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ASSESSMENT OF ASPHALT CONCRETE PAVEMENT UTILIZING DISPERSED BASALT FIBERS IN VIET NAM

Major: Transport construction engineering
Code: 9580205

SUMMARY OF DOCTORAL THESIS

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INTRODUCTION

I. The necessity of the topic

Asphalt concrete (AC) pavement is commonly used worldwide and in Vietnam. In regular projects and locations, traditional asphalt using binder without additives generally meets the requirements. However, under the harsh environmental conditions todays Vietnam, or high-level roads with large traffic volumes, asphalt mixtures without additives easily appear damaged, and their service life is limited and could not achieve the desired performance as designed.

In order to improve the quality of asphalt pavement, there have been many solutions applied in Vietnam and worldwide such as: Adjusting mixure composition, improving asphalt binder quality, improving asphalt mixture quality with additional additives, etc. Using reinforced fibers is one of the solutions to enhance several physical and mechanical properties of asphalt mixture. Commonly used fibers include: asbestos, carbon, aramid, cellulose, polyester, polypropylene, steel, glass, basalt...

Basalt fiber is a material of natural origin. Basalt fiber has superior properties compared to glass fiber in terms of hardness, high tensile resistance, resistance to chemicals, temperature, and environmental friendliness. Basalt fibers are used as fireproof materials in the aerospace and automotive industries, and are also used as synthetic materials to produce other popular products. In terms of cost, basalt fiber is relatively reasonable compared to other fibers commonly used such as glass, cellulose, carbon... In Vietnam, there have been a number of works conducted using glass, forta FI, cellulose... for AC modification, however, there has been no research on using basalt fiber for asphalt mixtures. Based on the above, the chosen topic: "*Assessment of asphalt concrete pavement utilizing dispersed basalt fibers in Viet Nam*", which focuses on researching and assessment of the influence of basalt fibers on the physical and mechanical properties of AC mixture. This topic is necessary, and has scientific and practical significance.

II. Research purposes

- Research the bonding mechanism and distribution of basalt fibers in AC, thereby determining the optimal binder content for AC mixtures using basalt fibers;
- Design AC mixture using basalt fibers with different contents, compare with control AC of the same composition through physical and mechanical properties;
- Applying machine learning (ML) algorithms to support the design and prediction of some physical and mechanical properties of AC using basalt fibers;
- Suggestion AC pavement using basalt fibers for some roads in Vietnam, auditing with current methods and standards, preliminary determination of costs, towards manufacturing AC using basalt fibers at the mixing station.

III. Scope of the study

- AC mixture with nominal maximum aggregate size of 12.5mm using basalt fibers with different contents as the surface layer for AC pavements;
- Overall analysis of the use of reinforced fibers and basalt fibers used for AC mixtures in Vietnam and worldwide;

- Conduct laboratory experiments, determination of technical specifications of AC using basalt fibers with different contents and control AC mixture;
- The scope of research is limited to: 12.5 mm AC, 60/70 asphalt binder; basalt fiber of natural origin from China, and has a diameter of 12 µm and a length of 12mm.

IV. Scientific and practical significance of the research topic

- Analyze and clarify the foundation for using dispersed basalt fibers in AC, and analyze the bonding mechanism between basalt fibers and AC;
- Analyze the composition and structure of the AC mixture using dispersed basalt fiber, thereby highlighting the advantages and disadvantages through physical and mechanical criteria and providing the scope of application of this new material in Vietnam;
- Analyze and propose the AC pavement of AC using basalt fiber that satisfies all exploitation characteristics according to current Vietnamese standards.
- Applying ML models to build a tool to quickly predict some physical and mechanical properties of asphalt using dispersed basalt fibers;
- Determine the technical criteria of AC using basalt fibers when designing AC pavement according to TCCS38:2022 standards and mechanistic– empirical (M-E) method;
- Proposing a number of AC pavement roads for using AC incorporating basalt fibers in Vietnamese conditions.

CHAPTER 1. OVERVIEW OF REINFORCED AND BAZAN FIBERS USED FOR ASPHALT CONCRETE MIXTURES

1.1. Asphalt concrete with fibrous additives for road surface layer

Using reinforced fibers is one of the solutions to enhance the physical and mechanical properties of the AC mixture. Commonly used fibers include: asbestos, carbon, aramid, cellulose, polyester, polypropylene, steel, glass... This method has been employed since the 50s of the last century and has been used in many countries, such as the United States, Japan, Korea, China... Basically, fibers added to the AC mixture with two main roles: (i) limiting the flow ability of asphalt in the asphalt mixture (such as SMA mixture, open-graded asphalt mixture); (ii) Increase tensile resistance when bending, increase fatigue life under the effect of uniform load as well as improve rutting characteristics.

1.2. Basalt fibers used for asphalt concrete

1.2.1. Overview of basalt fibers

Basalt fiber is a material of natural origin. Basalt fiber has superior properties compared to glass fiber in terms of hardness, very high tensile resistance, resistance to chemicals, temperature, and environmental friendliness. Basalt fibers are used as fireproof materials in the aerospace and automotive industries, and are also used as synthetic materials to produce many other popular products. In terms of price, basalt fiber is relatively reasonable compared to other fibers commonly used in the world such as glass fiber, cellulose fiber, carbon fiber...

Formed from volcanic basalt, basalt fibers have many beneficial properties. Besides having a high elastic modulus and high temperature resistance, basalt fiber also has very high sound insulation and anti-vibration properties. With many outstanding properties, research on the application of basalt fiber is strongly developed and is a research direction that many scientists are interested in.

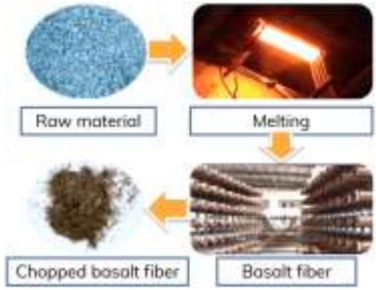


Fig. 1.2. Basalt fiber production process.

1.2.2. Properties and applications of basalt fibers

Studies have shown that, when comparing the properties of popular commercial fibers, basalt fibers have superior properties compared to glass fibers in terms of hardness, very high tensile resistance, and resistance to chemicals and heat. level, environmentally friendly. A number of studies have evaluated the effects of fiber length and basalt fiber content on the mechanical properties of composite materials fabricated on polyester resin. The results of the characterization of the composites show that the fiber length has a significant influence on the mechanical properties of the composites and also on the fiber content.

1.2.3. Research on the design of asphalt concrete using basalt fibers

Important physical properties to consider when analyzing basalt fibers are length, tensile strength, elastic modulus, elongation at break, and melting temperature. These properties have a direct impact on the performance of adhesives and asphalt mixtures. The uniform distribution of fibers as a type of non-directional reinforcement has a significant impact on the ability to improve the quality of the asphalt mixture. Currently, researchers around the world have used three methods to add basalt fibers to the asphalt mixture: wet mixing, dry mixing and a combination of both wet mixing and dry mixing.

- Wet mixing method: a high-speed shear mixer is used and the fibers are mixed with binder before mixing with aggregate.
- Dry mixing method: fibers are mixed with aggregate first, then mixed with binder. The dry mixing method is superior and more popular than the wet mixing method because it does not require a high-speed shear mixer. Furthermore, the disadvantage of fiber agglomeration in the dry mixing method is less than that in the wet mixing method.
- Combined dry mixing and wet mixing method: aggregate and binder are mixed together first, then fibers are added.

1.3. Research on asphalt concrete using basalt fibers

World studies show that basalt fibers are randomly distributed in the three-dimensional space of the asphalt mixture. Basalt fibers help disperse stress and avoid excessive stress. The results show that basalt fibers play a "bridging" role, helping to improve the crack resistance of the asphalt mixture, while slowing down the development of cracks.

In addition, the basic physical and mechanical criteria of asphalt using basalt fibers were evaluated such as Marshall parameters, rutting and dynamic stability, moisture resistance, and elastic modulus. However, there are still many important indicators of BTN that have not been researched.

Currently, in Vietnam there are no publications on concrete using basalt fibers.

1.4. Research using ML to predict asphalt concrete characteristics

In recent years, with the strong development of 4.0 technology, along with its simplicity, automation, efficiency and high application, many studies have focused on the use of ML based on experimental results. This technique is becoming popular and is used in many fields, especially the construction and transportation industries.

1.5. Evaluate domestic and foreign research results

Based on the combined results of reinforcing fibers and basalt fibers used for asphalt mixtures in Vietnam and around the world, it can be seen that using fibers in general and basalt fibers in particular, helps to strengthen some Physical and mechanical properties of the asphalt mixture, especially the improvement of rutting and DS.

1.6. Identify the research problems of the thesis

- Research on morphology, fiber distribution, structure of asphalt concrete using basalt fibers with different basalt fiber contents.
- Propose the process of manufacturing asphalt using basalt fibers and 60/70 petroleum-based asphalt, determine the mixing temperature and compaction of the asphalt mixture.
- Experimental research on physical and mechanical criteria of asphalt concrete using basalt fibers to serve the design of soft concrete structures according to TCCS 38:2022/TCDBVN and experimental mechanical methods. Thereby evaluating the applicability of asphalt materials using basalt fibers in the construction of asphalt pavements.
- Applying ML algorithms to build tools to quickly and accurately predict some physical and mechanical properties of asphalt using basalt fibers. This is useful for materials engineers, helping to save time and costs in future research.

