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Tyler E. Rutherford

University of Tennessee - Knoxville, truther2@vols.utk.edu

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I am submitting herewith a thesis written by Tyler E. Rutherford entitled "Laboratory Investigation of Type I and Type II Hardened Cement Emulsified Asphalt Mortar." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

Baoshan Huang, Major Professor

We have read this thesis and recommend its acceptance:

David B. Clarke, Xiang Shu

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Laboratory Investigation of Type I and Type II Hardened Cement Emulsified Asphalt Mortar

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Tyler E. Rutherford
December 2014

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DEDICATION

This work is dedicated to my wonderful wife and lifelong friend, Samantha Rutherford, and my amazing family. Thank you for all of your love and support.

ACKNOWLEDGEMENTS

First and foremost I would like to thank my advisor, Dr. Baoshan Huang, for all of the opportunities he has given me over the past four years. Thank you for setting me on the path to a brighter future, and giving me the knowledge and wisdom needed to traverse it.

I would also like to show my gratitude to my committee members, Dr. Xiang Shu and Dr. David Clarke, for their assistance in helping me prepare my thesis as well as helping me promote my research. Your time and efforts are greatly appreciated.

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Finally, I would like to thank my mom and dad for all their love and support, my sisters for making me laugh through the worst of times, and my wife, Samantha, for always being by my side. Your encouragement has meant the world to me.

ABSTRACT

The research presented in this thesis investigated the mechanical and viscoelastic properties of a relatively new construction building material that has been given a lot of attention in the past decade. Cement emulsified asphalt mortar (CEAM) has unique properties that differ from concrete and asphalt binder alone as this hybrid material combines the high strength of portland cement composites and the flexibility of asphalt materials. Functioning as a damping material for ballastless high-speed rail track bed, CEAM has the potential to be utilized in other areas of construction.

The work presented in this thesis is broken down into two studies, each examining the CEAM over a range of asphalt binder/cement (B/C) ratios. The first study examined the uniaxial compressive strength (UCS), indirect tensile (IDT) strength, tensile strength ratio (TSR), dynamic modulus, phase angle, and shrinkage of type II CEAM at three different B/C ratios. The cement hydration heat of the paste was measured and the microstructures of CEAM were examined to analyze the interaction between cement and asphalt and to explain its effect on the mechanical properties of CEAM. The results from this study showed that CEAM exhibited loading rate- and temperature-dependent properties, indicative of a typical viscoelastic material, and laid the groundwork for the following study.

The second study built upon the results of the first work and examined the mechanical and viscoelastic properties of type I and type II CEAM using cationic and anionic emulsions. Cationic emulsion proved to yield greater strength development at the cost of workability for both type I and type II CEAM. In addition the results showed a sizable difference in measurable properties at the highest and lowest B/C ratios while indicating possibly comparable results mid-range B/C ratios showing the versatility of the material.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

RESEARCH BACKGROUND, OBJECTIVES, AND LITERARY OVERVIEW

1.1 Research Background

Cement emulsified asphalt mortar (CEAM) is a hybrid material that is currently being studied throughout the world. It has been used in many countries with much success as a key component in high-speed railway ballastless slab track design. Additionally, many researchers are beginning to explore the possibilities of using CEAM in other areas as a general construction building material. However, little research into the advancement of this material has been conducted in the United States.

The two main components of CEAM are the portland cement and asphalt binders. Typical portland cement concrete that is used for construction gains its strength when mixed with water through a process known as hydration. Emulsified asphalt is a combination of asphalt droplets, water, and emulsifying agents that keep the asphalt binder globules dispersed. When combined the portland cement helps separate, or break, the asphalt binder from the water by absorbing the water for the hydration process. The newly free asphalt binder then coats the cement paste creating a cohesive binding agent. CEAM is generally placed into two main types: low modulus of elasticity mixes (type I) and high modulus of elasticity mixes (type II). The ratio of asphalt binder to cement ratio (B/C) is important in developing the balance between strength and flexibility that separates the two types of CEAM. A great deal of research has gone into studying this delicate interaction and the performance capabilities of the resulting material.

There are still several variables that need to be considered in order to properly employ this material for use in the United States. Mix design, mixing rate, and curing methods all have the ability to affect the performance of the CEAM. The mechanical and viscoelastic properties of CEAM need to be studied using aggregates, emulsions, and admixtures readily available in the United States. The purpose of this study is to create the groundwork needed to spark interest into CEAM.

1.2 Research Objectives and Significance

The following research objectives are addressed herein:

1. Begin preliminary testing of type II CEAM using three B/C ratios.
2. Investigate mechanical properties by evaluating the uniaxial compressive strength (UCS), indirect tensile strength (IDT), dynamic modulus (E*), phase angle, damping ratio, and shrinkage of the material.
3. Apply the findings of the preliminary testing to examine the mechanical and viscoelastic properties of both type I and type II CEAM covering six B/C ratios.
4. Study the effect of using anionic and cationic emulsion on UCS for type I and type II.
5. Evaluate the IDT, E*, and damping ratios of type I and type II using the preferred emulsion type.
6. Use scanning electron microscopy (SEM) to better understand the interaction between the primary binders.

Completion of these research objectives sheds new light on the interaction that occurs between emulsified asphalt and portland cement and creates the groundwork for future research into the applications of CEAM. Furthermore, the mechanical and viscoelastic properties that are studied give comparable results that may be used to spark interest into an exciting new construction material.

1.3 Literary Overview

A majority of the research involving CEAM currently being conducted has been focused on improvements to high-speed railways. Functioning as a cushion layer, CEAM has been a key component in the construction of ballestless concrete slab track in countries such as Japan, China, and Germany (Esveld 2003, Jia *et al.* 2011, Zeng *et al.* 2013). At present, there are two main types of CEAM for use in high speed rail: type I (low modulus of elasticity) that is applied to unit slab track and type II (high modulus of elasticity) that is applied to continuous slab track. Typical convention utilizes a cationic emulsified asphalt for type I and an anionic emulsified asphalt for type II (Chen *et al.* 2012). Due to the importance of strength development many researchers have studied the strength mechanisms of CEAM. Wang *et al.* (2011) found that the structural framework for type II mortar was dependent on the hardened cement paste for strength, whereas the framework for type I utilized both the hardened cement paste and asphalt membrane. Oruc *et al.* (2007) found results showing that mechanical properties of CEAM were significantly improved by the addition of cement. And Al-Khateeb *et al.* (2011) found the addition of cement in low quantities could improve the stiffness and rutting parameters without significantly reducing the viscoelastic properties. Based on these three studies it could be suggested that the CEAM could present a wide range of varying strength results based on the B/C ratio. These results agreed with the findings of Pouliot *et al*. (2003) who demonstrated that the hydration process of cement could be affected by the presence of emulsion.

In addition to the important of strength development, the viscoelastic characteristics of the CEAM are vital for the material to function as a dampening layer. Zhang *et al*. (2012) investigated the rheological properties of fresh cement asphalt and discovered that the temperature sensitivity of the rheological properties depended on the type and content of asphalt emulsion. Additionally Kong *et al.* (2014) examined the viscoelastic temperature dependent qualities of high and low B/C ratio mixes and found that both the compressive strength and the elastic modulus of CEAMs decrease with an increase of B/C and testing temperatures, and that the higher the B/C ratio the more significant temperature susceptibility of CEAMs mechanical properties were observed.

1.4 Arrangement of Dissertation

This dissertation is divided into four chapters. Chapter one provides background and literature support for the studies presented herein. Chapter two is a journal article that has been published and is an introductory study into CEAM. The paper investigates the mechanical properties of type II CEAM using three B/C ratios. Chapter three is a journal article that is currently being reviewed for submission and is a continuation of the previous paper. The paper investigates the properties of both type I and type II CEAM and examines the interaction between the binders when mixed with both anionic and cationic charged emulsions. The final chapter, chapter four, presents an outline of the conclusions from both studies as well as recommendations for future research in this area.

CHAPTER II

LABORTARY INVESTIGATION OF MECHANICAL AND PROPERTIES OF CEMENT EMULSIFED ASPHALT MORTAR

Rutherford T, Wang Z, Huang B, Shu X, and Clarke D. Laboratory investigation into mechanical properties of cement emulsified asphalt mortar. Construction and Building Materials, 2014; 65: 76-83.

Tyler E. Rutherford was the principle researcher and co-author of "Laboratory investigation into mechanical properties of cement emulsified asphalt mortar". Tyler's contribution was conducting all testing and data analysis, and co-writing the text contained in the manuscript. Dr. Wang Zhenjun conducted the literature review and co-wrote the text contained in the manuscript. Dr. Baoshan Huang, Dr. Xiang Shu, and Dr. David Clarke provided guidance and ideas throughout the research process as well as editorial assistance.

2.1 Abstract

The present study investigated the mechanical properties of cement emulsified asphalt mortar (CEAM) as a damping material for ballastless high-speed rail track bed. CEAM has unique properties that differ from concrete and asphalt alone as this hybrid material combines the high strength of portland cement composites and the flexibility of asphalt materials. In this study, uniaxial compressive strength (UCS), indirect tensile (IDT) strength, tensile strength ratio (TSR), dynamic modulus and phase angle, and shrinkage were tested on CEAM samples at three different asphalt /cement (A/C) ratios. The cement hydration heat of the paste was measured and the microstructures of CEAM were examined to analyze the interaction between cement and asphalt and to explain its effect on the mechanical properties of CEAM. The results from this study show that CEAM exhibited loading rate- and temperature-dependent properties, indicative of a typical viscoelastic material. Cement could hydrate effectively and both cement and asphalt acted as a binder in the hybrid material as they were in cement or asphalt mix alone. The

A/C ratio showed a significant effect on the mechanical properties and cement hydration heat of CEAM.

