Effect of Taconite on Healing and Thermal Characteristics of Asphalt Binder

Mingxia Li[1]*, Guoxiong Wu[2], Elham H. Fini[3], Carlos J. Obando[4], Miao Yu[5], Weiran Zou[6]

DOI: 10.1061/(ASCE)MT.1943-5533.0004111

Journal of Materials in Civil Engineering, © ASCE, ISSN 0899-1561

[1]School of Civil Engineering, Chongqing Jiaotong University, No.66 Xuefu Avenue, Nan'an District, Chongqing, China, 400074, limingxia@hotmail.com

[2]School of Civil Engineering, Chongqing Jiaotong University, No.66 Xuefu Avenue, Nan'an District, Chongqing, China, 400074, wgx_ph.d@163.com

[3]School of Sustainable Engineering and Built Environment, Arizona State University, 660 S.College Avenue, Tempe, AZ 85287 efini@asu.com

[4]School of Sustainable Engineering and the Built Environment, Arizona State University, 660 S. College Avenue, Tempe, AZ 85287, cobandog@asu.edu

[5]School of Civil Engineering, Chongqing Jiaotong University, No.66 Xuefu Avenue, Nan'an District, Chongqing, China, 400074, myu2@mtu.edu.com

[6]School of Civil Engineering, Chongqing Jiaotong University, No.66 Xuefu Avenue, Nan'an District, Chongqing, China, 400074, radioheadfans@163.com

* Corresponding author. E-mail: limingxia@hotmail.com; phone: 480-930-0629

Abstract: Based on the promoting effect of metal material on the healing property of asphalt binder, this study evaluated the merits of using taconite (an iron-containing filler from iron-mine tailings) to promote the healing performance of asphalt binder. Samples of asphalt binder modified with three different dosages of taconite were tested by a thermal conductivity (TC) device. The presence of taconite can provide TC values in asphalt mastic and thereby allow inductive heating to improve healing in asphalt pavement. Laboratory experiments were used to evaluate the healing property of asphalt mastic containing 10%, 20%, or 30% wt. taconite. The healing property was measured using a healing index based on the complex modulus. The TC values were tested using a new testing method, and then the relationship between TC values and healing performance was analyzed. In the range of content of taconite used in this study, thermal conductivity gradually increased with increased taconite. The results of the study showed that the presence of taconite improved the healing property of asphalt mastic. For healing time 900s, loading strain 5%, and degree of damage 50%, an increased dosage of taconite led to an increased healing property of modified asphalt binder, although the increase in the promoting effect on healing performance was not large. This study also evaluated the effect of several factors that influence the healing property of asphalt mastics. The content of taconite, the healing time, the loading strain level, and the degree of damage affected the healing performance of asphalt mastics modified by taconite. Since taconite is a by-product of mining iron-bearing sedimentary rock in which the iron minerals are interlayered with quartz, chert, or carbonate, our use of this so-called waste from mining and its application in construction is expected to promote resource conservation and recycling while enhancing sustainability in pavements.

Keywords: taconite, asphalt, rheology, healing, influencing factor, thermal conductivity

1 Introduction

Extending the service life of asphalt pavement through various modification procedures has been a focus of the asphalt industry. Recently, the potential for healing cracks in asphalt pavement has received increased attention (Ayar, 2016). To improve the healing property of asphalt binder, studies have attempted to use microcapsules, hollow-fiber tubes, and nanoparticles (White et al., 2002; Alvaro et al., 2010; Van der Zwaag et al., 2010; Schlangen et al., 2013; Santagata et al., 2015 and 2016; Chen et al., 2015). In addition to liquid modifiers and polymers, there are solid additives such as minerals and steel wool (Wang et al., 2016; Wang et al., 2016; Norambuena-Contreras et al., 2016; Albert et al., 2020).