1.7. Research methods

The thesis uses a combination of theoretical, experimental, statistical probability, modeling, and ML methods.

CHAPTER 2. DESIGN AND PREPARATION OF AC MIXTURE USING BAZAN FIBER WITH APPROPRIATE RATIO

Chapter 2 of the thesis focuses on research and analysis of basalt fibers in asphalt mixtures. The goal of this chapter is to build a theoretical and practical basis to better understand the principle of basalt fiber improving the properties of asphalt, thereby building an experimental program and determining the optimal resin content for the mixture. BTN uses basalt fibers.

2.1. Develop an experimental program for asphalt mixture using basalt fibers

- Design method: Marshall;
- Type of AC: AC 12.5 mm;
- Aggregate was collected at Sunway quarry, Quoc Oai, Hanoi;
- Mineral powder was taken from Kien Khe quarry, Ha Nam;
- Binder: Asphalt binder 60/70 was provided by Petrolimex Asphalt Company Limited, Vietnam;

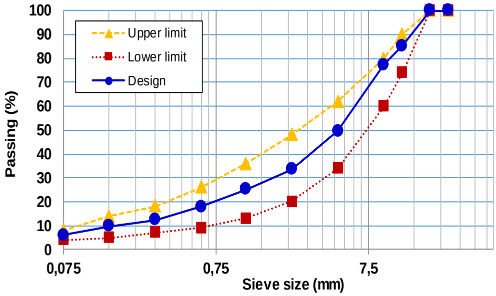


Fig. 2.2. Designed aggregate gradation curves.

- Fiber: Basalt fiber used in the research was sourced from China, with a yellow brown color and 12 mm length;
- Fiber content is added to the asphalt mixture using dry mixing process with content varying from 0%; 0.1%; 0.2%; 0.3%; 0.4% and 0.5% by mixture weight;
- Choose mixing method: dry mixing. The mixing time for basalt fiber and asphalt was chosen to be 2 minutes, based on most experimental results in previous studies with mixing times ranging from 90 seconds to 2 minutes;

2.2. Analysis of bonding and distribution of basalt fibers in AC mixtures

2.2.1. Studying AC morphology using scanning electron microscope (SEM)

SEM was used to analyze the morphology of basalt fibers and basalt fibers mixed in AC;

2.2.2. Experimental results of SEM morphological analysis of ACs

2.2.2.1. Bonding and distribution between basalt fibers and asphalt

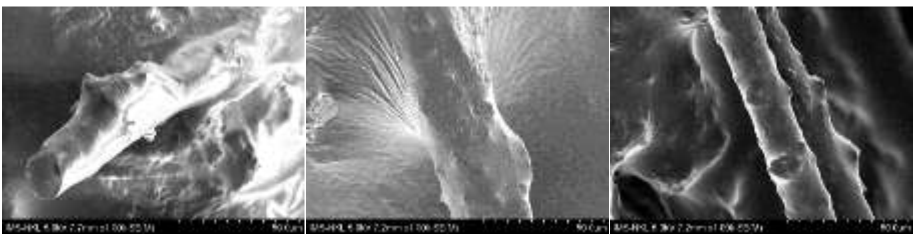
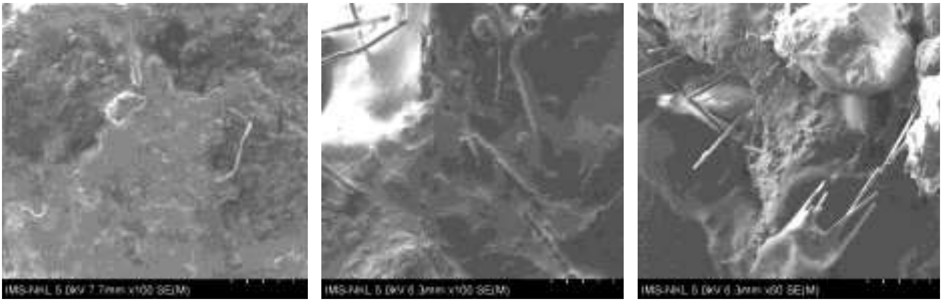


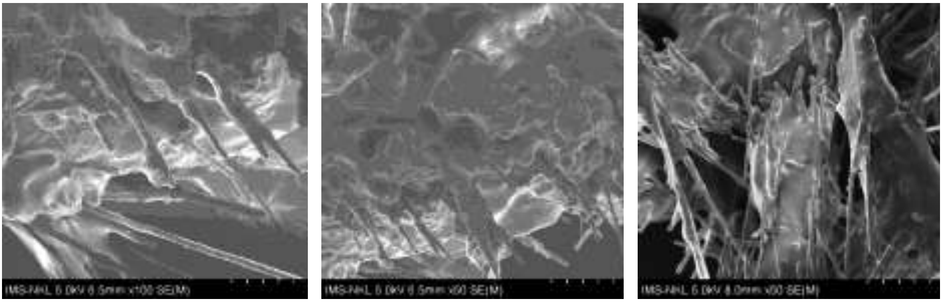
Fig. 2.6. Bonding between basalt fiber and binder.

Figure 2.6. shows that not only is the fiber surface covered with asphalt, the adhesion between the roots of basalt fibers and binders is also very good. The results of SEM images can be explained based on three theories, which are surface infiltration theory, transition layer theory and chemical bonding theory. With these theories, by adding basalt fibers into asphalt, the interference effect of phases in the asphalt mixture has fundamentally changed, helping to improve the macroscopic performance of AC.

2.2.2.2. Effect of basalt fiber content in asphalt mixture



a) AC with no basalt content **b) AC with 0.1% basalt** **c) AC with 0.2% basalt**



d) AC with 0.3% basalt **e) AC with 0.4% basalt** **f) AC with 0.5% basalt**

Hình 2.7. Distribution of basalt fibers with different contents

a) AC with 0.3% basalt **b) AC with 0.3% basalt** **c) AC with 0.3% basalt**

Fig. 2.8. Bonding between basalt fibers in the asphalt mixture

It is seen that when the basalt fiber content is low (0.1%; 0.2%), the fiber mixture is evenly distributed, however, because of the low content, a spatial network structure cannot be formed, making poor fiber-to-fiber connection (Fig. 2.7b, c). With higher basalt fiber content of 0.3% and 0.4%, the fibers are evenly distributed in the mixture (Fig. 2.7d, e), the fibers cross vertically and horizontally, forming a spatial network structure (Fig. 2.8a, b). The space network between fibers not only help dispersing the load, but also has the ability to overcome sliding between particles, linking the mixture into a unified mass, and avoiding crack development. With higher fiber content, reaching a value of 0.5% (Fig. 2.7f, Fig. 2.8c), the fibers will be unevenly distributed, leading to bunching, and the effect of the fibers will not be maximized.

2.3. Application of ML in designing AC using basalt fibers

2.3.1. Application of ML in predicting physical and mechanical properties of AC

This section presents the application of ML algorithms to develop a model to predict the MS and MF of AC using basalt fibers. To build correlation between experimental parameters and prediction criteria, this research builds two datasets for MS and MF. The data used for the training and validation process is collected from published and peer-reviewed works.

2.3.2. Several algorithms and techniques

- Extreme Gradient Boosting model;
- Sailfish Optimizer optimization algorithm;
- Aquila Optimizer optimization algorithm;
- Cross validation technique;
- Indicators to evaluate the model's predictive capacity: coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE).

2.3.3. Development of ML tool to support the design of AC using basalt fibers

This study provides a tool to support the prediction of several physical and mechanical properties of AC using basalt fibers, including MS and MF. The process is carried out through main steps including:

- Prepare database for forecasting problems;
- Build a prediction model and optimize the model's hyperparameters;
- Evaluate the optimized model and determine the best model;
- Develop tools to support BTN component design;
- Details of these steps are presented in the next steps.

2.3.4. Database construction

MS database includes 99 experimental samples, MF database includes 59 experimental samples. The two databases have 10 input parameters, including: fiber tensile strength (X_1), fiber content (X_2), fiber length (X_3), fiber diameter (X_4), needle penetration (X_5) , softening point (X_6), binder content (X_7), 2.36 mm aggregate (X_8), 4.75 mm aggregate (X_9) and 9.5 mm aggregate (X_{10}). It should be noted that, here, inputs such as X_8, X_9, and X_{10} represents the amount of aggregate (by weight) passing through different sieve sizes of 2.36, 4.75, and 9.5 mm, respectively.

2.3.5. Hyperparameter tuning of XGB model

Two algorithms, namely AO and SFO, are used to tune the hyperparameters of the XGB model. In the AO and SFO algorithms, the important parameters that need to be adjusted are the population size (n_p) and the number of iterations for optimal search.