Keywords: Cement emulsified asphalt mortar, Mechanical properties, Viscoelasticity, Damping, Shrinkage, Cement hydration heat

2.2 Introduction

High-speed railways have been getting worldwide attention in these days. One requirement to build high-speed rails is to move away from ballasted tracks and towards non-ballasted concrete slab tracks. Traditional ballasted track design consists of rail laid on timber or concrete ties and supported by an aggregate bed (Esveld 2003). Although it is functional for low speed transportation, this design is not suited for high speed rail systems as the increased speed can cause issues with the track, such as lateral and horizontal movement in the track known as “floating” and churning of the stone ballast (Esveld 2003 and Esveld 1997). The non-ballasted concrete slab track is a widely used high speed railway track structure that addresses these issues and is currently being used in many countries such as Japan, China and Germany (Esveld 1997). Typical concrete slab track designs consist of a concrete track slab placed on top of a concrete bed, with a cushion layer in between to help dampen the system (Figure 2.1). The material commonly used as a cushion layer for this structure, cement emulsified asphalt mortar (CEAM), is a mix of cement, asphalt emulsion, fine aggregate, and several chemical admixtures (Tan *et al.* 2013) CEAM is a key component of ballastless high-speed rail track system and its mechanical properties (such as strength, stiffness, and damping) play an important role for a smooth and safe ride (Esveld 1997, Tan *et al.* 2013, Wang *et al.* 2011). CEAM has unique properties that differ from concrete and asphalt alone as this hybrid material combines strength of cement mortar and flexibility of asphalt binder.

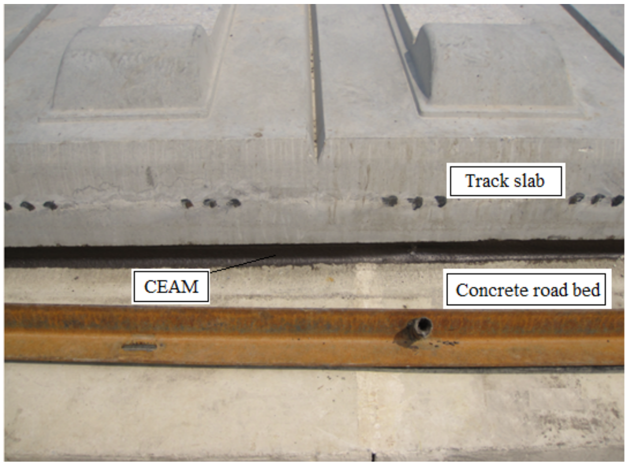


Figure 2.1. Slab track of high-speed rail.

Many studies have been conducted to investigate the behavior and performance of the CEAM mixtures. However, the earlier studies have been focused on the beneficial effects of portland cement as an additive to asphalt emulsion in cold mixes (Terrell *et al.* 1971, Schmidt *et al.* 1973, Brown *et al.* 2000). Until recently researchers have started to explore the possibility of using CEAM as a cushion material for high-speed rails. Since this material consists of two types of binder – portland cement and asphalt binder, both binders play important roles in the performance of CEAM. Oruc *et al.* (2007) studied the influence of cement on the mortar at high cement contents. Their test results show that mechanical properties of CEAM were significantly improved by the addition of cement. Zhang *et al.* (2012) investigated the rheological properties of fresh cement asphalt paste (CA paste), and examined the effects of asphalt emulsion, temperature, and time. Their study shows that the anionic asphalt emulsion is more effective than the cationic type in that the former exhibits favorable adsorption onto the surface of cement grains. They also found that the temperature sensitivity of the rheological properties of the CA paste depends on the type and content of asphalt emulsion. Pouliot *et al.* (2003) explored the interaction between cement and asphalt emulsion particles, demonstrating that the hydration process of cement was affected by the presence of a small quantity of emulsion. Their study shows that the presence of asphalt droplets leads to a significant reduction in compressive strength and elastic modulus as well as a slight decrease in flexural strength of the CEAM. Wang *et al.* (2012 and 2010) found that binder contents could affect the mastic-aggregate interface adhesion, internal air voids and their distribution in the cement asphalt emulsion materials. Lu *et al.* (2009) used F-type superplasticizer (FSP) as the isolation layer outside the micelles in cationic emulsified asphalt in CEAM. They found that asphalt emulsion and cement could mix effectively without the generation of any viscosity by demulsification. They also added sodium carboxymethylcellulose (CMC-Na) to improve and restrain settlement and stratification of fresh CEAM.

2.3 Objective and scope

The objective of this study was to investigate the mechanical properties of CEAM for use in the rail industry. The study was focused on the effects of asphalt to cement ratio (A/C) on the mechanical properties of CEAM. The properties evaluated include uniaxial compressive strength (UCS), indirect tensile strength (IDT), dynamic modulus (E*) and phase angle as well as damping ratio, and shrinkage of the material at different asphalt to cement (A/C) ratios. In order to explain the effects of A/C ratio on the material, the heat of hydration was tested and the microstructures were also examined.

2.4 Materials

The mix design used in this study are presented in Table 2.1. All mixes were made using Type III portland cement. Based on the preliminary research by the authors (Wang *et al.* 2010 and Wang *et al.* 2012), Type III portland cement was chosen for its high early strength to help counteract the slow setting time and retarding effect of the emulsion (Tan *et al.* 2013). For design purposes anionic type SS-1H emulsified asphalt with 60% residue was used following the recommendation from the manufacturer based on its slow setting speed in order to prolong the time for sample preparation. High range water reducer (HRWR) and air entertainer (AE) admixtures were added to increase the workability and performance of CEAM. A sufficient number of small air bubbles produced by AE can help enhance the damping ability of CEAM (Liu *et al.* 2010). Fly ash (FA) was incorporated to decrease viscosity of the mortar to make it easier to be mixed and constructed (Wang *et al.* 2008). The mixes were divided into 3 groups based on their asphalt residue to cement ratio (A/C): Group A (A/C = 0.22), Group B (A/C = 0.43), and Group C (A/C = 0.65). The research efforts were made to balance the content of asphalt emulsion and cement in the CAEM so that the mortar is flexible and also strong enough to support high speed railway traffic loading. Figure 2.2 shows the gradation of natural sand used in the mixes.

Table 2.1 Proportions of CEAM (kg/m3)

group	cement	emulsified asphalt	water	natural sand	FA	HRWR	AE
A	400	144	197	1006	40	11	2.2
B	400	288	140	919	40	11	2.2
C	400	432	82	833	40	11	2.2

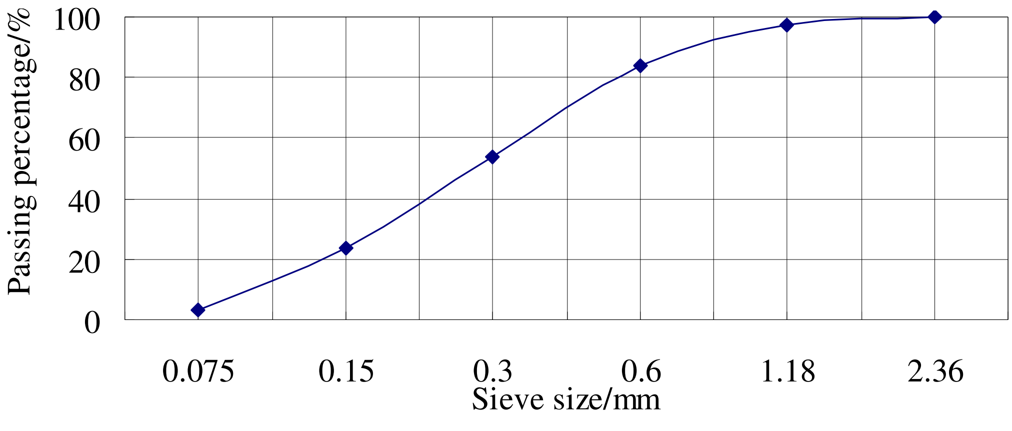


Figure 2.2 Natural sand gradation for CEAM.

2.5 Sample preparation

A mechanical mixer was used to mix the CEAM to ensure consistency in the samples. The specimens to be used for compressive strength test were cast using 50mm steel cube molds. After 48 hours the samples were demolded and field cured in a temperature controlled room at 20 °C for 28 day in guidance of ASTM C31 (2012). For the IDT strength and dynamic modulus tests, samples were cast using 100 mm diameter and 200 mm high cylinder molds. The samples were then demolded and cured in a wet curing room until tested. For the IDT strength test, the samples were cut into 50 mm thick specimens before testing. The samples for dynamic modulus test were cut into 150 mm high specimens to fit the sample size requirement for this test.

For the shrinkage test, samples were cast using a double compartment steel mold in accordance with ASTM C490 (2013). The samples were demolded and field cured in a temperature controlled room for 28 days.

2.6 Experimental procedures

2.6.1 UCS test

The UCS measurements on 50 mm mortar cubes were performed after 3 and 28 days of curing according to the instruction for compressive strength test of cement emulsified asphalt mortar (Ministry of Railways Type II 2008). The loading rate applied to each sample was 100N/s for compressive strength testing. Figure 2.3 shows the samples during testing.