Taconite is a hard, dense, iron-bearing sedimentary rock composed of alternating chert and slate units of varying thickness. Taconite contains an intimate mixture of quartz and magnetite (Fe_3O_4), plus varying amounts of iron oxides, carbonates, and silicates (Davis, 1964). Studies have shown that taconite can be added to an asphalt mixture to promote pavement performance, improving damage resistance and structural strength (Moon et al., 2014; Dave et al., 2013; Zanko et al., 2003; Clyne et al., 2010). Other studies found that mixtures prepared with taconite performed slightly better than mixtures prepared with standard aggregates, as measured by a semi-circular bending test and an indirect tensile test (Velasquez et al., 2009). Asphalt mastic containing 5% taconite presents similar properties at low temperature and better performance at high temperature compared to the corresponding asphalt binder. For example, asphalt mastic containing 5% taconite has greater resistance to rutting at high temperature (Moon et al., 2014). But some researchers have also pointed out that the use of up to 50% taconite in place of standard aggregate leads to a moderate decrease in fatigue life and fracture resistance (Moon et al., 2019).

Adding thermal conductive fillers in polymers and asphalt binders is a practical approach to increase thermal conductivity (TC) and raise the softening point (Chen et al., 2016; Tait et al., 2011; Eskandarsefat et al., 2019). TC can influence the temperature of samples, and there is a positive correlation between temperature and healing property at a special condition (Xiang et al., 2019). So the introduction of metal fillers can promote the healing property of asphalt binder. While there have been some studies on the effect of taconite on the thermo-mechanical properties of asphalt binder, to the best of our knowledge, there are no studies on the effect of taconite on asphalt binder's healing property.

It has been shown that an asphalt binder having a high healing capacity will have a better life span (Li et al., 2020). An asphalt binder's healing capacity is affected by many factors such as composition and aging status (Hung et al., 2020; Oldham et al., 2021). This paper investigated whether the introduction of taconite to asphalt binder enhances the asphalt binder's healing capacity. The results of the study showed that taconite can be a good additive for asphalt mastic to improve its healing property by promoting its thermal conductivity. The thermal conductivity of asphalt binder with several dosages of taconite was tested, and the relationship between the thermal conductivity and the healing performance of the modified asphalt binder was analyzed. Those results can enrich the understanding of the promoting effect of taconite on the healing property of asphalt binder. The results can also increase the use of taconite.

2 Materials and Methods

2.1 Materials

The asphalt used in this study is PG 64-22 from HollyFrontier Corporation in Arizona (Table 1). Taconite was acquired through Minnesota Mine Tailing, MN. The properties of taconite are given in Table 2. Four dosages of taconite based on mass ratio (0%, 10%, 20%, 30%) were introduced to asphalt binder, then its self-healing property was evaluated for each dosage. To prepare the specimens, taconite was added to the asphalt binder and mixed for 5 min. Following that, each sample was stored for tests.

2.2 Evaluation of healing

To evaluate the healing property of asphalt binder samples containing taconite, a rheometry test was conducted using time sweep (loading-rest-loading) according to the DSR test in ASTM-D7552-09 (2019). Samples of 8-mm diameter and 2-mm thickness were tested at 25°C. It was found that when the loading strain was too small, it would take a long time to finish the loading test. But if the loading strain was too large, the sample would be damaged totally and quickly, leading to no healing phenomenon [Li et al., 2020]. A 5% loading strain and a 10 HZ loading frequency were applied to ensure that the asphalt binder was in a viscoelastic state (Lv et al., 2017). The test requires a minimum of three replicates; in this study, we chose to test five replicates to enhance the accuracy of results. Each sample was loaded until its complex shear modulus (G^*) was reduced to 50% of the initial value. The initial value was named as (G_0); 50% of the initial value G_0 was named as (G_a). Then loading was stopped, and the sample was given a resting period of 900s. After the resting period, the new complex shear modulus was called G_b. The healing index was calculated using Equation 1 (Chen et al., 2018).

$$HI = \frac{G_b - G_a}{G_0 - G_a}$$

where:
G_0 is the initial dynamic shear modulus at the beginning of the first loading,
G_a is the ending dynamic shear modulus before the resting interval, and
G_b is the new dynamic shear modulus after the resting period.

In order to explore the factors influencing the healing property of asphalt binder modified with taconite, the healing time, loading strain level, and degree of damage were chosen to evaluate the effects of those factors on healing performance.