2.3.6. Prediction results of XGB model for MS and MF

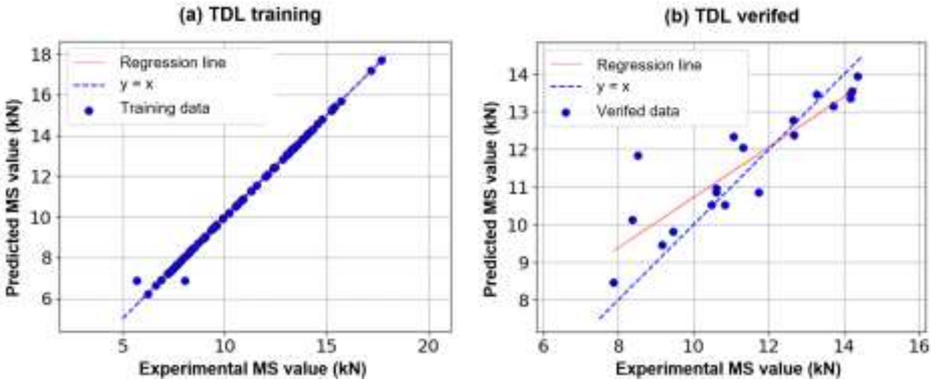


Fig. 2.10. Regression analysis for MS dataset: (a) training, (b) testing

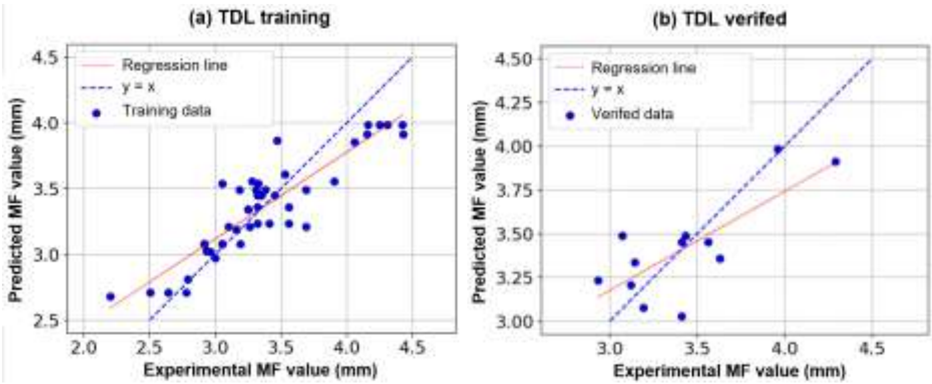


Fig. 2.11. Regression analysis for MF dataset: (a) training, (b) testing

– Fig. 2.10 shows the relationship between the experimental MS values and the values generated from the XGB_SFO_40 model. The XGB_SFO_40 model has a performance R = 0.998, RMSE = 0.189 kN, MAE = 0.036 kN, and MAPE = 0.005 for the training data. For the validation data, these values are R = 0.976, RMSE = 0.451 kN, MAE = 0.367 kN, and MAPE = 0.033, respectively. It can be seen that the prediction ability of the XGB_SFO_40 model for the MS prediction problem of AC incorporating basalt fiber asphalt is good.

– Fig. 2.11 shows the relationship between the actual MF value and the predicted MF value given as a regression plot. The XGB_SFO_30 model gives error R = 0.927, RMSE = 0.185 mm, MAE = 0.144 mm, and MAPE = 0.043 for the training data. For the testing data, these values are R = 0.909, RMSE = 0.1572 mm, MAE = 0.125 mm, and MAPE = 0.036, respectively. With the above prediction results of the model, it shows that the XGB_SFO_30 model for predicting MF of asphalt concrete using basalt fibers has strong prediction ability.

2.3.7. Development of ML tool to support the design of AC components

This section presents the process of optimizing the design of the AC composition, the XGB_SFO_40 model is used to find the values of the input variables (X_1-X_{10}) such that the MS value of the asphalt mixture using basalt fibers achieve the highest value. The trends found in 40 AC samples using AIML are good indications for conducting experiments in this work. Notably, the proposed AIML model does not use the experimental data in this PhD thesis but completely based on the available AC samples using basalt fibers in the relevant literature (Fig. 2.12).

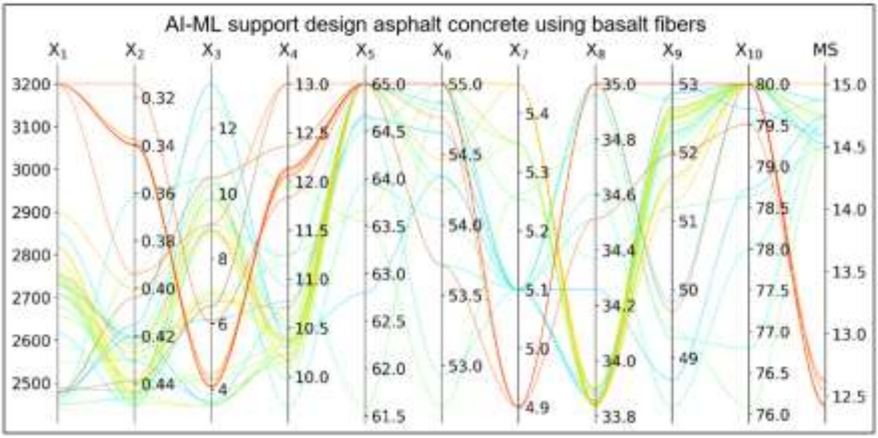


Fig. 2.12. 40 AC samples generated by the XGB_SFO_40 model.

2.4. Optimum asphalt content determination for AC using basalt fibers

2.4.1. Marshall stability (MS) analysis

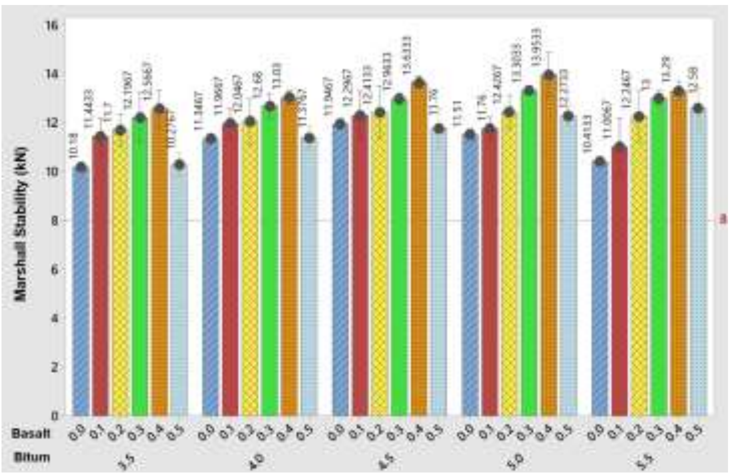


Fig. 2.14. Marshall stability (MS) results of all AC samples.

MS reached the highest value at all AC contents when using basalt fiber with a content of 0.4%. When basalt fiber is not used, MS reaches the lowest value when using an asphalt content of 3.5%; 4.0%; 5.0% and 5.5%. When using basalt fiber with a content of 0.5%, MS reached the lowest value with an asphalt content of 4.5%.

2.4.2. Marshall flow analysis (MF)

Fig. 2.16 is a summary chart of MF of AC mixture according to asphalt and basalt content. Refer to technical requirements according to Decision 858 and TCVN 13567:2022, MF of asphalt mixture is in the range of 1.5 to 4.0 mm. Thus, except for the AC mixture that does not use basalt fibers with an asphalt content of 5.5%, all remaining asphalt mixtures satisfy the technical requirements for MF.

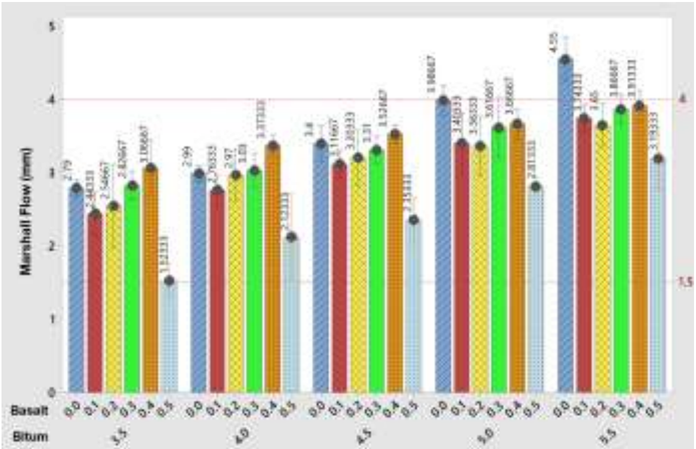


Fig. 2.16. Marshall flow (MF) results of all AC samples.

2.4.3. OAC determination of AC mixtures with different basalt fiber contents

Detailed design results for asphalt content selection with fiber content: 0.0%; 0.1%; 0.2%; 0.3%; 0.4% and 0.5% are shown below:

Table 2.15. OAC with respect to fiber content.

Content	AC_Basalt 0.0	AC_Basalt 0.1	AC_Basalt 0.2	AC_Basalt 0.3	AC_Basalt 0.4	AC_Basalt 0.5
Basalt content (%)	0.0	0.1	0.2	0.3	0.4	0.5
OAC (%)	4.6	4.7	4.9	5.1	5.3	5.4

2.5. Conclusion of chapter 2

– The dry mixing method was chosen to introduce basalt fibers into AC mixture, and the asphalt mixture design gradation curve was determined after mixing;

– Based on SEM analysis, the basalt fiber content of 0.3% and 0.4% facilitate fibers distribution more evenly in the AC mixture than the remaining fiber contents;

– This work buitt a ML-based tool for MS and MF, thereby using this tools to simulate and optimize the design of AC using basalt fibers, and find value ranges for aggregate content, asphalt binder and basalt fibers need to be considered when conducting experimental research;

– AC using basalt fiber with a content of 0.4% is used to conduct physical and mechanical properties experiments in the next chapters of this PhD theses. In addition, AC samples with other fiber contents (0; 0.1%; 0.2%; 0.3%; 0.5%) are also considered for testing to evaluate and comparison in terms of mechanical and physical properties.