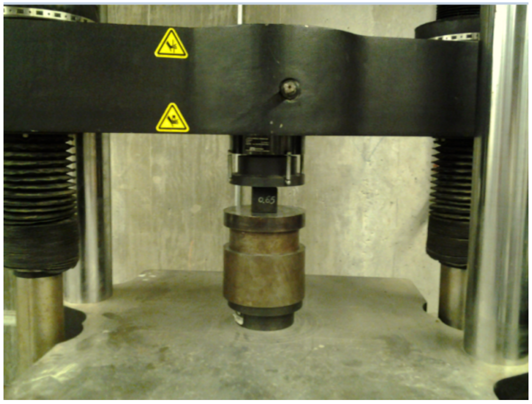


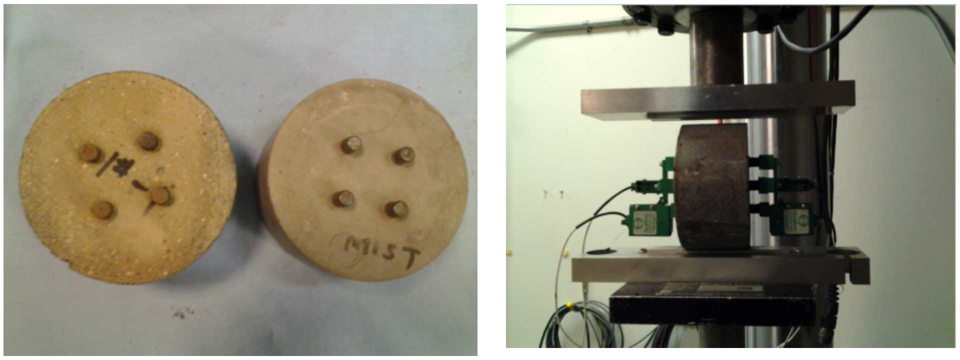
Figure 2.3 UCS testing apparatus.

2.6.2 IDT strength test

Before testing, brass gage studs were attached to each specimen to be used with 4 strain gages to measure the vertical and horizontal strain measurements. In accordance with ASTM D6931 (2012), specimens were monotonically loaded to failure along the vertical diametric axis at the constant rate of 50mm/min, at the temperature of 20 °C. Figure 2.4 displays the samples before and during testing. The IDT strength was calculated using Equation (1):

$$S_t = \frac{2000P}{\pi D t} \tag{1}$$

where, S_t = IDT strength; P = maximum load; t = specimen height; and D = specimen diameter.



(a) Samples (b) Test setup

Figure 2.4 IDT samples and test setup.

It should be mentioned that one set of samples from each group was selected for moisture susceptibility test. According to ASTM D7870 (2013), the moisture-induced stress tester (MIST) was used for the moisture conditioning to simulate the conditions of repeated generation of pore pressure in a saturated ballastless track structure under rail load. The MIST apparatus was run for 500 cycles in a water bath of 40 °C with a constant air pressure of 276 kPa. The number of cycles used for the MIST conditioning was chosen based on the authors' previous work (Chen and Huang 2008).

2.6.3 Dynamic modulus test

The testing procedure for dynamic modulus test was derived from NCHRP 9-29 (Bonaquist 2008). An Asphalt Mixture Performance Tester (AMPT) was used to test the material. The specimens were demolded and cut to 100 mm x 150 mm cylinders and steel studs were attached. Three linear variable displacement transducers (LVDTs) were used at 120° angles to capture deformation of the specimen during test. Using an environmental chamber testing was conducted at 20°C, 40°C, and 60°C. Figure 2.5 shows the samples before and during testing. A continuous uniaxial sinusoidal compressive stress was applied to the unconfined specimen at various test frequencies ranging from 0.1 Hz to 25 Hz. The dominant ground vibration is in the frequency range for the ballastless track (Zhai *et al.* 2010). The applied stress and the strain response of the specimen were measured and used to calculate the dynamic modulus. The dynamic modulus |E*| was calculated using Equation (2):

$$\left|E^*\right| = \frac{\sigma_0}{\varepsilon_0} \tag{2}$$

where, σ_0, ε_0 = magnitudes of applied loading stress and induced axial strain, respectively.

(a) Samples (b) Test setup

Figure 2.5 Dynamic modulus samples and test setup.

It is noted that phase angle, another essential property for characterizing viscoelastic materials, can also be obtained from the dynamic modulus test. Then the damping ratio, the parameter for characterizing the energy dissipation capacity of CEAM, can be obtained using Equation (3):

$$\zeta = \frac{1}{2}\tan\delta \tag{3}$$

where, ζ = damping ratio; and δ = phase angle.

2.6.4 Shrinkage test

The length measurements were taken each day starting with the 3rd day to allow the material enough time to set and be removed from the molds. A length comparator (Figure 2.6) was used to accurately measure the displacement of the material over the time span using Equation (4):

$$L = \frac{L_x - L_i}{G} \times 100 \tag{4}$$

where, L = change in length at age x (%); L_x = comparator reading of specimen at age x minus comparator reading of reference bar at age x; L_i = initial comparator reading of specimen minus comparator reading of reference bar at that same time; and G = nominal gauge length.

Figure 2.6 Length comparator apparatus.

2.6.5 Heat of hydration test

In order to explain how the emulsified asphalt affects the cement paste, the heat of hydration for the paste was studied using an I-Cal 8000 isothermal calorimeter shown in Figure 2.7. A paste containing only the cement, asphalt, and water portions from each mix group and a control paste of cement and water were mixed. No admixtures were added to the pastes for this portion of the study. The samples were mixed by hand in the provided containers and tested for 7 days to ensure the peak energy output was met.

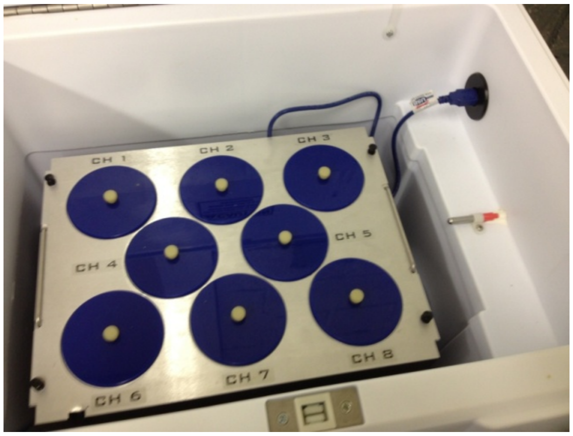


Figure 2.7 I-Cal 800 isothermal calorimeter temperature control unit.

2.7 Results and discussion

2.7.1 UCS results

Figure 2.8 shows the UCS results obtained for the CEAM with different A/C ratios after 3 and 28 days of curing. From Figure 2.8, a significant reduction in the compressive strength of CEAM was observed as the asphalt content increased. As the A/C ratio increased from 0.22 to 0.43, the UCS decreased by up to 65% for 3-d samples and 57% for 28-d samples. The reduction in UCS is evidently attributed to the increase in the small asphalt droplets dispersed in the rigid cement matrix. This means that the A/C ratio had a significant effect on the UCS of CEAM.

Compared to its 3-d strength, the 28-d strength of Group A (A/C = 0.22) increased by 32%. However, the 28-d strength improvements over 3-d UCS were 73% and 74% for

Groups B and C, respectively. The improvement was caused by the further cement hydration and the reduction of water in asphalt emulsion.

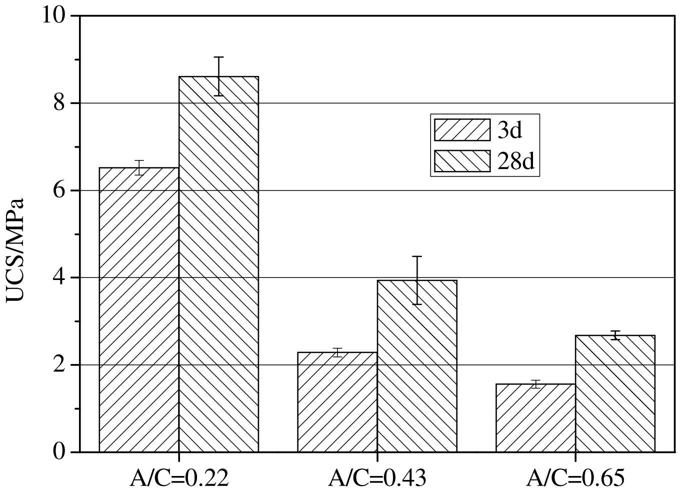


Figure 2.8 UCS testing results.

2.7.2 IDT results

Figure 2.9 shows the results from the IDT strength test. As the A/C ratio of the material increased from 0.22 to 0.65, the IDT strength of CEAM significantly decreased. The IDT strength of Group A with A/C ratio of 0.22 was 530kPa, more than twice the strength of Group C with A/C ratio of 0.65 (216kPa). Therefore, the increase in asphalt emulsion content decreased the IDT strength of CEAM.

Figure 2.10 shows the effect of moisture conditioning on the IDT strength of CEAM. It can be seen that the MIST-conditioned specimens suffered a 10-20% reduction in IDT strength. With the increase in asphalt emulsion content, the tensile strength ratio became smaller, indicating that CEAM may become more susceptible to moisture damage with the increase in asphalt content.

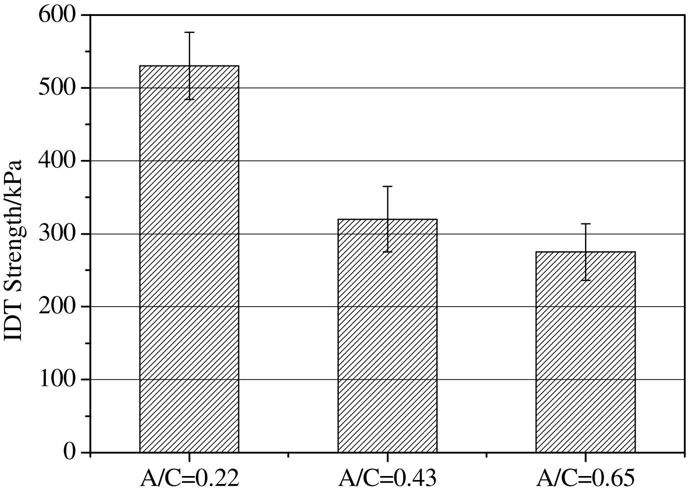


Figure 2.9 IDT strength testing results.