2.3 Thermal conductivity test

The sample's mold for the thermal conductivity test was a cylinder with dimensions 2.51cm(h)×1.95cm(r). The thermal conductivity of asphalt binders with different contents of taconite was determined based on the method developed by Obando and Kaloush (Obando et al., 2020). These are the steps of the experiment:
(1) Preheat the oven to 160°C.
(2) Put samples in the oven and heat them until they can be easily introduced into the mold.
(3) Pour samples into the testing mold (Figure 1). Ensure that the pouring process is slow, and ensure that the pouring height is slightly higher than the height of the mold.

(4) Place samples with mold in a flat position for a period of time to cool to room temperature, being careful to avoid contaminating the surface of the test piece.

(5) Place samples in the cooling device for about 20 minutes, then remove the samples from the mold, remove the excess asphalt binder on the edge, and pay attention to ensure that the height of the samples is consistent.

(6) Make a small hole with a height of 2.5 cm in the middle of each sample to facilitate insertion of the temperature sensor. Use white insulating foam sealant to seal around the temperature sensor, to prevent air or water from entering, and to block the inflow of heating from above the sample, which would affect the measurement.

(7) Put samples into a heating device with a water-bath temperature of 30°C (as shown in Figure 2). To ensure that the ambient temperature is consistent with the water-bath temperature, place the entire device in a chamber at the same temperature.

(8) Stop the test after 2h, remove the device, export the data from the temperature sensor through software, and calculate the thermal conductivity of samples using the computing method in Obando and Kaloush.

3 Results and Discussion

3.1. Effect of taconite dosage on healing property

The dosages of taconite used were 0%, 10%, 20%, and 30%. The degree of damage was 50%, and the healing temperature was 25°C. The healing index of each specimen was obtained after a process of loading-healing-loading. It can be seen from Figure 3(a) that compared with the healing index of asphalt binder modified with 10% taconite, the healing index of asphalt binder modified with 30% taconite was higher by 5.4, when the healing time was 900s, the loading strain level was 5%, and the degree of damage was 50%. For all three content levels of taconite, the improvement effect of taconite on the healing index of asphalt binder consistently increased with increasing taconite dosage. The result differs from the research on the healing performance of asphalt binder with pure Fe_2O_3 as a filler, where the trend in improvement was first increasing and then decreasing (Li et al., 2020).

3.2. Effect of healing time on healing property

To study the effect of healing time on the healing property of asphalt binder modified with taconite, the healing times used were 300s, 600s, and 900s, the degree of damage was 50%, and the loading strain level was 5%. Five replicate tests were conducted, and three similar data were used to compute the results. The results are shown in Figure 3(b).

Compared to a taconite concentration of 10%, the healing index for 30% taconite concentration was higher by 6.97, 2.64, and 5.4 for healing times of 300s, 600s, and 900s, respectively. When the taconite concentrations were respectively 10%, 20%, and 30%, the healing index of asphalt mastic for 900s was higher than that for 300s by 25.15, 20.78, and 23.58. Thus, a longer healing time led to better healing performance. This is mainly because a longer healing time results in more heat storage, and there is more time to ensure that the asphalt binder flows to the damaged location to complete the healing process.

3.3 Effect of loading strain on healing property

The magnitude of the loading strain influences the linear viscoelastic property of asphalt binder. When the loading strain is too large, the fatigue performance of the asphalt material cannot be reflected normally due to the small number of loading cycles (Shan, 2010). To study the effect of loading strain on healing performance of asphalt mastic modified by taconite, three strain levels of 3%, 5%, and 7% were used to explore the healing performance of asphalt binders modified with 10%, 20%, or 30% taconite. The test temperature was 25℃, the healing time was 900s, and the degree of damage was 50%. The test results are shown in Figure 3(c).

When the loading strain level was 3% or 7%, the asphalt binder with 20% taconite had the strongest healing performance. When the strain level was 5%, as the content of taconite increased, the healing index of the modified asphalt binder gradually improved. When the loading strain level increased from 3% to 5% and then from 5% to 7%, the healing index of the asphalt binder modified with 10% taconite changed by +11.11 and -28.41, respectively. As for the asphalt binder with 30% taconite, the healing index changed by +9.64 and -37.14, respectively. Based on those results, it can be concluded that there is a best loading strain level among the three strain levels tested in this study, and when the loading strain level increased, the influence of taconite on the healing index of modified asphalt binder showed a non-synchronous growth trend. As the content of taconite in asphalt binder increased, the healing index of the modified asphalt binder did not continue to increase under the 3% and 7% loading strain levels. This is similar to the research results when asphalt binder was modified with Fe_2O_3 (Li et al., 2020).