CHAPTER 3. EXPERIMENTAL STUDY TO DETERMINE THE MECHANICAL PROPERTIES OF AC USING BASALT FIBER

Chapter 3 selects the properties for evaluating the AC mixtures using basalt fibers, then conducts experimental research and assess the results obtained.

3.1. Selection of properties to be evaluated

The criteria for evaluating the AC mixture in the study are proposed based on the characteristics of the asphalt mixture, and also serve to calculate the design of flexible pavement structures according to TCCS 38:2022/TCDBVN, including the followings:

1. Test to evaluate rutting depth;
2. Tensile strength at 15°C.
3. Testing to evaluate the crack resistance of asphalt material - according to ASTM D8225-19 standard through the CTIndex.
4. Static elastic modulus at temperatures 15°C, 30°C, 60°C;
5. Experiment to evaluate dynamic elastic modulus according to AASHTO TP62;

A total of 05 mechanical properties were tested for 06 types of asphalt with different basalt fiber content: 0.0% (control sample); 0.1%; 0.2%; 0.3%; 0.4% and 0.5%.

3.2. Rutting depth evaluation

The assessment of rutting depth was done according to method A (Decision 1617/QĐ-BGTVT). The results obtained are the depth in water environment and the plastic film peeling point (if any). Fig. 3.4 displays the results of the rutting depth test of control and basalt fiber ACs.

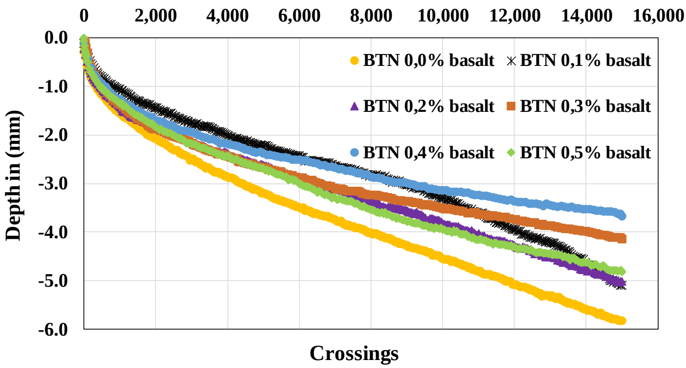


Fig. 3.4 Rutting depth results of the control and basalt fiber ACs.

Test results show that, after 15,000 runs in water environment at 50°C, the rutting depth of all 6 types of AC is smaller than the allowable value (12.5 mm) as required by Decision No. 1617/QĐ -BGTVT. AC using basalt fibers with a content of 0.4% has the smallest rutting depth (3.67 mm), followed by AC using basalt fibers with a content of 0.3% (4.18 mm); AC uses basalt fiber with a content of 0.5% (4.81 mm), AC uses basalt fiber with a content of 0.2% (4.99 mm), AC uses basalt fiber with a content of 0.1% (5.13 mm). The control AC mixture without using basalt fibers has the largest rutting depth (5.83 mm), see Fig. 3.4. Thus, the use of basalt fibers for asphalt concrete with fiber content of 0.1%, 0.2%, 0.3%, 0.4% and 0.5% is effective in reducing rutting depth, The corresponding decrease in value is 12%; 14%; 28%; 37%; and 17% compared to the control sample. Experimental results have shown good rutting resistance of AC mixtures using basalt fibers compared to conventional asphalt mixtures without using fibers.

3.3. Tensile strength testing

Flexural tensile strength is an important parameter that represents the bearing capacity of the asphalt mixture used in calculating the design of flexible pavement structures according to TCCS 38:2022 standards.

The results of the tensile strength test in Fig. 3.7 show that, compared to the control AC, using basalt fibers has significantly improved the tensile strength of the AC mixtures. When using basalt fiber with a content of 0.3%, the tensile strength reaches the maximum value (10.19 MPa). AC using basalt fiber with a content of 0.4% has the second highest tensile strength (9.819MPa). For the control AC, the tensile strength reaches the smallest value (8.168 MPa).

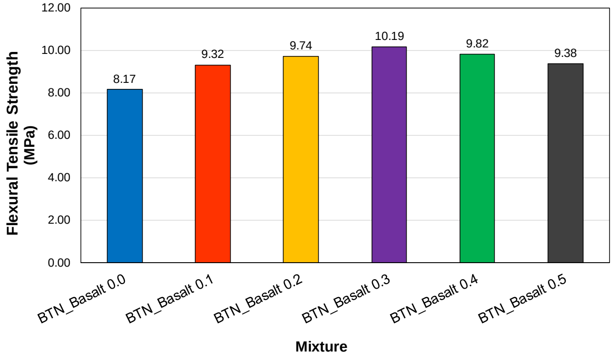


Fig. 3.7. Tensile strength results of different AC types with different fiber contents.

Asphalt using basalt fibers with gradually increasing content from 0.1% to 0.3%, the tensile strength gradually increases, the level of increase compared to control AC is 14%, 19% and 25%, respectively. When continuing to increase the fiber content to 0.4% and 0.5%, the tensile strength value begins to decrease, but still increases compared to the control AC by 20% and 15%, respectively.

It can be seen that the addition of basalt fibers increased the tensile strength of AC mixture. Basalt fibers help increase the flexibility of the asphalt mixture, acting as a reinforcing agent, and improve the asphalt mixture's resistance to cracking at low temperatures. Basalt fibers adhered to the asphalt, helping to harden the fibers. This hardening effect avoided the formation of cracks, absorbed part of the stress and increased the material's resistance to cracking at low temperatures.

3.4. Experiment to evaluate the cracking resistance of AC mixture

Cracking resistance assessment was conducted according to ASTM D8225-19 standard.

The CT_{Index} results shown in Fig. 3.14 show that all 6 types of asphalt in the study are greater than the minimum value ($CT_{Index} \geq 80$) set by the State of Oklahoma. Compared to the control AC without using basalt fiber, the AC using basalt fiber with content from 0.1% to 0.4% has a significantly higher CT_{Index}, with an increase in fiber content of 0.1%, 0.2%, 0.3% and 0.4% are 8.29%; 21.13%; 64.78%; 90.97%. The CT_{Index} reaching

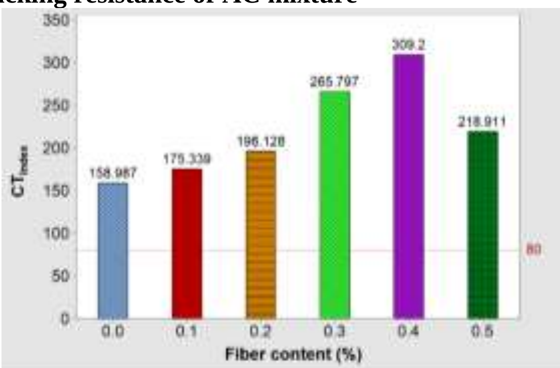


Fig. 3.14. CT_{Index} results of different AC types with different fiber contents.

the highest value (309.20) is the AC mixture using 0.4%basalt fibers. However, when the basalt fiber content reaches 0.5%, the CT_{Index} begins to decrease to 218.91. This shows that the proportion of asphalt in the AC mixture and the effect of basalt fibers have a great influence on the CT_{Index}. Using basalt fibers helps significantly improve the crack resistance of AC mixtures. Asphalt has the CT_{Index} reaching the highest value when using a fiber content of 0.4%.

3.5. Experiment to determine static elastic modulus

The static elastic modulus (E) is tested according to the static creep compression test model and referred to Appendix C of TCCS 38:2022 standard. The asphalt sample is made into a cylindrical shape with a diameter and height of 100mm, subjected to long-term loads to meet the compressive stress in the asphalt sample at 0.5 MPa. The experiment used Gyratory Testing machines manufactured by Daiwa Kenko, Japan. The sample compression process uses UTM equipment manufactured by Cooper, UK.

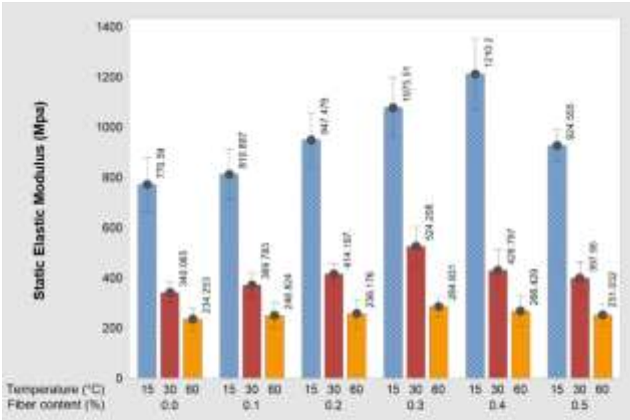


Fig. 3.20. Static elastic modulus of 6 AC types.

The results of E modulus tests at 15°C, 30°C and 60°C of 6 types of mixtures are shown in Fig. 3.20. The results show that, at temperatures of 15°C, 30°C and 60°C, the E modulus of AC using basalt fibers (at all 5 fiber contents) is higher than E modulus of control AC sample.

At a temperature of 15°C, the E modulus of AC using basalt fibers with a content of 0.4% reaches the largest value (1210.20 MPa), 57% higher than that of control AC. With decresing order is AC using basalt fiber content of 0.3%, 0.2%, 0.5% and 0.1%.