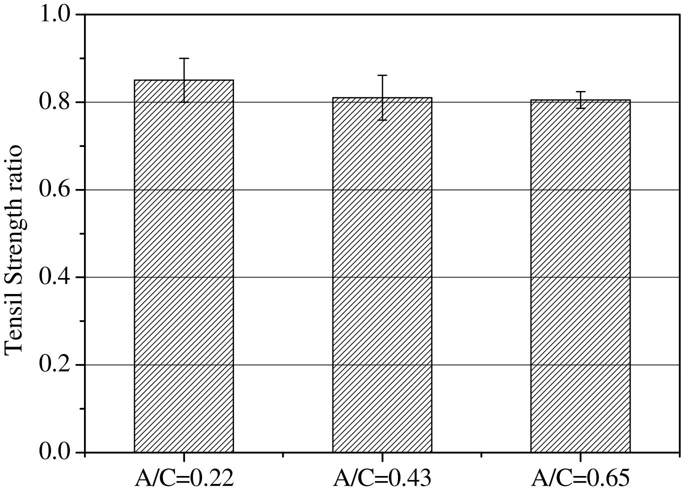


Figure 2.10 TSR testing results.

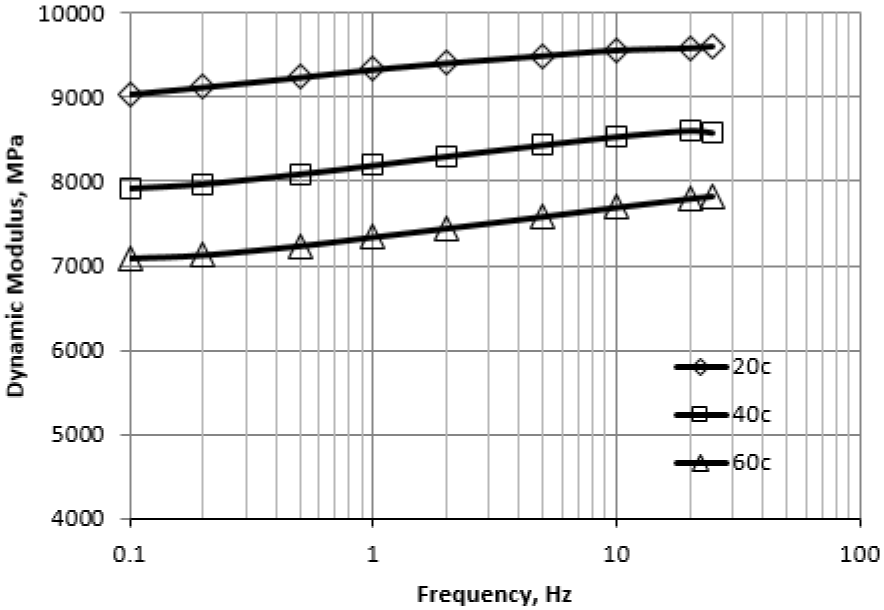
2.7.3 Dynamic modulus results

Figure 2.11 shows the dynamic modulus results at various loading frequencies and three temperatures. The results clearly show that CEAM is a typical loading rate- and temperature-dependent viscoelastic material (Tan *et al.* 2013). The dynamic modulus of CEAM increased with the increase in loading frequency. On the other hand, as temperature increased, the dynamic modulus decreased. Figure 2.11 also shows that with the increase in asphalt emulsion content, the dynamic modulus significantly decreased, which is consistent with its effect on the UCS and IDT strength.

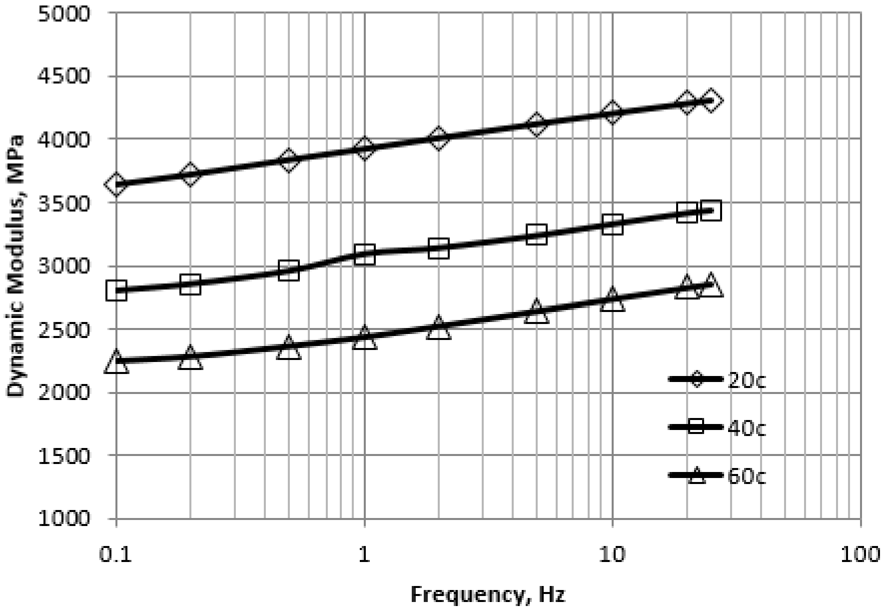
Figure 2.12 shows the phase angle results of the CEAM. In addition to dynamic modulus, phase angle is another parameter for characterizing the viscoelastic properties of a material. For a perfectly elastic material, the applied cyclic stress is always in phase with the resulting strain, resulting in a zero phase angle. For a purely viscous material, the strain always lags the stress by 90°. The ordinary viscoelastic materials have a phase angle between 0 and 90°. Figure 2.12 shows that the phase angle of CEAM ranged from one degree to fourteen degrees in this study, indicating that CEAM is a typical viscoelastic material with the capability of energy dissipation. The viscous property of CEAM was imparted by the addition of asphalt component in the material. However, compared to asphalt binders and mixtures (Shu and Huang 2008), CEAM had a much smaller phase angle. This is due to the fact that asphalt binders act as a matrix in asphalt mixtures and bind the fine and coarse aggregate particles together, whereas in CEAM, asphalt components were embedded in the cement paste matrix and constrained by the matrix. The viscous effect of asphalt was significantly reduced by cement paste.

Figure 2.13 shows the damping ratio values of the CEAM of Group B (A/C = 0.43). It can be seen that damping ratio was not a fixed value. Rather it changed with the variation in loading rate and temperature. Generally, the damping ratio of CEAM fell within the range of 1% and 7% depending on the amount of asphalt binder. The damping ratio of CEAM was much smaller than asphalt binder and mixture, due to the aforementioned reasons. However, compared to portland cement paste, mortar, or concrete (Swamy *et al.* 1971, Wen and Chung 2000, Chung 2003), CEAM showed a higher damping ratio, indicating that its energy dissipation capability was increased with the addition of emulsified asphalt. It was seen that increasing both the asphalt to cement ratios and temperature lead to an increase in the damping ratios.

Figure 2.11 Dynamic modulus results for each A/C ratio at different temperatures.

