied in the same way one more time to specimens to determine the healing rate.

2.8. Self-Healing Process via Microwave Heating

After the IDT test was completed, cold specimens were let to get warm at room temperature. The microwave healing process was started once damaged specimens reach ambient temperature.

In the first step, two halves of the damaged specimens were put together and fixed with a rubber band. Then the specimen was heated in the microwave oven for 60 s in 800 W option (Fig 4). During the heating process, the specimen was let to revolve in the microwave oven. Throughout the heating process, there was a 10-second break after the first 30 s in order to prevent a possible dangerous situation that may be caused by smoke and sparkles that appeared sometimes. At the last step, the surface temperature of the specimen was measured via an infrared thermometer.

Once the microwave heating process finished, specimens were kept at room temperature, which was about 17 °C, for 24 hours. Then healed specimens were kept in a freezer for 24 hours, approximately at -15 °C, before performing the IDT test again (Fig. 5).

The microwave heating time used in the self-healing process was selected based on similar literature considering the energy that the specimen could be exposed. For instance, Tabakovic et al. (2019) [2] applied 3 min microwave heating in 300 W power option to a similar-size specimen. It is equal to 900 W*min energy. Correspondingly, in this study, heating was applied for 1 min in 800 W option that equals to 800 W*min energy. Thus, applied heating time was close to the previous study in terms of energy.

2.9. Determining the Healing Index

IDT strength of circular specimens was calculated according to ASTM D6931-17, and the formula is given in Eq. (1). Where S_t is IDT strength (kPa), P is the maximum load (N), t is specimen height immediately before the test (mm), and D is specimen diameter (mm).