At temperatures of 30°C and 60°C, the E modulus of AC using basalt fibers with a content of 0.3% reaches the largest value (524.21 MPa and 284.83 MPa), higher than that of the control AC by 54% and 22%, respectively.

Basalt fibers can absorb some light components of asphalt to improve its viscosity, and basalt fibers are randomly distributed in the three-dimensional space of the asphalt mixture, helping to disperse stress and avoid excessive stress. level. Therefore, the static elastic modulus of asphaltene can be enhanced with the addition of basalt fibers. However, it is important to use basalt fiber at a reasonable level to maximize the effectiveness. Because when using high levels of basalt fiber, it can lead to fiber clumping or uneven distribution in the AC.

3.6. Experiment to evaluate dynamic elastic modulus

Dynamic elastic modulus (|E*|) testing was performed in the laboratory according to the guidelines of AASHTO TP 62 standard.

All samples were placed in a thermostatic chamber so that a stable temperature could be maintained. The test was conducted on a CRT NU-14 device (manufactured by Cooper - UK). The experimental temperature range ranges from 10°C-60°C. Experiment |E*| for asphalt samples, the basalt fiber content is 0%; 0.1%; 0.2%; 0.3%; 0.4%; 0.5% is conducted at 6 frequency levels from 0.1 Hz to 10 Hz (0.1 Hz; 0.5 Hz; 1 Hz; 5 Hz; 10 Hz and 25 Hz) and 6 temperature levels from 10 °C-60°C (10°C, 20°C, 30°C, 40°C, 50°C, 60°C), ensure the sample is compacted to achieve a V_a = 7±0.5% .

The influence of frequency and temperature on |E*| is shown more clearly in Fig. 3.25, Fig. 3.26. At a temperature of 10°C and a frequency of 25 Hz, |E*| has the greatest value for all 6 types of AC mixtures. At a temperature of 60°C and a frequency of 0.1 Hz, |E*| has the smallest value for all 6 types of asphalt mixtures.

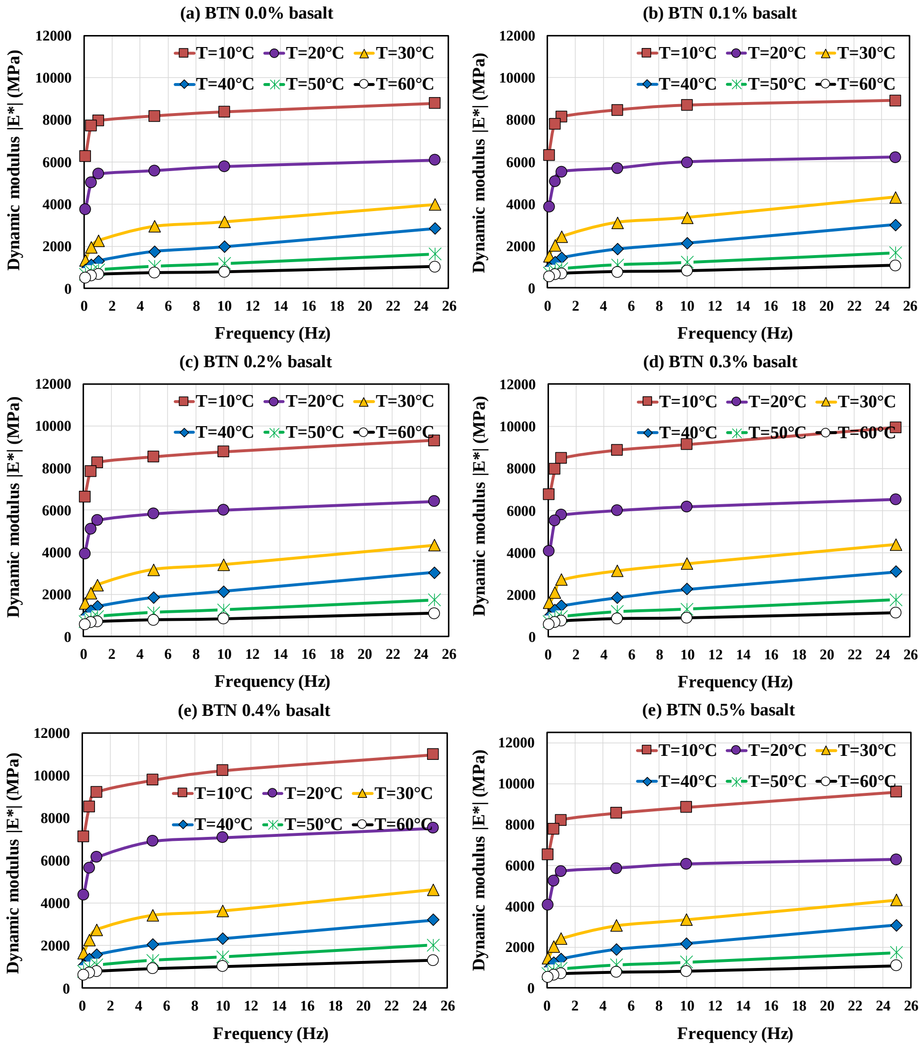


Fig. 3.25. Influence of the frequency to |E*| of 6 types of AC.

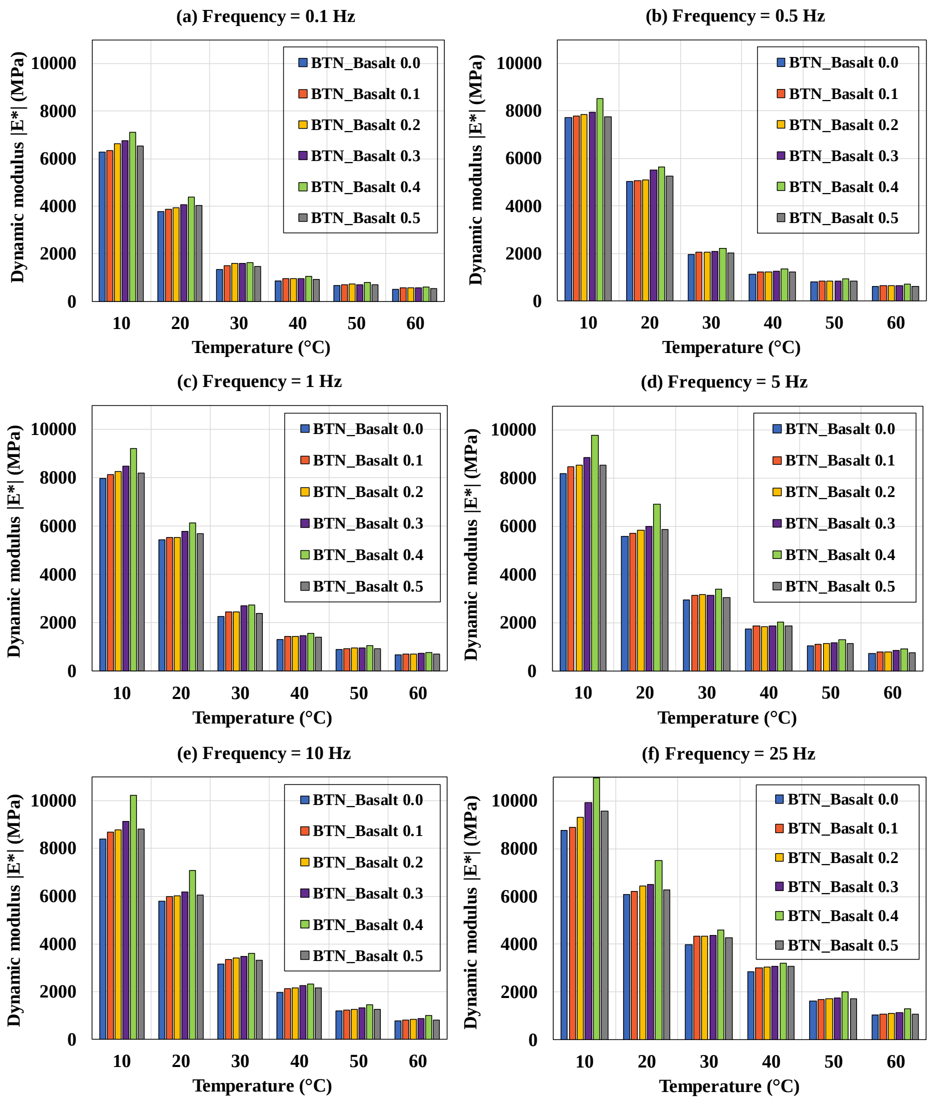


Fig. 3.26. Influence of the temrepature to |E*| of 6 types of AC.

The change in |E*| modulus of the mixtures with frequency and temperature is shown in Figure 3.27. Experimental results for all mixtures show that, |E*| all decreased when the experimental temperature increased from 10°C to 60°C.