3.4 Effect of the degree of damage on healing property

Micro-crack damage in asphalt pavement can be partially or completely repaired when given enough recovery time. However, when the damage is too large, to a certain extent it cannot be repaired by depending only on the self-healing property of the asphalt binder. In order to explore the degree of such healable damage, three damage degrees of 30%, 50%, and 70% were adopted as the studied indicators, the healing time was 900s, the loading strain level was 5%, and the healing property of a taconite-modified asphalt binder mixture was tested. Five replicate tests were conducted and three similar data were used to compute the results. The results are shown in Figure 3(d).

When the content of taconite modification in asphalt binder was 10%, 20%, or 30%, and the degree of damage was 30%, the healing index of asphalt mastic with 30% taconite was the best compared to that of other two mastics. They were 38.3, 41.47, and 44.32, respectively. When the degree of damage was 50%, the healing index values were 37.00, 39.14, and 42.4, respectively. When the degree of damage was 70%, the healing index values were the worst: 13.02, 14.12, and 16.01, respectively. When the degree of damage increased from 30% to 70%, the healing index of asphalt binders modified with 10%, 20%, or 30% taconite was reduced by 25.28, 27.35, and 28.31, respectively. Thus, an increase in the degree of damage led to a decrease in the healing index of asphalt binder modified with taconite, and when the degree of damage was 70%, the healing index of asphalt binder with taconite was sharply lower. Therefore, during the daily maintenance phase of asphalt pavement, maintenance and repair should be carried out as soon as possible when the road is in a low-damage condition, to prevent further deterioration that would shorten the service life of the road.

3.5 Thermal characteristics

The thermal conductivity values for asphalt binders with different contents of taconite are shown in Figure 4. When the content of taconite increased from 10% to 30%, the thermal conductivity of modified asphalt binder increased from 0.1582W (m-K) to 0.1870W (m-K). This result shows that the introduction of taconite into asphalt binder can increase the sensitivity of asphalt binder to temperature, and in the content range of taconite explored in this study, the thermal conductivity of modified asphalt binder would gradually increase with increasing content of taconite. The optimal value for the content of taconite for thermal conductivity was not apparent. That is due to the fact that taconite, as a metal filler including 15-30% iron composition, can improve the thermal conductivity of asphalt mastic (DeDene et al., 2016). When the dosage of taconite included in asphalt binder is increased, it would help make the distribution of taconite in asphalt binder more even and further promote its thermal conductivity.

Higher thermal conductivity indicates that the heat can be absorbed more rapidly by the modified asphalt binder, which increases the heat flux density. When the heat flux density is enhanced, it can speed up the increasing of temperature. Besides, the healing behavior of asphalt is based on its temperature. A higher temperature can decrease the viscosity and increase the rheological property of asphalt binder; then it can flow to the damaged area to heal cracks. According to those theories, the taconite can make the temperature of asphalt binder increase more quickly and get to a critical point that drives asphalt binder to start the healing behavior.

Since thermal conductivity is an important factor that initiates crack healing, good thermal conductivity of modified asphalt binder helps to promote crack healing. This result can also briefly explain why an increase in taconite content led to an increase in the healing index of the modified asphalt binder; there was no phenomenon of an optimal value of the healing ability as reported in research for Fe_2O_3-asphalt cement (Li et al., 2020). This can also show that the self-healing test results of the asphalt binder modified with taconite are reliable.

4. Conclusion

This paper investigated whether the introduction of taconite as a filler to PG 64-22 asphalt binder would enhance its healing property. It was found that taconite can be a good filler for asphalt mastic to improve its healing property by promoting its thermal conductivity. Cracking and subsequent healing are highly impacted by the properties of the binder and mastics rather than the stone-aggregate skeleton (Shen et al., 2009). Therefore, this study focused on mastic-level properties. Typically, 0%-50% mineral filler is used in common asphalt-mastic mixtures. Therefore, we introduced 10%-30% taconite into asphalt binder to simulate the mastic portion of asphalt pavement, excluding the stone-aggregate skeleton. The followings are the conclusions drawn from this study:

- For healing time 900s, loading strain 5%, and degree of damage 50%, an increased dosage of taconite led to an increased healing index of modified asphalt binder, although the increase in the promoting effect on the healing performance was not large. This trend in healing performance differed from the research results of asphalt binder with pure Fe_2O_3 as a filler.