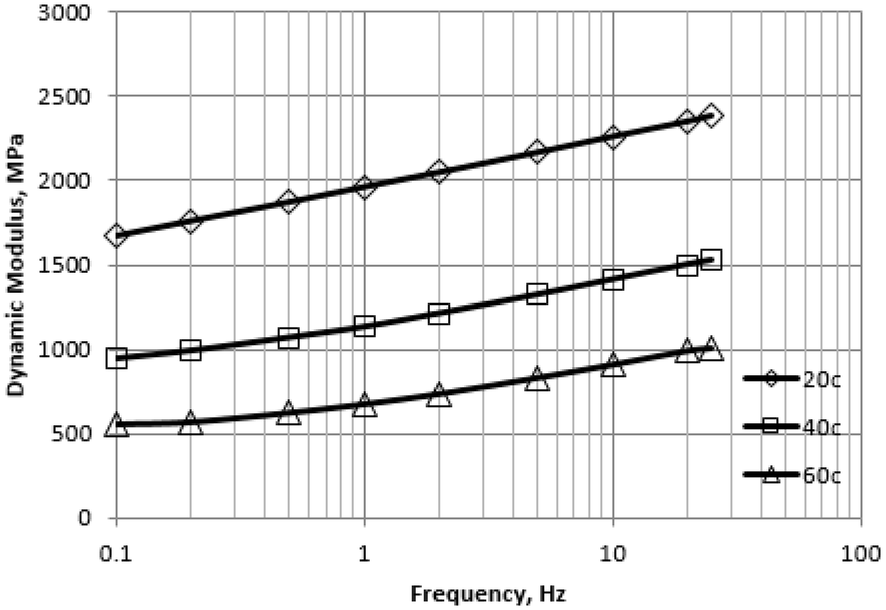


(a) A/C=0.22



(b) A/C=0.43

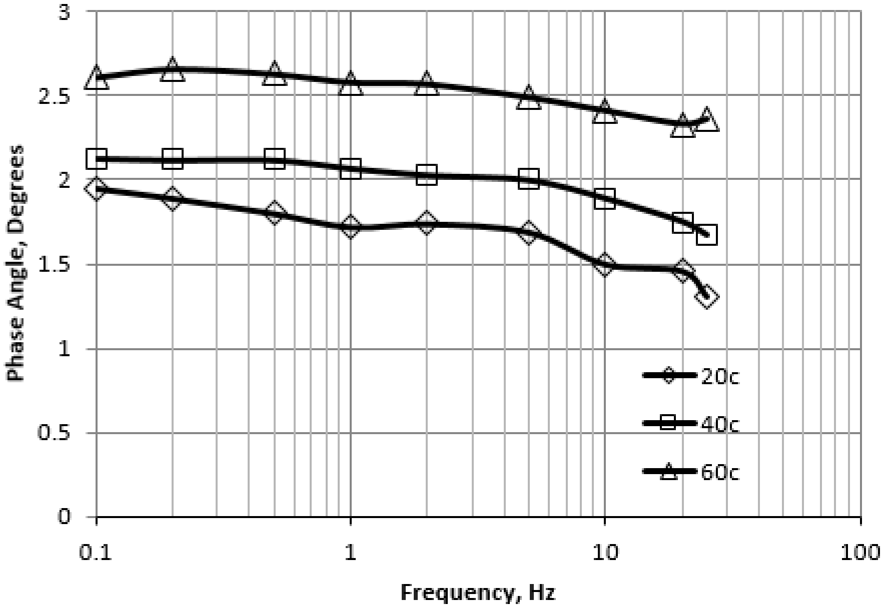
Figure 2.11



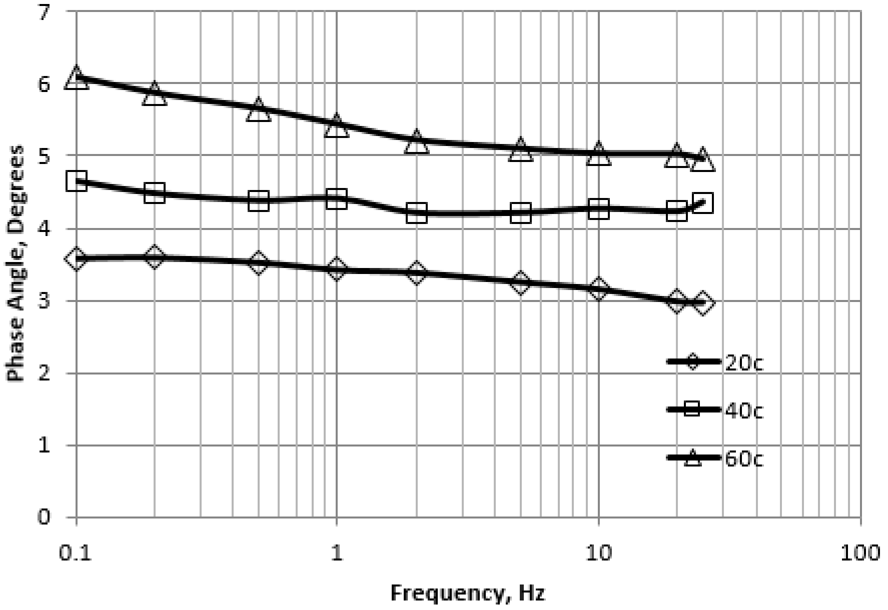
(c)A/C=0.65

Figure 2.11 continued

Figure 2.12 Phase angle results for each A/C ratio at different temperatures.

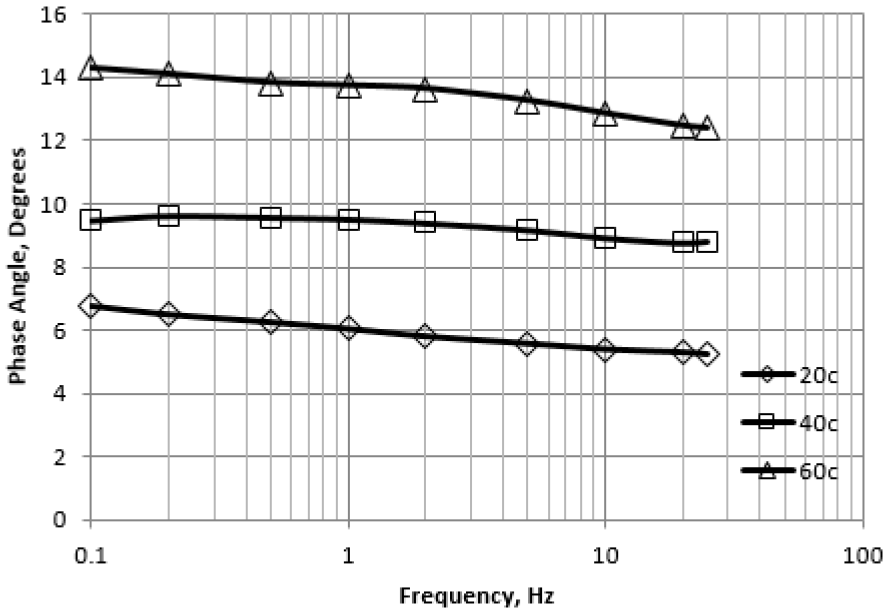


(a) A/C=0.22



(b) A/C=0.43

Figure 2.12



(c) A/C=0.65

Figure 2.12 continued

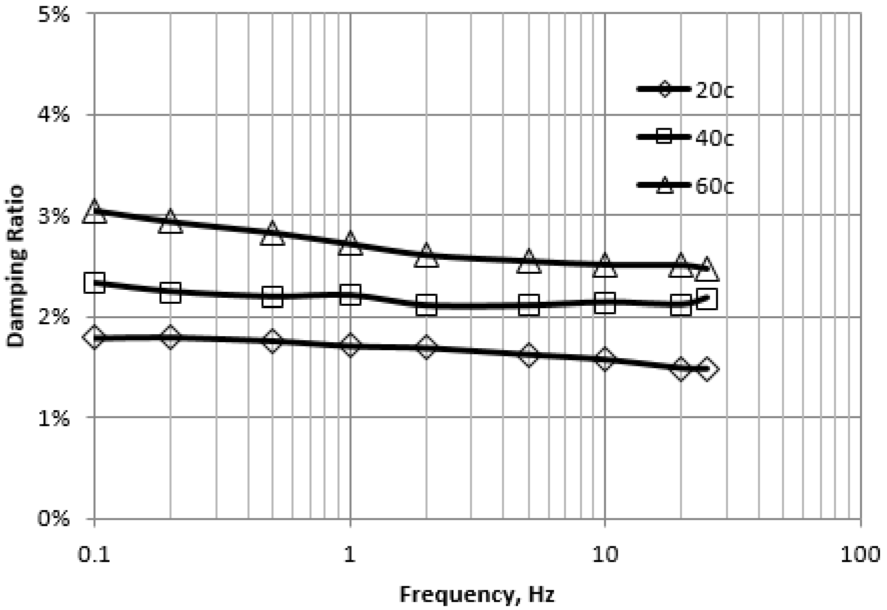


Figure 2.13 Damping ratio results (A/C=0.43).

2.7.4 Shrinkage results

The shrinkage development of CEAM was observed over a period of 28 days and is shown in Figure 2.14. The results show that CEAM shrank fast at early ages and the shrinkage appeared to level off at the end of 28 days. In this study, the group with the A/C ratio of 0.43 showed the least amount of shrinkage and its maximum shrinkage was 0.12%, whereas the group with the highest A/C ratio showed the largest shrinkage with a maximum value of 0.34%. It is believed that the shrinkage of CEAM was affected by the hydration of portland cement and the breaking of the emulsion. A higher asphalt emulsion content seemed to increase the shrinkage of CEAM.

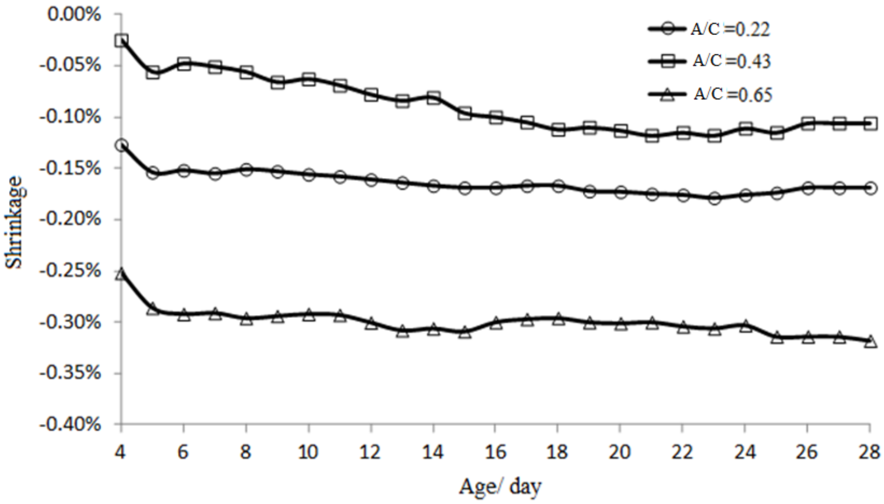
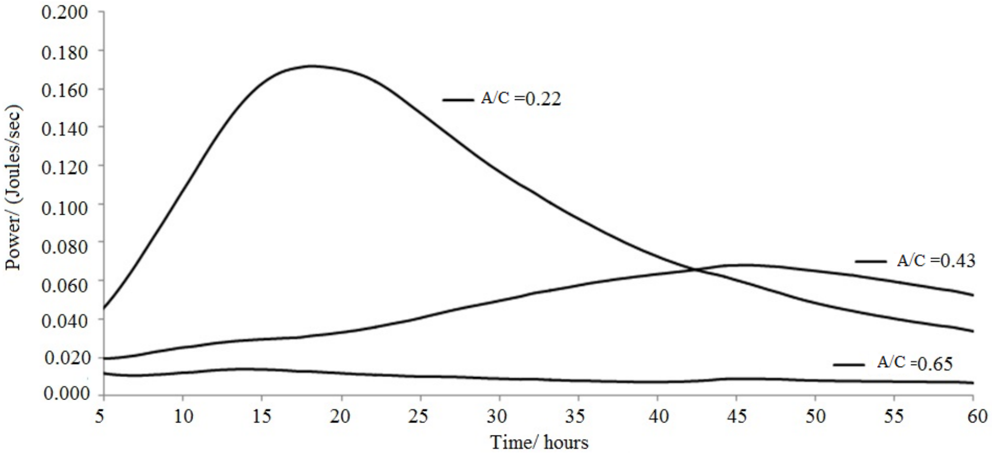