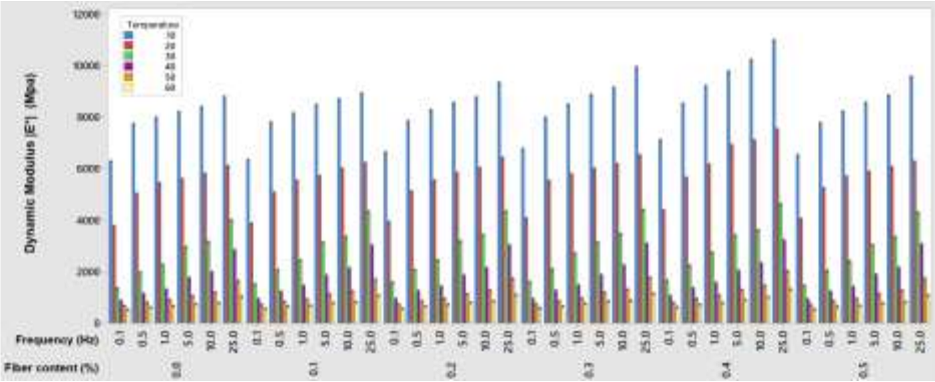


Fig. 3.27. |E*| modulus of different ACs corresponding to 6 values of frequency and temperature.

3.6.1. Construction of dynamic modular master curves

Master curve |E*| is a characteristic curve for the viscoelastic properties of AC in a wide range of frequencies and temperatures. The master curve is built from the frequency-temperature correlation rule. To construct the master curve |E*|, experimental results are gathered to get data on |E*| over a range of temperatures and frequencies. A reference temperature of 30°C is chosen. Isothermal curves corresponding to temperatures greater than 30°C is shifted to the left, while curves corresponding to temperatures lower than 30°C is shifted to the right by the shift factors a_T. This shifting process is repeated until the curves merge to create a continuous smooth curve (see Fig. 3.29).

3.6.2. Dynamic modular modeling

The simulation of experimental data |E*| of AC is implemented by model 2S2P1D. The 2S2P1D model is a general model built on a combination of physical components, including 2 springs, 2 parabolic elements, and 1 dashpot. The model uses 7 input parameters to model the linear viscoelastic properties of AC, as shown in Table 3.17. Modeling results of the master curve |E*| of BTN is shown in Fig. 3.32.

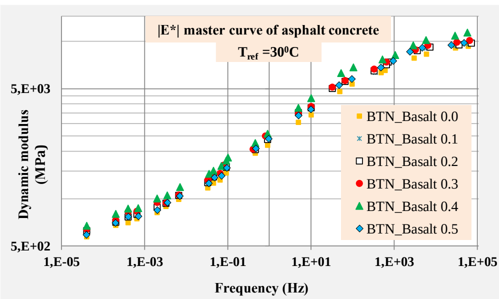


Fig. 3.29. |E*| master curve of 6 ACs at reference temperature of 30°C.

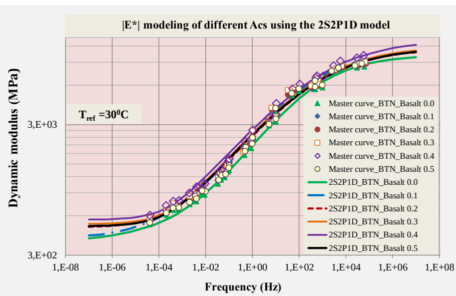


Fig. 3.32. |E*| modeling of different Acs using the 2S2P1D model.

Table 3.17. 2S2P1D model parameters in modeling the |E*| modulus.

AC	E_{00} (MPa)	E_0 (MPa)	k	h	δ	τ (s)	β
BTN_ Bassalt 0.0	400	14 600	0,280	0,35	9,25	0,63	2 100
BTN_ Bassalt 0.1	420	16 000	0,260	0,41	6,90	0,45	2 800
BTN_ Bassalt 0.2	490	16 500	0,240	0,51	7,85	0,45	3 050
BTN_ Bassalt 0.3	520	17 000	0,239	0,58	8,27	0,55	3 200
BTN_ Bassalt 0.4	560	19 000	0,233	0,59	8,72	0,55	3 300
BTN_ Bassalt 0.5	500	16 600	0,238	0,57	8,21	0,55	3 100

Table 3.18. Assessment of prediction results of |E*| using 2S2P1D.

AC	R^2	S_e/S_y	Rate
BTN_ Bassalt 0.0	0,9875	0,129	Very good
BTN_ Bassalt 0.1	0,9621	0,223	Very good
BTN_ Bassalt 0.2	0,9773	0,173	Very good
BTN_ Bassalt 0.3	0,9770	0,1743	Very good
BTN_ Bassalt 0.4	0,9801	0,1621	Very good
BTN_ Bassalt 0.5	0,9726	0,1901	Very good

To evaluate the suitability of the 2S2P1D model with the experimental results, this study uses the Goodness of Fit method. The results of the coefficient of determination (R^2) and S_e/S_y are shown in Table 3.18. From the findings, it can be seen that the 2S2P1D model is suitable to simulate the master curve |E*| of AC using basalt fiber, and control AC.

3.7. Conclusion of chapter 3

- AC using basalt fibers has better rutting depth in water environments than control mixtures that do not use basalt fibers. AC using basalt fibers with a content of 0.4% has the smallest rutting depth (3.67 mm), the control AC mixture without using basalt fibers has the highest LV rutting depth (5.83 mm).
- The tensile strength of AC when using basalt fibers is significantly improved. When using basalt fiber with a content of 0.3%, the tensile strength reaches the maximum value (10.19 MPa). AC using basalt fiber with a content of 0.4% has the second highest tensile strength (9.819MPa). Regarding the control AC does not use basalt fibers, the tensile strength reaches the smallest value (8.168 MPa).
- Using basalt fibers helps improve the cracking resistance of AC at all fiber contents from 0.1% to 0.5%. The CTIndex reached the highest value (309.20) when using basalt fiber with a content of 0.4%.
- The E modulus of AC using basalt fibers at all fiber contents and at 3 experimental temperatures 15°C, 30°C and 60°C are higher than that of control AC. At a temperature of 15°C, the E modulus of AC using basalt fibers with a content of 0.4% reaches its maximum value, 57% higher than the control AC. At temperatures of 30°C and 60°C, the E modulus of AC using basalt fibers with a content of 0.3% reaches a maximum value, 54% and 22% higher than the control AC.
- AC uses basalt fibers with |E*| modulus higher than the control AC without using basalt fibers at all temperatures and frequencies. AC uses basalt fiber with a content of 0.4% has highest |E*| modulus at all temperatures and frequencies, followed by AC using basalt fibers with a content of 0.3%; 0.5%, 0.2%, 0.1%. AC does not use basalt fibers has the lowest |E*| modulus.

- The |E*| master curves at a reference temperature of 30°C is constructed showing that the |E*| of AC using basalt fibers is higher than the control AC without using basalt fibers at different temperatures and frequencies.
- The 2S2P1D model is built appropriately to model |E*| of different types of AC (using basalt fibers, control AC) and used to determine the |E*| modulus of asphalt using basalt fibers at any temperature and frequency.

Summary of the research findings in Chapter 3 shows that AC mixtures using basalt fibers have good mechanical properties compared to asphalt mixtures that do not use basalt fibers. In particular, asphalt using 0.4% basalt fibers has many better mechanical properties than conventional asphalt and asphalt using basalt fibers with content of 0.1%, 0.2%, 0.3%, 0.5%. Therefore, AC using basalt fiber with a content of 0.4% is used for further assessment in the next chapter.

CHAPTER 4. PREDICTING THE PHYSICAL PROPERTIES OF AC USING MACHINE LEARNING AND APPLICATION OF AC USING BASALT FIBERS IN PAVEMENT ENGINEERING

Chapter 4 applies Machine Learning (ML) to build BTN's Marshall stability prediction tool using basalt fibers to guide future research. In addition, from the experimental results of the physical and mechanical properties of AC using basalt fibers such as static elastic modulus, tensile strength and dynamic modulus in Chapter 3, this chapter uses basalt fiber AC with a content of 0.4% as the surface layer of pavement structures. Some typical flexible pavement structures on national highways in Vietnam using AC 12.5 surface layer were selected, then replaced AC 12.5 with AC using basalt fibers with a content of 0.4% according to calculations to analyze and evaluate following the TCCS 38:2022/TCDBVN and experimental mechanical design method (M-E). Finally, Chapter 4 calculates the cost of constructing pavement structures when using basalt fibers and proposes directions for manufacturing AC using basalt fibers for on-site experiments.

4.1. Application of ML in predicting the MS

4.1.1. MS database construction

The MS database is compiled from international publications (including 99 samples) and AC samples conducted within this work in Chapter 2 (including 90 samples). The assembled MS experimental database thus includes a total of 189 samples and 10 input variables as introduced in Chapter 2.

4.1.2. ML tools and models for estimating the MS

Similar to Chapter 2, the XGB model is used to predict the MS of AC using basalt fibers in Chapter 4. The parameter optimization process of the XGB model is performed similarly in Chapter 2 with two optimizations algorithms, namely AO and SFO.

4.1.3. **ML model development to predict the MS of AC using basalt fibers**

The regression plot of the XGB model results is shown in Fig. 4.2. It can be observed that the experimental and predicted values are close to the regression line and the diagonal. The XGB_SFO_40 has performance R = 0.901, RMSE = 0.352 kN, MAE = 0.290 kN and MAPE = 0.024. It is seen that the prediction ability of the XGB_SFO_40 model for prediting MS of basalt fiber AC is good.

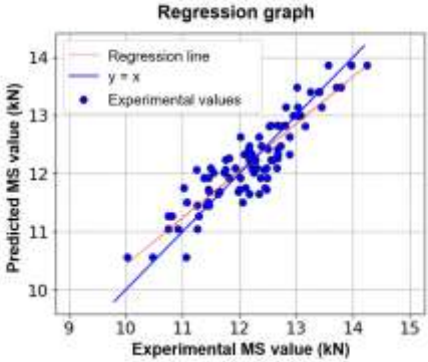


Fig. 4.2. Regression graph showing the prediction results by XGB model.