- A longer healing time led to better healing performance. Compared to 300s of healing time for degree of damage 50%, the healing index for 900s healing time was higher by 25.15, 20.78, and 23.58 for taconite concentrations of 10%, 20%, and 30%, respectively.
- There was a best loading-strain level among the three strain levels used in this study; it was 5%. When the strain level increased, the influence of taconite on the healing performance of asphalt binder showed a non-synchronous growth trend.
- When the degree of damage was 70%, the healing performance of asphalt binder with taconite was sharply lower compared to when the degree of damage was 50%. Therefore, during the daily maintenance phase of asphalt pavement, maintenance and repair should be carried out as soon as possible while the road is in low-damage condition, to prevent the damage from further deterioration that would shorten the service life of the road.
- The introduction of taconite can increase the sensitivity of asphalt binder to conduction heating; in the content range of taconite explored in this study, thermal conductivity gradually increased with increased taconite. It can be concluded that the improving effect of taconite on healing performance is due to taconite's ability to enhance the thermal conductivity of modified asphalt binder.

Acknowledgments

The research was funded by the China Scholarship Council (Certificate number: 201908500149), which also supported the author’s living cost in the U.S. We also received support from the Postgraduate Research Innovation Fund Project of Chongqing Jiaotong University (2018B0103). The conduct of research was also partially supported by 2014 Chongqing University Outstanding Achievement Transformation Funding Project (KJZH14104) and the National Science Foundation (Award Number 1928807). The authors greatly appreciate Jeff Long and Peter Goguen with Arizona State University for assistance and guidance with the conduct of laboratory experiments.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

References

ASTM-D7552-09. “Standard Test Method for Multiple Stress Creep and Recovery (MSCR) of Asphalt Binder Using a Dynamic Shear Rheometer”.

Ayar P, Navarro M.F, Rubio-Gámez C.M. (2015). “The healing capability of asphalt pavements: a state of art review”, *J. Clean. Prod.* 113.28-40. https://doi.org/10.1016/j.jclepro.2015.12.034

Chen H.Y, Ginzburg V.V, Yang J, Yang Y.F, Liu W, Huang Y, Du L.B, Chen B. (2016). “Thermal conductivity of polymer-based composites: fundamentals and applications”. *Prog. Polym. Sci*. 59: 41-85. https://doi.org/10.1016/j.progpolymsci.2016.03.001

Chen L.X, Xiang H, He Z.Y, Wang D.M, Xu X.X. (2019). “Analysis of self-healing evaluation index of asphalt cement based on DSR”. *Journal of Building Materials*. (3). (in Chinese). http://kns.cnki.net/kcms/detail/31.1764.TU.20181112.1320.016.html

Chen Y.L, Gong M.H, Yao Z.G, Dong X.X, Song K.M. (2015). “Investigation on the self-healing abilities of base and ionomer-modified asphalt binders with a T-Peel test”. *International Symposium on Frontiers of Road and Airport Engineering*. Shanghai, P64. https://doi.org/10.1061/9780784414255.007

Clyne T.R, Johnson E.N, Worel J. (2010). “Use of Taconite Aggregates in Pavement Applications: Minnesota Department of Transportation”, Final report #MN/RC-2010-24. https://www.lrrb.org/pdf/201024.pdf

Dave E, Baker J. (2013). “Moisture Damage Evaluation of Asphalt Mixes That Contain Mining By-products”. *Transportation Research Record* 2371(1):113-120. https://doi.org/10.3141/2371-13

Davis E.W.(2004). “Pioneering with taconite: Minnesota Historical Society”, 246 p

DeDene C.D, Gorman J.M, Marasteanu M.O, Sparrow E.M. (2016). “Thermal conductivity of reclaimed asphalt pavement (RAP) and its constituents”. International Journal of Pavement Engineering. Vol. 17, No. 5: 435-439. https://doi.org/10.1080/10298436.2014.993201