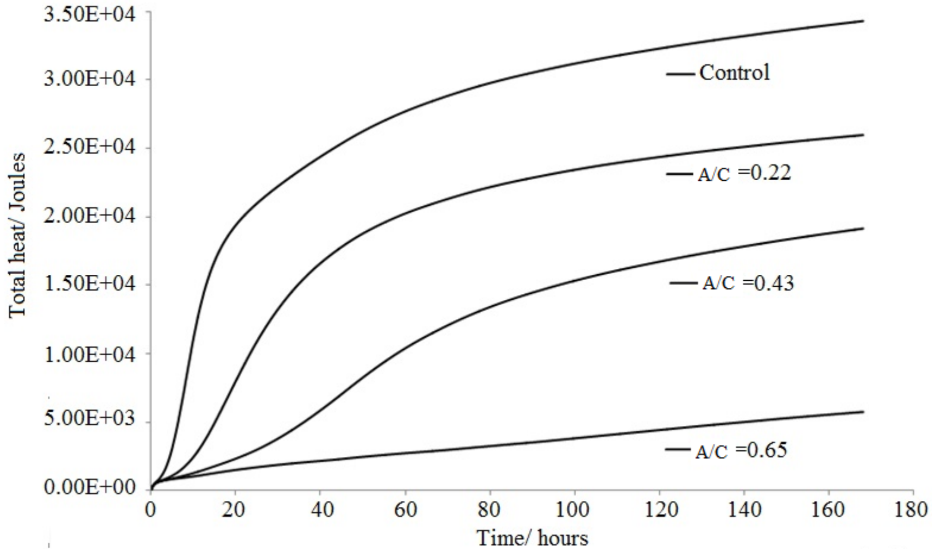
Figure 2.14 Shrinkage testing results for 28 days.

2.7.5 Hydration heat results

Figure 2.15 shows the accumulative heat and the heat release power during cement hydration. It can be seen that the emulsified asphalt had a significant retarding effect on cement hydration and this retarding effect increased drastically with the increase in A/C ratio (Tan *et al.* 2013). In Figure 2.15(a), Group A with the A/C ratio of 0.22 showed a clear peak of heat release rate, whereas Group B with 0.43 A/C ratio showed a much lower and duller peak that occurred much later than Group A. Group C (A/C = 0.63) did not even show any peak of heat release rate and the rate itself was the slowest among the three. Figure 2.15(b) shows significant differences in the accumulative heat among the three CEAM materials and the control mix composing of just cement and water. The total heat released by Group A was 25% lower than that of the control and Group C only released about 20% of the heat over the seven days. This is consistent with the findings from the study by Wang *et al.* (2011), which showed that asphalt emulsion delayed the early hydration of cement and the asphalt membrane had a negative effect on the further hydration of the cement. Just like other cement-based materials, as long as the hydration of portland cement continues, the mechanical properties of CEAM will also continue to change with the hydration.



(a) Heat release power



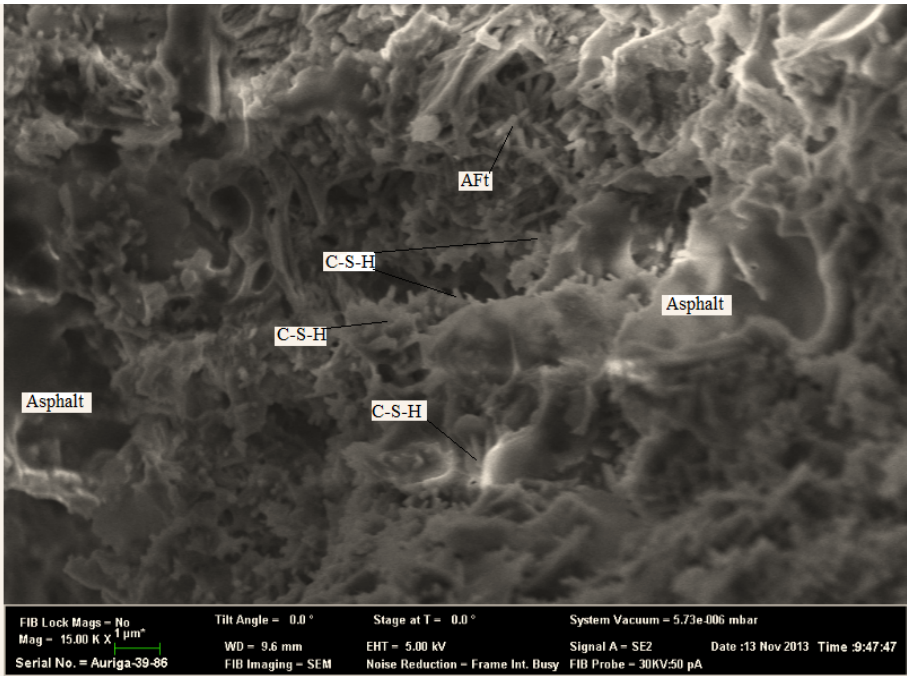
(b) Accumulative heat release

Figure 2.15 Results from cement heat of hydration testing.

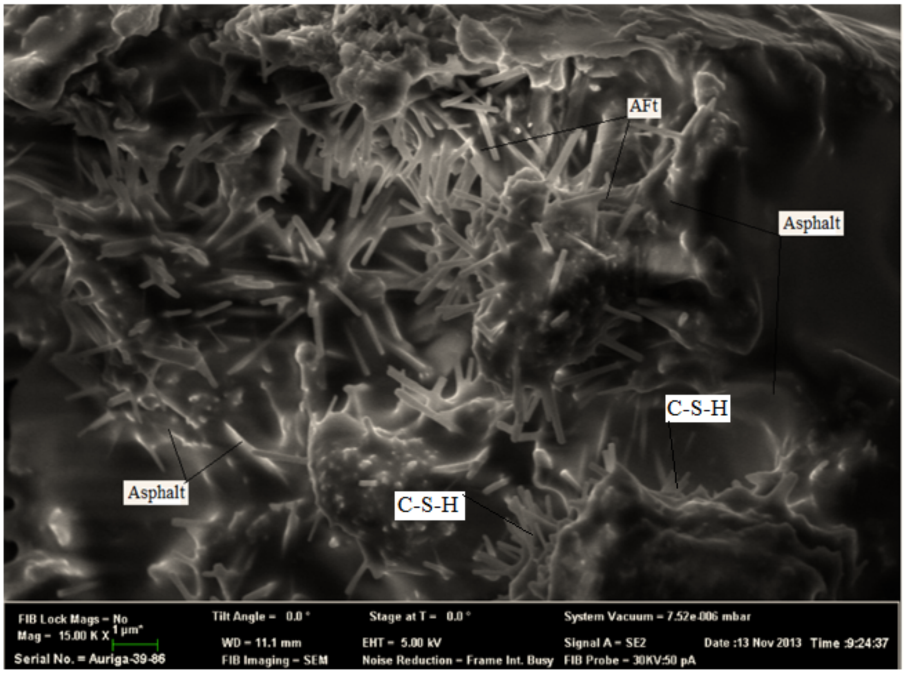
2.7.6 SEM observation

Figure 2.16 shows the SEM pictures of the CEAM. The cement hydration products, such as calcium silicate hydrates (C-S-H) and ettringite (AFt), can be clearly seen in Figure 2.16. C-S-H is the main binding phase in all portland cement-based materials. The strength of hardened portland cement paste depends in part on the ability of the C-S-H to bind effectively other products of hydration and aggregates (Richardson 1999). The cement particles in CEAM hydrate in much the same manner as it would in other normal cementitious composites. The hydration products can pierce the asphalt film, smooth areas (Figure 2.16a), and form bonds with other hydration products or the sand surface. The cementitious phase in the CEAM was dispersed within the asphalt binder. The cement hydration consumed a portion of the water that occupies the micro air void spaces between asphalt emulsion and sand, which had a stiffening effect on asphalt binder (Du 2013). However, AFt crystal grew well and there was few C-S-H observed in Figure 2.16b, indicating that more asphalt prevented the C-S-H formation. AFt showed needle-like morphology and the needles interlocked with each other, which also contributed to the stiffening of the CEAM. For Group C, there were even less AFt and C-S-H hydrates that can be observed from Figure 2.16(c). This indicates that the higher A/C may lead to formation of less cement hydration products. Although the water phase in asphalt emulsion can react with cement particles, they could also be wrapped by asphalt film in CEAM, preventing formation of more cement hydration products. The stiffening and strengthening effect of cement particles is significantly decreased by the presence of viscous asphalt binder.

Figure 2.16 SEM pictures taken at 15k x $^{1\mu m}$ magnification.