4.1.4. Development of a GUI interface for estimation of MS of basalt fiber AC

This section presents the GUI tool set up to predict the MS of AC using basalt fibers. This is an advanced software application, providing an intuitive graphical user interface. It allows users to enter data, adjust the inputs, and view modeling-based MS prediction results, thereby analyzing data on the interaction and performance of basalt fibers in AC. This is a particularly useful tool for engineers and researchers in evaluating and improving asphalt quality (Fig. 4.4).

4.2. Traffic situation on high-level roads in Vietnam and proposed structure of soft pavement structure

4.2.1. Traffic status of current national highways in Vietnam

The reality shows that the national highways (NHs) in Vietnam today such as NH1, NH5, NH18, NH3 and a number of other NHs that are in operation all have very high traffic volumes, with a large number of vehicles, large axle loads, multi-axle vehicles account for a relatively high proportion. The phenomenon of rutting occurring a lot on NHs has proven that they are under heavy load and traffic, and this is the main cause of damage.

4.2.2. Some typical pavement structures of NHs in Vietnam

In Vietnam, NHs often use typical soft pavement structures as below:

– Surface layer: Made up of 1-2 layers of hot mix asphalt (HMA), with or without a functional asphalt layer on the top, normal surface layer thickness is 12÷14 cm.

– Foundation layer: Divided into upper foundation and lower foundation. The upper foundation layer usually uses type 1 aggregate gradation with or without cement reinforcement. The lower foundation layer can use type 1 aggregate gradation, type 2 aggregate gradation, gravel aggregate gradation, and cement reinforced sand.

The bottom layer of the pavement usually uses selected hill soil or sand with a thickness of 30÷50 cm, achieving density K ≥ 0.98.

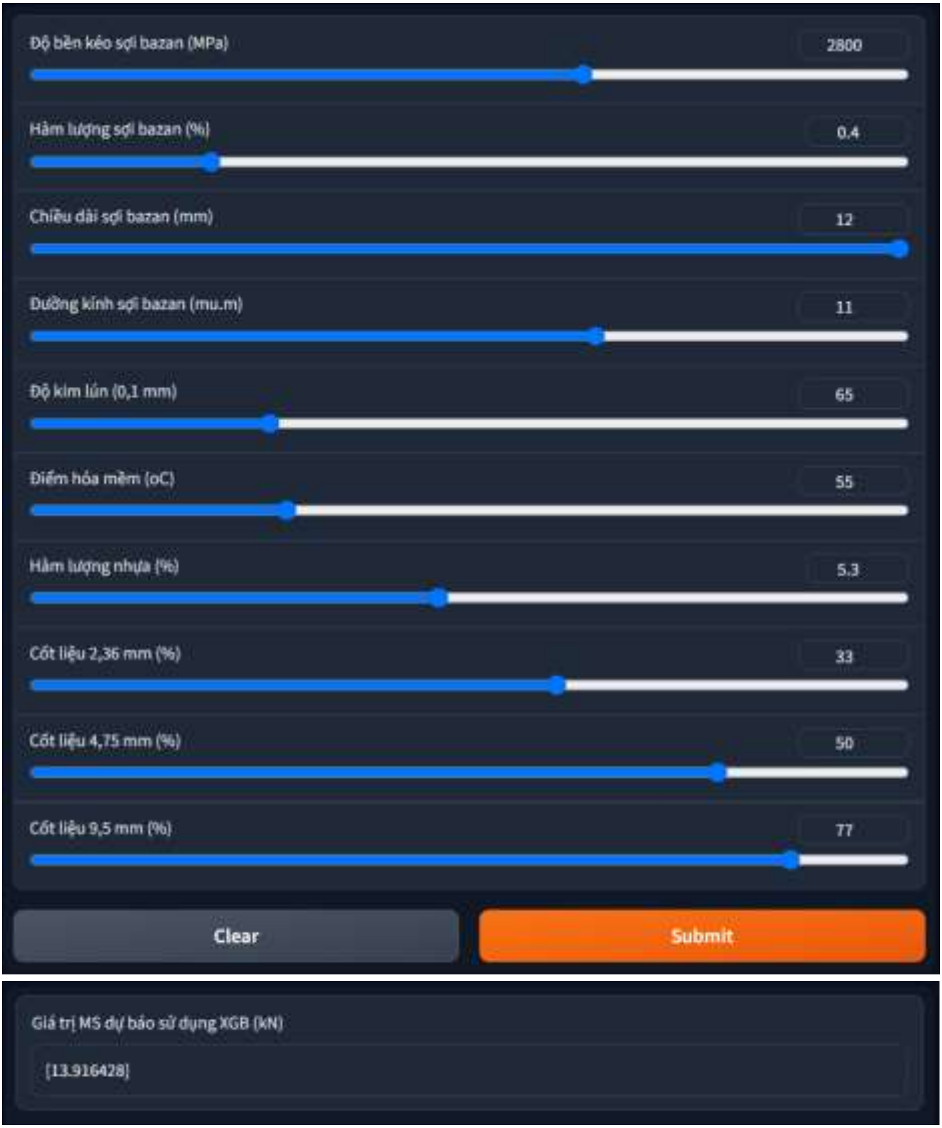


Fig. 4.4. GUI illustration to predict basalt fiber AC's MS.

4.2.3. Proposal for pavement structure containing AC using basalt fiber as the surface layer for NHs in Vietnam

To compare and evaluate AC using basalt fibers when being used as a surface layer, this study proposes a pavement structure of NH32 as shown in Table 4.3.

4.3. Assessment of pavement structures according to TCCS 38:2022/TCDBVN

Table 4.3. Pavement structures proposed in this study

TT	Material layers	Thickness of layer 1, cm (KC1)	Thickness of layer 2, cm (KC2)	Thickness of layer 3, cm (KC3)
1	AC 12.5	5	-	-
2	AC_Basalt 0.4	-	4	5
3	AC 19	7	7	7
4	Type 1 crushed stone aggregate	15	15	15
5	Type 1 crushed stone aggregate	30	30	30
6	Graded aggregate	30	30	30
	Total	**87**	**86**	**87**

The results of the pavement structure audit according to TCCS 38:2022 show the advantages of AC_Basalt 0.4 when used as the top layer. Specifically, 4cm thick AC_Basalt 0.4 can be used to replace the 5 cm thick AC 12.5 layer but still ensures the same conditions of elastic deflection, tensile strength and shear-slip resistance. In case of using AC_basalt 0.4 with a thickness equivalent to the control asphalt, the overall elastic modulus of the structure using fibers is higher than the control structure.

4.4. Assessment of pavement structures according to M-E method

Table 4.9. M-E analysis after 15 years.

No	Evaluation criterial	Target	KC 1		KC 2		KC 3	
			Predicted	Evaluate	Predicted	Evaluate	Predicted	Evaluate
1	Terminal IRI (m/km)	**4**	3.64	Pass	3.64	Pass	3.63	Pass
2	Permanent deformation – total pavement (mm)	**25.0**	24.45	Pass	24.49	Pass	24.05	Pass
3	AC bottom-up fatigue cracking (m/km)	**25.0**	1.82	Pass	1.91	Pass	1.81	Pass
4	AC thermal cracking (m/km)	**190**	5.15	Pass	5.15	Pass	5.15	Pass
5	AC top-down fatigue cracking (m/km)	**380**	117.33	Pass	116.44	Pass	113.14	Pass
6	Permanent deformation – AC only (mm)	**12.5**	11.36	Pass	11.13	Pass	11.08	Pass

Darwin-ME 2.3.1 software is used to analyze pavement structure according to the M-E method. In particular, traffic data were surveyed and selected to characterize traffic scale on NHs in Vietnam; Climate data collected characterizes Hanoi; The data of the material layers are tested in the laboratory. The findings according to M-E after 15 and 16 years of use are shown in Table 4.9, 4.10. From these results, the following observations can be drawn:

- When the exploitation period is 15 years, KC2 uses asphalt containing 0.4% basalt fiber as the top layer with a thickness reduced by 20% compared to KC1 but still ensures exploitation properties equivalent to KC1.

- When the exploitation period is 16 years, KC3 satisfies all exploitation characteristics, while KC1 and KC2 do not reach the total depth of the entire structure.

Table 4.10. M-E analysis after 16 years.

No	Evaluation criterial	Target	KC 1		KC 2		KC 3	
			Predicted	Evaluate	Predicted	Evaluate	Predicted	Evaluate
1	Terminal IRI (m/km)	**4**	3.68	Pass	3.68	Pass	3.67	Pass
2	Permanent deformation – total pavement (mm)	**25.0**	25.0	**Fail**	25.04	**Fail**	24.59	Pass
3	AC bottom-up fatigue cracking (m/km)	**25.0**	1.87	Pass	1.97	Pass	1.85	Pass
4	AC thermal cracking (m/km)	**190**	5.15	Pass	5.15	Pass	5.15	Pass
5	AC top-down fatigue cracking (m/km)	**380**	124.75	Pass	123.32	Pass	119.83	Pass
6	Permanent deformation – AC only (mm)	**12.5**	11.73	Pass	11.50	Pass	11.44	Pass

Thus, the results of M-E method pavement analysis when used for 15 and 16 years show that AC using 0.4% basalt fiber when applied as the top layer will bring economic and technical benefits compared to AC without using basalt fibers.