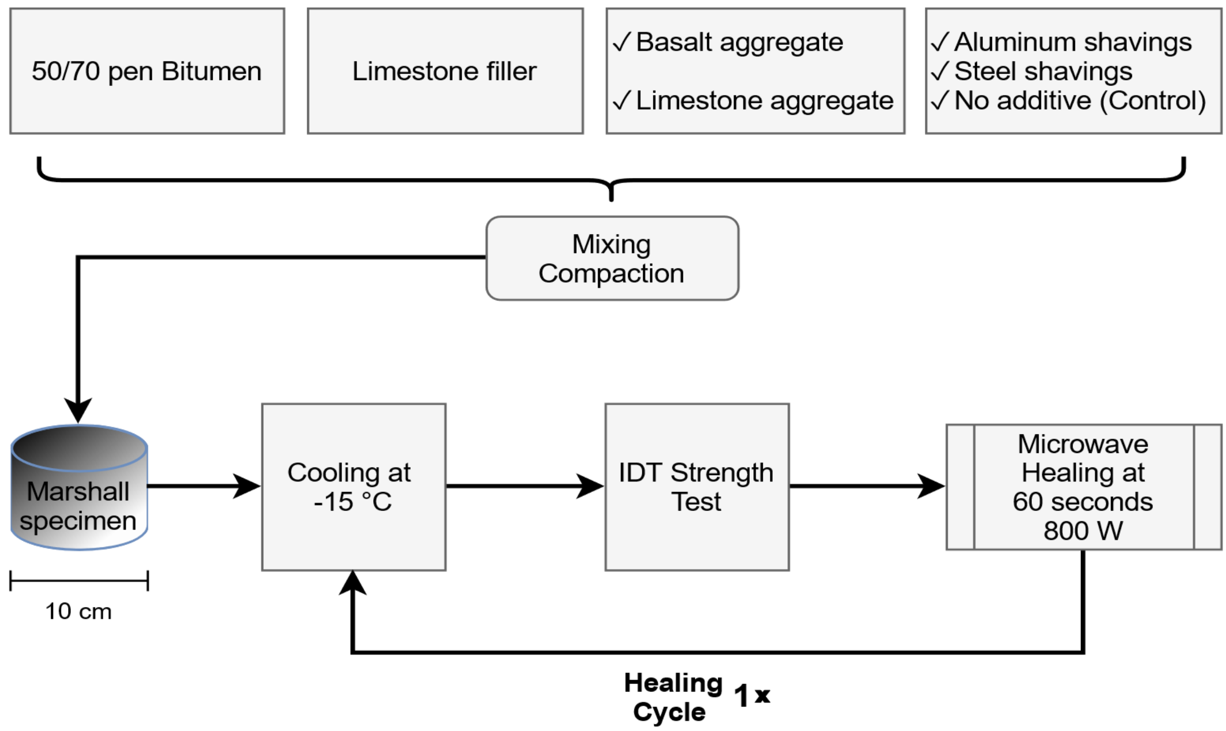

Figure 5. Flow chart of the experimental process

$$S_t = \frac{2000 \times P}{\pi \times t \times D} \quad (1)$$

The ratio of healed specimen's IDT strengths to initial IDT strength was determined as the healing index. The formula is shown in Eq. (2). Where S_1 is the IDT strength of the healed specimen (kPa), S_0 is the initial IDT strength of the specimen (kPa), and HI is the healing index (%).

$$HI = \frac{S_1}{S_0} \times 100 \quad (2)$$

2.10. Statistical Tests

Descriptive and inferential statistical tests were applied to analyze obtained results in SPSS Version 23. First of all, the Shapiro-Wilk normality test was carried out in order to decide that parametric or nonparametric tests can be used. According to the result, Spearman correlation, Mann-Whitney U, T-test, ANOVA, and Kruskal-Wallis analyses were performed.

3. RESULTS AND DISCUSSION

3.1. Aggregate Heating Rates

The microwave heating rate of BA and LA are illustrated in Fig 6a. Error bars in the figure represent the standard deviation. Based on the results, BA showed better heating performance than LA. The slope of the estimated regression line can be considered as the microwave absorption capacity of aggregates. A higher slope means better microwave absorption. The slope of BA was 0.343, while the slope of LA was 0.136. In other words, the microwave heating performance of BA almost three times higher than LA. Thus, BA could be a better option for self-healing asphalt mixtures than LA due to its microwave absorption capacity.

There are several possible explanations for the result that BA is a better microwave absorber than LA. Trigos (2020) [8] has reported some of the reasons that might affect the microwave heating rate of the aggregates based on the current literature: (1) dielectric values of minerals or rocks, (2) iron content, (3) mineralogical and chemical composition, (4) size of the crystals that form minerals. BA must differ from LA in terms of some of these properties, which could lead to BA is a better microwave absorber than LA.

3.2. IDT Strength Test and Self-Healing

The test results of the asphalt concrete specimens are demonstrated in Fig 6b, Fig 6c, and Fig 6d. The error bars in the charts represent the standard error of the values, and the total sample size is 30, with 3 specimens from each group.

3.2.1. The effect of aggregate type

Fig 6d illustrates that BA enhanced HI in almost every specimen group compared to LA. According to the Mann Whitney U test, the rise in the HI was found to be statistically significant (Table 5). It was estimated that since BA absorbs more microwave and get warm easier than LA, BA specimens were showed better healing performance. However, when surface temperatures of specimens are evaluated, it could not be seen that basalt was a better microwave absorber (Fig 6c) because surface temperatures of the asphalt concrete might not have represented internal temperatures accurately.