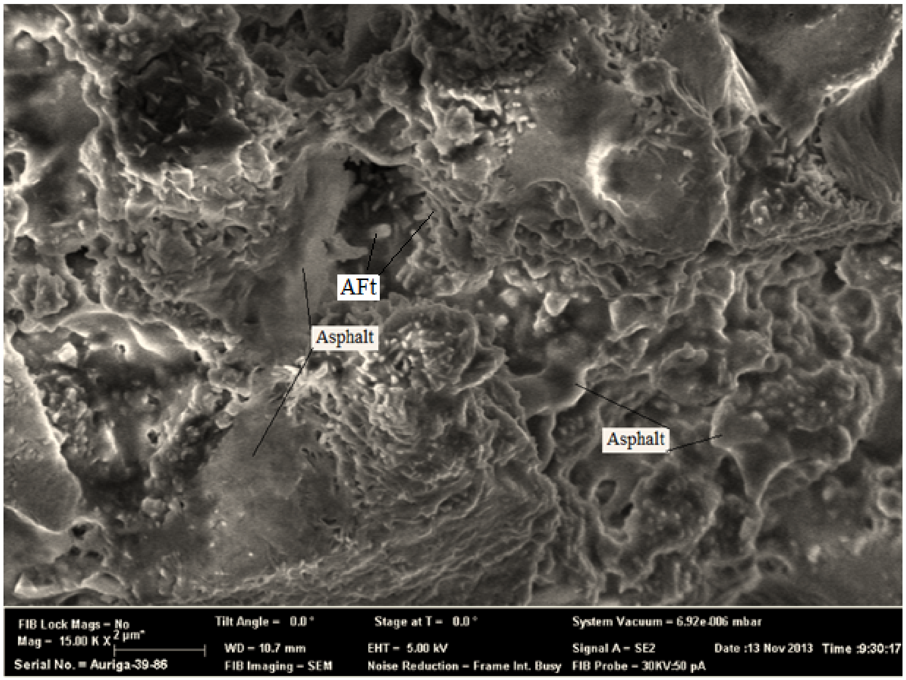


a) A/C=0.22



b) A/C=0.43

Figure 2.16



c) A/C=0.65

Figure 2.16 continued

2.8 Summary and Conclusions

A laboratory study was conducted to investigate the properties of CEAM. The UCS, IDT strength, dynamic and phase angle, shrinkage, and cement hydration heat were tested for the CEAM with different A/C ratio. Based on the results from the study, the following conclusions can be obtained:

1. CEAM exhibited the properties of a hybrid material, combining the high strength of portland cement mortar and the energy dissipation capability of asphalt.
2. The A/C ratio showed a significant effect on the mechanical properties of CEAM. As the A/C ratio increased, the UCS, IDT strength, TSR, and dynamic modulus of CEAM decreased and the shrinkage increased.
3. Asphalt had a significant retarding effect on the cement hydration of CEAM. With the increase in A/C, the retarding effect became more significant. The reduction in IDT strength and dynamic modulus could be attributed to the retarding effect of asphalt.
4. The damping characteristics of CEAM were imparted by the addition of asphalt. The damping ratio of CEAM was much lower than asphalt binder and mixture, but greater than ordinary portland cement composites. Both asphalt binder content and temperature proved to be vital to determining the damping properties. The reduced damping properties of CEAM were attributed to the fact that asphalt component was constrained by stronger portland cement paste.

5. The cement in low A/C CEAM could hydrate in much the same manner as it does in normal cementitious composites, stiffening CEAM and improving its mechanical properties. The increase in A/C prevented formation of more cement hydration products.

2.9 Acknowledgements

The authors would like to thank the financial sponsorship provided by the U.S. DOT through the National University Rail Center (NURail). The authors would also like to thank Drs. Xiaoyang Jia, Qiao Dong, Changjun Zhou, Benjamin Bowers, and Christian Canady for their assistance in this project. A special thank goes to Hudson Materials for donating the anionic emulsified asphalt for the project.

CHAPTER III

INVESTIGATION OF MECHANICAL AND VISCOELASTIC PROPERTIES OF HARDENED CEMENT EMULSIFED ASPHALT MORTAR

A version of this chapter is currently being reviewed for submission for publication by Tyler Rutherford, Zhenjun Wang, Baoshan Huang, Xiang Shu and David Clarke:

Tyler E. Rutherford was the principle researcher and author of “Investigation of Mechanical and Viscoelastic Properties of Hardened Cement Emulsified Asphalt Mortar.” Tyler’s contribution was conducting all literature review, testing, data analysis, and writing the text contained in the manuscript. Dr. Wang Zhenjun, Dr. Baoshan Huang, Dr. Xiang Shu, and Dr. David Clarke provided guidance and ideas throughout the research process as well as editorial assistance.

3.1 Abstract

This study is a continuation of the authors’ previous work and investigates the mechanical and viscoelastic properties of two types of hardened cement emulsified asphalt mortar (CEAM) for use as a construction building material. CEAM has unique properties that combine the high strength of portland cement and the flexibility of asphalt materials with the performance characteristics highly dependent on the emulsion type and ratio of asphalt binder to cement (B/C ratio). For the purpose of this study the CEAM mixtures were divided into two types, high and low modulus of elasticity, and tested using various B/C ratios. The properties evaluated include uniaxial compressive strength (UCS), indirect tensile strength (IDT), dynamic modulus (E*), and damping ratio at different B/C ratios. In order to explain the effects of the B/C ratios on the material, the microstructure was examined using scanning electron microscopy (SEM). The results of this study show cationic emulsion provides greater strength development at the cost of workability for both type I and type II CEAM. The IDT strength, E*, and damping ratios were examined using Chinese high speed rail standards of cationic emulsion for type I and anionic emulsion for type II hardened CEAM. The results showed sizable differences in viscoelastic and mechanical properties at the highest and lowest B/C ratios while indicating possibly comparable results mid-range B/C ratios showing the versatility of the material.

Keywords: Cement emulsified asphalt mortar, Low modulus, High modulus, Mechanical properties, Viscoelastic, UCS, IDT, damping, SEM

3.2 Introduction

In an effort to examine innovative means of economical and sustainable infrastructure new materials and methods are being tested daily. Hardened cement emulsified asphalt mortar (CEAM) is a composite material that has effectively been used in countries such as China, Japan, and Germany for use as a component in high speed railways (Esveld 2003, Jia *et al.* 2011, Zeng *et al.* 2013). Additionally CEAM has recently seen use as a paving material in areas as a bonding layer, as a rigid pavement, and as a waterproof and cohesive layer of bridge deck pavement (Chu *et al.* 2013, Du *et al.* 2014). Continual research is needed in order to explore the many possible uses for this construction material.

Typical slab track design for ballastless high speed rail consists of a prefabricated track slab, a leveling/damping layer of CEAM, and a concrete road bed as seen in Figure 3.1.

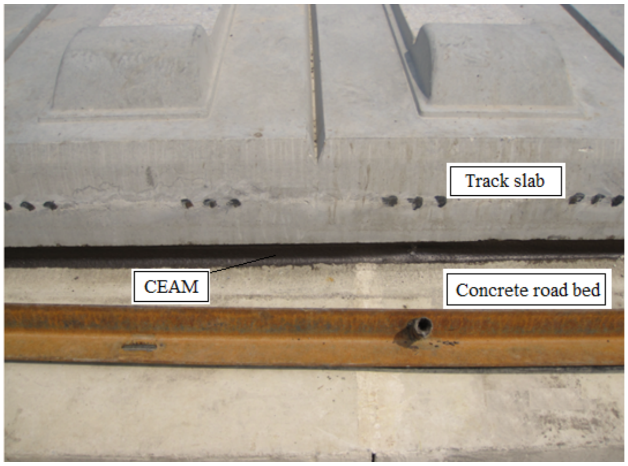


Figure 3.1 Slab track of high-speed rail.

At present, there are two main types of CEAM for use in high speed rail: type I (low modulus of elasticity) that is applied to unit slab track and type II (high modulus of elasticity) that is applied to continuous slab track. Typical convention utilizes a cationic emulsified asphalt for type I and an anionic emulsified asphalt for type II (Chen *et al.* 2012). This is largely to balance mechanical and viscoelastic properties in order to create the desired performance qualities. Type I CEAM uses cationic emulsion which makes a stronger bond between the asphalt and inorganic material due to the negatively charged particles of the cement and sand helping break the emulsion when absorbing water. However, the asphalt emulsion for type II CEAM uses anionic emulsion to ensure better cement compatibility (or chemical stability) because of the large cement content (Wang and Liu 2012). Presently many researchers have examined the function and performance of CEAM mix designs for use in high speed rail. Wang *et al.* (2011) studied the strength development of both type I and type II CEAM. They found that the structural framework for type II mortar was dependent on the hardened cement paste for strength, whereas the framework for type I utilized both the hardened cement paste and asphalt membrane. Recently Kong *et al.* (2014) examined the viscoelastic temperature dependent qualities of high and low B/C ratio mixes. Their results shows that generally both the compressive strength and the elastic modulus of CEAMs decrease with an increase of B/C and testing temperatures, and that the higher the B/C ratio the more significant temperature susceptibility of CEAMs mechanical properties was observed. In a study by Wang *et al.* (2012) it was concluded that the size and formation of air voids were a function of both aggregate gradation and binder content. For use as a construction building material, Huang *et al.* (2012) reported using CEAM as a semi-flexible pavement that utilized high carrying capacity and durability with good results. And for use in superpave pavement design, Al-Khateeb *et al.* (2011) studied the use of adding portland cement to asphalt and found the addition of cement in low quantities could improve the stiffness and rutting parameters without significantly reducing the viscoelastic properties.