Eskandarsefat S, Hofko B, Rossi C.O, Sangiorgi C. (2019). “Fundamental properties of bitumen binders containing novel cellulose-based poly-functional fibres”. *Compos. Part B* 163: 339-350. https://doi.org/10.1016/j.compositesb.2018.11.031

Garcia A, Schlanngen E, Ven M.V.D. (2010). “Two ways of closing cracks on asphalt concrete pavements: Microcapsules and induction heating”. *Key Engineering Materials*.417-418:573-576 https://doi.org/10.4028/www.scientific.net/KEM.417-418.573

Garcia A, Schlanngen E, Ven M.V.D. (2010). “How to make capsules containing containing rejuvenators for their use in asphalt concrete”. *Journal of Wuhan University of Technology*, 90(17):603. https://doi.org/10.3963/j.issn.1671-4431

Garcia A, Schlanngen E, Ven M.V.D, Sierra-Beltrán G. (2010). “Preparation of capsules containing rejuvenators for their use in asphalt concrete”. *Journal of Hazardous Materials*,184(1):603. https://doi.org/10.1016/j.jhazmat.2010.08.078

Hung A, Mousavi M, Fini H.E. (2020). “Implication of Wax on Hindering Self-Healing Processes in Bitumen”. *Applied Surface Science*. Vol. 523. https://doi.org/10.1016/j.apsusc.2020.146449

Li M.X, Wu G.X, Li X.K, Zou W.R, Cheng Y.H. (2020). “Study on the Damage and Healing Property of Fe_2O_3-asphalt Binder”. *Journal of Chongqing Jiaotong University (Natural Science)*.39(10):74-78 (in Chinese). http://xbzk.cqjtu.edu.cn/CN/abstract/abstract6457.shtml

Li M.X, Wu G.X, Fini E, Yu M, Xu Z.G. (2020). “Investigating the healing property of asphalt mixtures containing iron slag”. *Construction and Building Materials*. Vol. 261, 20 November,119446. https://doi.org/10.1016/j.conbuildmat.2020.119446

Lv Q, Huang W.D, Xiao F.P. (2017). “Laboratory evaluation of self-healing properties of various modified asphalt”. *Construction and Building Materials*. 136:192-201. https://doi.org/10.1016/j.conbuildmat.2017.01.045

Moon K.H, Falchetto A.C, Wang D, Kim Y. S. (2019). “Experimental Investigation on Fatigueand Low Temperature Properties of Asphalt Mixtures Designed with Reclaimed Asphalt Pavement and Taconite Aggregate”. *Transportation Research Record*, Vol. 2673(3) 472-484. https://doi.org/10.1177/0361198119835525

Moon K. H, Falchetto-Cannone A, Park J.Y, Jeong J.H. (2014). “Development of the High Performance Asphalt Mastic Using Fine Taconite Filler”. *KSCE Journal of Civil Engineering*, 18(6):1679-1687. https://doi.org/10.1007/s12205-014-1207-6

Norambuena-Contreras J, Serpell R, Vidal G V, González A, Schlangen E. (2016). “Effect of fibers addition on the physical and mechanical properties of asphalt mixtures with crack-healing purpose by microwave radiation”. *Constr.Build.Mater*. 127:369-382. https://doi.org/10.1016/j.conbuildmat.2016.10.005

Obando, C. J, Kaloush K.E. (2020). A Novel Method to Estimate Thermal Conductivity of Asphalt Binders. Tempe: 17th Arizona Pavements/Materials Conference.

Oldham D, Obando C. J, Mousavi M, Kaloush K.E, Fini H.E. (2020). “Introducing the Critical Aging Point (CAP) of Asphalt Based on Its Restoration Capacity”, Journal of Construction and Building Materials. Vol. 278, 5 April 2021, 122379. https://doi.org/10.1016/j.conbuildmat.2021.122379

Santagata E, Baglieri O, Tsantilis L, Chiappinelli G (2015). “Fatigue and healing properties of nano- reinforced bituminous binders”. *International Journal of Fatigue*,90:30. https://doi.org/10.1016/j.ijfatigue.2015.05.008