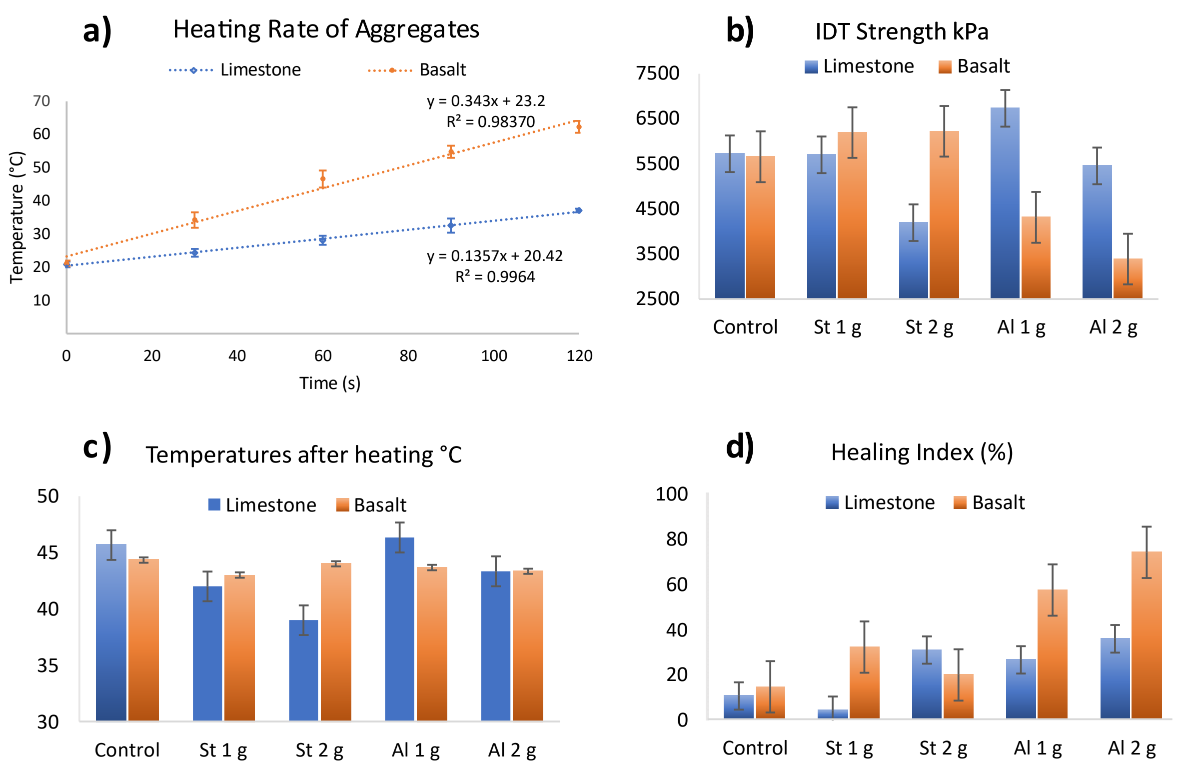

Figure 6. Results of the experiments a) microwave heating rate of aggregates b) initial IDT strength of specimens c) surface temperatures of specimens after microwave heating d) healing indexes (HI) of specimens

Table 5. Inferential test results of basalt aggregate (BA) and limestone aggregate (LA)

Test	Dependent Variable	Group Variable	p-Value
Man Whitney U Test	Healing Index (HI)	BA vs. LA	0.049*
T-Test	Initial IDT Strength	BA vs. LA	0.398

* Meaningful at the 0.05 level

The study showed that there is no remarkable difference between the asphalt specimens containing BA and LA in terms of low-temperature tensile strength. Fig 6b demonstrates that both control specimens had very close values in initial IDT strength. Although some changes were seen in some specimen groups, there was no statistically significant difference between BA and LA according to the performed T-test (Table 5). Although BA is usually considered as high strength material, it did not make any contribution to the IDT strength of asphalt specimens. Since porous asphalt concrete has high air void content, aggregates grains must have created a weak composition with less interlock; therefore, the strength of aggregate grains might not have been effective in asphalt concrete.