4.5. Preliminary assessment of the cost of constructing pavement structures when using basalt fibers

The preliminary estimate of AC construction costs is presented in detail in Table 4.11.

Table 4.11. Cost estimation of different pavement structures.

No	Content	Unit	Type		
			KC1	KC2	KC3
I	PRODUCTION COST				
	AC 12.5	đ/T	1,056,671		
	BTN_Basalt 0.4	đ/T		1,701,670	1,701,670
II	CONSTRUCTION COSTS	đ/ m²	818,530	860,680	910,419
	AC 12.5 (5 cm)	đ/ m²	183,758	-	-
	BTN_Basalt 0.4	đ/ m²	-	225,909	275,648
	AC 19 (7 cm)	đ/ m²	201,876	201,876	201,876
	Type 1 crushed stone aggregate (15 cm)	đ/ m²	82,192	82,192	82,192
	Type 2 crushed stone aggregate (30 cm)	đ/ m²	158,887	158,887	158,887
	Thickness of graded aggregate 30 cm	đ/ m²	155,041	155,041	155,041
	Bituminous prime coat TCN 1 kg/m²	đ/ m²	23,725	23,725	23,725
	Bituminous tack coat TCN 0,5 kg/ m²	đ/ m²	13,050	13,050	13,050

Preliminary cost calculation results show that, although the production cost of AC_basalt 0.4 is 1.6 times higher than that of control AC, the total cost when using AC_Basalt 0.4 of 4 and 5 cm thickness is only 1.05 and 1.11 times higher. However, the preliminary estimation is based on the basalt fiber price on the market, given that its practical application is not high, the volume of use is small, so the price is not competitive. In the future, when basalt fiber is widely used in construction, and in large quantities, the cost of basalt fiber would certainly be reduced.

4.6. Preliminary proposal for basalt fiber AC on-site mixing experiments

In general, the production of basalt fiber AC at the mixing plant is almost similar to regular AC. Attention should be taken when adding fibers to the AC mixture to avoid clumping and ensure maximum uniform dispersion. Thus, the fiber must be stored in a clean, sealed, moisture-proof container and there needs to be a dispersion device during the process of putting the fiber into the mixer. Using the dry mixing method as mentioned in chapter 2, the study proposes the main steps in the production process of AC_Basalt outside the mixing plant as follows:

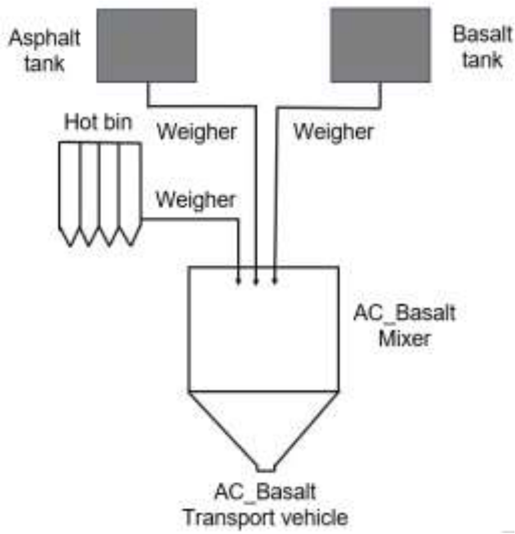


Fig. 4.7. Production of basalt fiber AC at the mixing plant

- Large, small aggregates and mineral powders, after being heated at 165 - 170°C, are weighed and measured according to the design and then put into the asphalt mixer.
- Basalt fibers stored in a closed container are also weighed and measured according to the designed content and put into the mixer with the aggregate for 2 minutes.
- After being heated to a liquid temperature, the asphalt is weighed and measured in the correct proportions and put into the mixer for 2 minutes. The production process is always well controlled at temperature of 150°C ± 5°C.

It should be noted that choosing a total mixing time of 4 minutes is a safe choice, helping to minimize errors during the experiment and ensure that the basalt fibers are mixed evenly. To have a more reasonable mixing time, it is necessary to conduct other tests to consider the effect of mixing time on the physical and mechanical properties of AC. Thereby, it is possible to minimize mixing time while still ensuring the performance of AC.

4.7. Conclusion of chapter 4

From the research results in chapter 4, the following observations can be drawn:

- ML algorithms can be applied to build tools to quickly and accurately predict MS of basalt fibers AC. Evaluation of the built ML model compared and verified with the experimental results in the PhD thesis showed good prediction performance;
- The results of the pavement audit according to TCCS 38:2022 of the 3 proposed structures are all passed;
- Analysis M-E method shows the advantage of AC using 0.4% basalt fibers when used as the top layer compared to the use of 12.5 regular AC. With a design term of 15 years, pavement using AC 0.4% basalt fiber of 4 cm thickness (20% thickness reduction) is equivalent to the use of AC 12.5 of 5 cm thickness. When the design term is 16 years, 0.4% basalt fiber AC of 5cm thickness satisfies all exploitation characteristics, while control AC does not meet the requirements;

- Results of determining the costs of construction show that when using 0.4% basalt fiber AC with thickness of 4 and 5cm as the top layer is 1.05 and 1.11 times higher;
- Preliminary directions for basalt fibers AC mixing have been proposed for on-site experiment at the mixing plant.

CONCLUSIONS AND RECOMMENDATIONS

I. CONCLUSIONS

1. Achievements

1 AC using basalt fibers can be utilized in Vietnamese conditions, ensuring the technical requirements of road surface according to current Vietnamese standards. OAC of AC mixtures is determined for all basalt fiber content, including 0.1%, 0.2%; 0.3%; 0.4% and 0.5%;

2 AC with 0.4% of basalt fiber content is chosen to improve several physical and mechanical properties of AC such as MS, rutting depth, cracking resistance, tensile strength, R_{ku}, E modulus and |E*| modulus, all suitable for Vietnamese conditions.

3 Calculation, simulation, audit and evaluation of pavement structure using 0.4% basalt fiber AC. Initial findings show that this is an effective solution to reduce the thickness and improve the quality of exploitation of pavement structure.

4 Construction of master curves |E*| of all basalt fiber AC at a reference temperature of 30°C, allowing the determination of |E*| for all types of ACs at specified temperatures and frequencies. The possibility of applying the 2S2P1D model to model the |E*| of basalt fibers AC is proven.

5 Deployment of a GUI tool to predict the MS of basalt fibers AC. This tool provides an intuitive graphical user interface, allowing users to enter data, adjust inputs, and thereby analyze data on the interaction and performance of AC basalt fibers.

2. Limitations

1 Only laboratory testing was conducted, without on-site experiments;

2 Only one type of basalt fiber with a 12mm length was used. No experiments with other fiber lengths, such as 3mm, 6mm, 9mm, 18mm and 24mm, were conducted.

II. RECOMMENDATIONS

From the research results in the laboratory, it is recommended that the mixture of asphalt mixture using basalt fiber can be applied in field testing on high-level motorway sections with large traffic volume in Vietnamese conditions.

III. FURTHER RESEARCH DIRECTIONS

1 Experimental research for other types of AC, other aggregate types using limestone, other asphalt binder, moving towards more universal experimental data for Vietnamese conditions;

2 Experimental research with other types of basalt fibers (with different fiber lengths and diameters) to have a more general assessment of the influence of basalt fibers on the physical and mechanical properties of AC;

3 Conduct more detailed technical and economic analysis and comparison of pavement structure using dispersed basalt fiber AC, thereby proposing mixing technology at the mixing plant and performing field experiments.

LIST OF PUBLISHED ARTICLES

1. **Ba-Nhan Phung**, Thanh-Hai Le, Thuy-Anh Nguyen, Huong-Giang Thi Hoang, Hai-Bang Ly (2023), *Novel approaches to predict the Marshall parameters of basalt fiber asphalt concrete*, Construction and Building Materials, Accepted 1 August 2023, https://doi.org/10.1016/j.conbuildmat.2023.132847.
2. **Ba Nhan Phung**, Thanh-Hai Le, Minh-Khoa Nguyen, Thuy-Anh Nguyen, Hai-Bang Ly (2023), *Practical Numerical Tool for Marshall Stability Prediction Based On Machine Learning: An Application for Asphalt Concrete Containing Basalt Fiber*, Journal of Science and Transport Technology, Accepted 29/9/2023, https://doi.org/10.58845/jstt.utt.2023.en.3.3.27-45.
3. **Ba Nhan Phung**, Thanh-Hai Le, Hai-Van Thi Mai, Thuy-Anh Nguyen, Hai-Bang Ly (2023), *Advancing basalt fiber asphalt concrete design: A novel approach using gradient boosting and metaheuristic algorithms*, Case Studies in Construction Materials, Accepted 2 October 2023, https://doi.org/ 10.1016/j.cscm.2023.e02528.
4. **ThS. Phùng Bá Nhân**, TS. Nguyễn Minh Khoa, TS. Lý Hải Bằng, TS. Lê Thanh Hải (2023), *Nghiên cứu đánh giá mô đun đàn hồi tĩnh của hỗn hợp bê tông nhựa sử dụng sợi basalt*, Tạp chí Giao Thông Vận Tải, số tháng 10 năm 2023, trang 75-78.