Santagata E, Baglieri O, Tsantilis L, Dalmazzo D, Chiappinelli G. (2016). “Fatigue and healing properties of bituminous mastics reinforced with nano-sized additives”. *Mechnics of Time-Dependent Materials*,20(3):367-387. https://doi.org/10.1007/s11043-016-9301-4

Schlangen E, Sangadji S. (2013). “Addressing infrastructure durability and sustainability by self-healing mechanisms-recent advances in self-healing concrete and asphalt”. *Procedia Engineering*, 54:39-57. https://doi.org/10.1016/j.proeng.2013.03.005

Shan L.Y. (2010). “Fatigue and Rheology Mechanism of Asphalt Binder Based on Viscoelastic Characteristic”. Harbin: Harbin University of Technolog. http://gb.oversea.cnki.net/KCMS/detail/detail.aspx?filename=1011278924.nh&dbcode=CDFD&dbname=CDFDREF

Shen S, Chiu H.M, Huang H. (2009). “Fatigue and healing in asphalt binders”. Proceeding of the 88th Annual Meeting of the Transportation Research Road. Washington DC. https://trid.trb.org/view/881132

Tait M, Pegoretti A, Dorigato A, Kalaitzidou K. (2011). “The effect of filler type and content and the manufacturing process on the performance of multifunctional carbon/poly-lactide composites” *Carbon* 49 (13):4280-4290. https://doi.org/10.1016/j.carbon.2011.06.009

Velasquez R, Turos M, Moon K. H, Zanko L, Marasteanu M. (2009). “Using recycled taconite as alternative aggregate in asphalt pavements”. *Construction and Building Materials*. 23:3070-3078. https://doi.org/10.1016/j.conbuildmat.2009.04.003

Wang H.P, Jun Y, Liao H, Chen X.H. (2016). “Electrical and mechanical properties of asphalt concrete containing conductive fibers and fillers”. Construction and Building Materials 122:184-190. https://doi.org/10.1016/j.conbuildmat.2016.06.063

Wang Z.G, Dai Q, Qing L, Porter D. (2016). “Investigation of microwave healing performance of electrically conductive carbon fiber modified asphalt mixture beams”. *Constr. Build. Mater*. 126:1012-1019. https://doi.org/10.1016/j.conbuildmat.2016.09.039

White S.R, Sottos N.R, Geubelle P.H, Moore J. S, Kessler M. R, Sriram S. R, Brown E. N, Viswanathan S. (2002). “Autonomic healing of polymer composites”. *Nature*,415(6873):794. https://www.nature.com/articles/35057232.pdf

Xiang H, Zhang W.W, Liu P, Yao Q.W, He Z.Y. (2019). “Optimum Healing Temperature and Healing Time of Recycled Asphalt Based on DSR”. *Journal of Chongqing Jiaotong University (Natural Science)*. Vol.38:56-60 (in Chinese). https://scjg.cnki.net/kcms/detail/detail.aspx?filename=CQJT201910009&dbcode=CJFQ&dbname=CJFD2019&v=MjY1OThSK0MzODR6aDRYbkQwTFRnMlgyaHN4RnJDVVI3dWZaT1J0RmluaFY3L0xKanpCZXJHNEg5ak5yNDlGYlk=

Zanko L.M, Niles H. B, Oreskovich J.A. (2003). “Properties and Aggregate Potential of Coarse Taconite Tailings from Five Minnesota Taconite Operations”. *University of Minnesota*, Duluth, Minn. https://conservancy.umn.edu/handle/11299/187138

Zwaag S.V. (2010). “Routes and mechanisms towards self-healing behavior in engineering materials”. *Bulletin of the Polish Academy of Sciences: Technical Sciences*,58(2):227. https://doi.org/10.2478/v10175-010-0022-6

Table 1. Properties of asphalt binder (PG64-22) used in this study

Technical index	Value
Specific Gravity @15.6 ºC	1.041
Cleveland Open Cup method Flash point ºC	335
Mass change after RTFO@%	-0.013
Absolute Viscosity @ 60 ºC, Pa.s	179

Table 2. Properties of taconite used in this study

Test Item	Result	Test Method
Specific Gravity (gr/cm^3)	2.803	AASHTO T84
Deleterious Materials	40-45%	AASHTO T176
Total % Absorption	1.5	AASHTO T84
Abrasion Resistance	< 40	AASHTO T96