Furthermore, the result of the correlation analysis between initial IDT strength and HI is listed in Table 6. According to results, there was a mild negative correlation between initial IDT strength and HI. In other words, specimens that have high initial strength were tent to heal less. The reason for this behavior could be the air void content in asphalt concrete that affects the strength. According to a previous study [17], increasing air voids leads to higher healing performance. Because asphalt concrete that has lower air void content tends to break in the aggregate grains. Similarly, in this study, specimens that had higher IDT strength had probably lower air void content, and they could not heal efficiently in comparison with low-strength specimens.

Table 6. Spearman correlation analysis

Variables		R	p-Value	N
Initial IDT Strength (kPa)	Healing Index (%)	-0.444*	0.014	30

*Correlation is significant at the 0.05 level

3.2.2. The effect of metal wastes

Fig 6d illustrates that aluminum shavings showed better healing performance than steel shavings in both BA and LA groups. A previous study using induction healing has also found a similar result [40]. This situation may be caused by the density difference between aluminum and steel. To be more specific, since aluminum has low density, it covers more space in the specimen so that aluminum could scatter more homogeneously than steel. Therefore, the microwave absorption efficiency of specimens with aluminum could be higher than specimens with steel. On the other hand, the Kruskal-Wallis test was performed to data in Fig 6d among ten specimen groups and no significant difference were found.

Specimens containing steel shavings have shown incoherent healing performance. Based on observation of the researchers who implement this experimental research, the reason for some incoherent results might stem from the metal shavings which were not scattered homogeneously in the asphalt mix. Although both steel and aluminum shavings were added to the mixture in the same way, the density and fiber structure of the metal shavings might have affected the mixing process.

Fig 6b interestingly demonstrates that initial IDT strength increased with aluminum shavings when LA was used, but it decreased when BA was used. In contrast, specimens with steel shavings showed higher IDT strength when they used with BA rather than LA. Accordingly, in order to enhance IDT strength, basalt aggregate should be used with steel shavings, and limestone aggregate should be used with aluminum shavings. In addition, according to the performed ANOVA test among ten specimen groups, a significant difference was found in 95% confidence rate. Nonetheless, Games-Howell post hoc analysis was illustrated that any binary comparisons of the specimen groups did not show a significant difference. Thus, metal waste addition might have caused no significant difference in the initial IDT strength of the asphalt concrete.

4. CONCLUSION

In this research, the aim is to assess the microwave healing potential of asphalt concrete containing BA and LA in addition to steel and aluminum shavings. Besides, microwave heating rates of BA and LA are determined. The following conclusions can be drawn from this study:

The most obvious finding to emerge from this study is that based on the microwave heating test of the aggregates, the microwave heating rate of BA was almost three times higher than LA. The study has also demonstrated that according to healing indexes, asphalt concrete specimens with BA showed better healing performance than LA. Therefore, using BA instead of LA in a microwave healing asphalt pavement may be almost three times energy efficient since basalt aggregate needs less energy to warm up.

There was no statistically significant difference between asphalt specimens with BA and LA in terms of low-temperature IDT strength. However, this result might be triggered by high air void content in the asphalt concrete. A further study assessing dense asphalt concretes could clarify this issue.

Another finding was that aluminum shavings showed better microwave healing than steel shavings in both BA and LA groups. This finding suggests that using aluminum shavings in self-healing asphalt mixture can be a good option in order to accelerate microwave heating. Nonetheless, this finding was found statistically insignificant. Therefore, it is recommended for future studies to increase the number of specimens in order to reduce errors.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGMENT

The authors would like to thank undergraduate students Fikret Akbaş and Eyyüp Kaan Buran, for their contribution to conducting some of the experiments for the research. The authors also would like to acknowledge Gazi University, Department of Projects of Scientific Investigation, for its support in implementing the experimental researches (Project no. 07/2019-06).

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS’ CONTRIBUTIONS

Mert Atakan: Conceptualization, designing the methodology, experiments, visualization, analysis of the results, interpreting of the results, writing the original draft, review & editing,

Kürşat Yıldız: Conceptualization, designing the methodology, interpreting of the results, supervision, review & editing

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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