3.3 Objective and Scope

The objective of this study was to investigate the viscoelastic properties of hardened CEAM for use as a construction building material. The study was focused on the effects of asphalt binder to cement ratio (B/C) on the viscoelastic properties of low modulus of elasticity (Type I) and high modulus of elasticity (Type II) CEAM. The properties evaluated include uniaxial compressive strength (UCS), indirect tensile strength (IDT), dynamic modulus (E*), and damping ratio at different B/C ratios. In order to explain the effects of the B/C ratios on the material, the microstructure were examined using scanning electron microscopy (SEM).

3.4 Material Selection

The mix designs used in this study are presented in Table 3.1. For design purposes anionic type SS-1H and cationic type CSS-1H emulsified asphalts were selected based on manufacturer recommendation for their slow setting speed in order to prolong the setting time for sample preparation. Both emulsions contained 60% residue and were considered to be comparable. Based on examinations from preliminary sample preparation all mixes were made using Type III portland cement to help strengthen the samples for demolding. Type III portland cement was chosen for its high early strength to help counteract the slow setting time and retarding effect of the asphalt emulsion. High range water reducer (HRWR) was added to increase the workability of the mortar. The mixes were divided into 2 groups based on their B/C ratio: Type I (0.73, 0.94, 1.16) and Type II (0.13, 0.34, 0.56). The range of B/C ratios were chosen in order to examine the balance between strength and flexibility in order to support various levels of loading. Figure 3.2 shows the gradation of natural sand used in the mixes.

Table 3.1 Proportions of CEAM (kg/m^3).

B/C Ratio	Cement	Emulsified Asphalt	Water	Natural Sand	HRWR
0.13	550	115.5	256.3	921.4	6.8
0.34	550	313.5	177.1	802.6	6.8
0.56	550	511.5	97.9	683.8	6.8
0.73	300	363.0	85.8	647.4	3.8
0.94	300	471.0	42.6	582.6	3.8
1.16	300	579.0	0.0	517.8	3.8

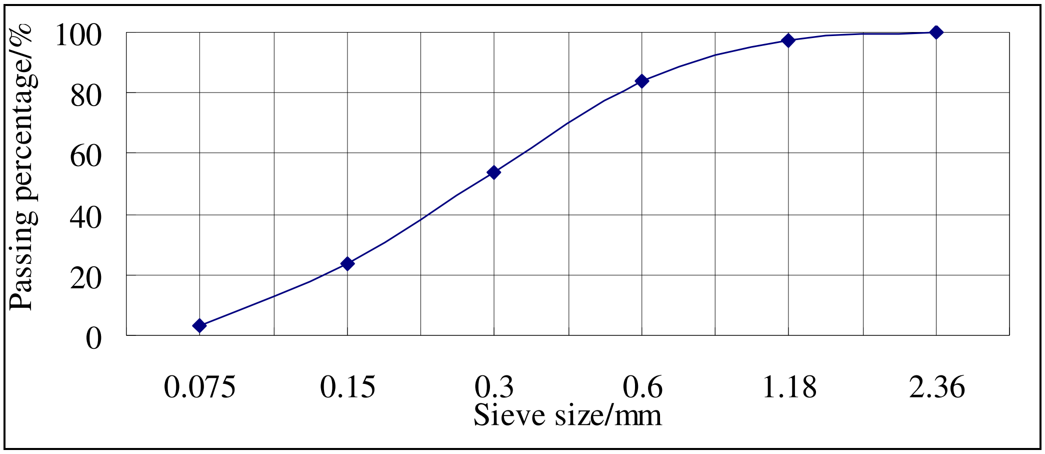


Figure 3.2 Natural sand gradation for CEAM.

3.5 Sample Preparation

All mixes were prepared in a temperature controlled environment. A mechanical mixer was used to mix the CEAM to ensure consistency in the samples. Careful attention was observed when mixing the materials and were added in the following order: asphalt emulsion, 50% total water mixed with water reducer, natural sand, and cement mixed with remaining 50% water. The total mixing duration was 3 minutes. All samples were field cured in a temperature controlled room at 20 °C for 28 day in guidance of ASTM-C31 (2012). The specimens to be used for compressive strength testing were made using both anionic and cationic emulsions for Type I and Type II to compare the effectiveness of different emulsion types and were cast using 50mm steel cube molds. After 48 hours the samples were demolded and field cured. For the IDT strength, dynamic modulus, and damping tests cationic emulsion was used for Type II and anionic emulsion was used for Type I based on Chinese specifications and preliminary UCS test results (Ministry of Railways Type I and Type II 2008). Samples for the IDT strength and dynamic modulus tests were cast using 100 mm diameter and 200 mm high cylinder molds. The samples were then demolded and field cured. For the IDT strength test, the samples were cut into 50 mm thick specimens before testing. The samples for dynamic modulus test were cut into 150 mm high specimens to fit the sample size requirement for this test.

3.6 Experimental Procedures

3.6.1 UCS Test

UCS testing on 50 mm mortar cubes were performed after 3, 7, and 28 days of curing in guidance with the compressive strength testing requirements of cement emulsified asphalt mortar developed for use in China (Ministry of Railways Type I and Type II 2008 and in accordance with ASTM C109 (2013). Both cationic and anionic samples were made for Type I and Type II mortars in order to examine the effect each emulsion type had on the low and high modulus mix designs. The loading rate applied to each sample was 1mm/min for Type I samples and 100N/s for Type II samples. Figure 3.3 shows a typical break for a Type II specimen. The workability of each mix was tested using a standard flow-table following ASTM C1437 (2013). Fresh CEAM samples were placed on the flow table and dropped 25 times within 15 seconds. The initial and the final diameters of the mortar sample were used to calculate the flow based on the percentage increase.

Figure 3.3 Completed USC test on Type II CEAM.

3.6.2 IDT Strength Test

Each 100mm diameter cylinder was cut into 3 equal 50mm thick cylinders. One set of samples from each group was selected for moisture susceptibility testing. According to ASTM D7870 (2013), the moisture-induced stress tester (MIST) was used for the moisture conditioning to simulate the conditions of repeated generation of pore pressure in a saturated ballastless track structure under rail load. The MIST apparatus was run for 1000 cycles in a water bath of 40 °C with a constant air pressure of 276 kPa. The number of cycles used for the MIST conditioning was chosen based on previous work by the authors (Rutherford *et al.* 2014, Chen and Huang 2008). In accordance with ASTM D6931 (2012), each IDT specimen was loaded to failure at a constant rate of 50mm/min, at the temperature of 20 °C. Figure 3.4 displays the test setup for the IDT testing. The IDT strength was calculated using Equation (1):

$$S_t = \frac{2000P}{\pi D t} \tag{1}$$

where, S_t = IDT strength; P = maximum load; t = specimen height; and D = specimen diameter.

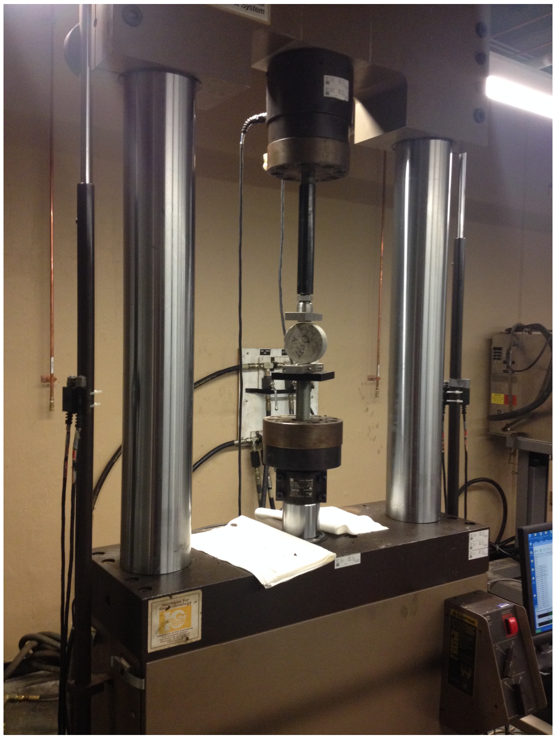


Figure 3.4 IDT test setup for 50mm samples.

3.6.3 Dynamic Modulus and Damping Ratio Test

An asphalt mixture performance tester (AMPT) with an environmental chamber was used to test the dynamic modulus and damping ratio of the material. The testing procedures were derived from NCHRP 9-29 (Bonaquist 2008). The demolded specimens were cut into 100 mm x 150 mm cylinders and 2 sets of 3 steel studs each were attached at 120° angles. During testing three linear variable displacement transducers (LVDTs) were used to capture the deformation of the specimen at 20°C. Figure 3.5 shows a typical testing setup for the AMPT. A continuous uniaxial sinusoidal compressive stress was applied to the unconfined specimen at various test frequencies ranging from 0.1 Hz to 25 Hz. This range was chosen in order to simulate both the dominant ground vibration for the ballastless track or comparable testing procedure for flexible pavement design (Zhai *et al.* 2010, Bennert and Williams 2009). The applied stress and the strain response of the specimen were measured and used to calculate the dynamic modulus |E*| using Equation (2):

$$\left|E^*\right| = \frac{\sigma_0}{\varepsilon_0} \tag{2}$$

where, σ_0 and ε_0 = magnitudes of applied loading stress and induced axial strain, respectively.

The damping ratio is the parameter for characterizing the energy dissipation capacity of the CEAM. The damping ratio was calculated using the phase angle determined from the AMPT test and Equation (3):

$$\zeta = \frac{1}{2}\tan\delta \tag{3}$$

where, ζ = damping ratio; and δ = phase angle.

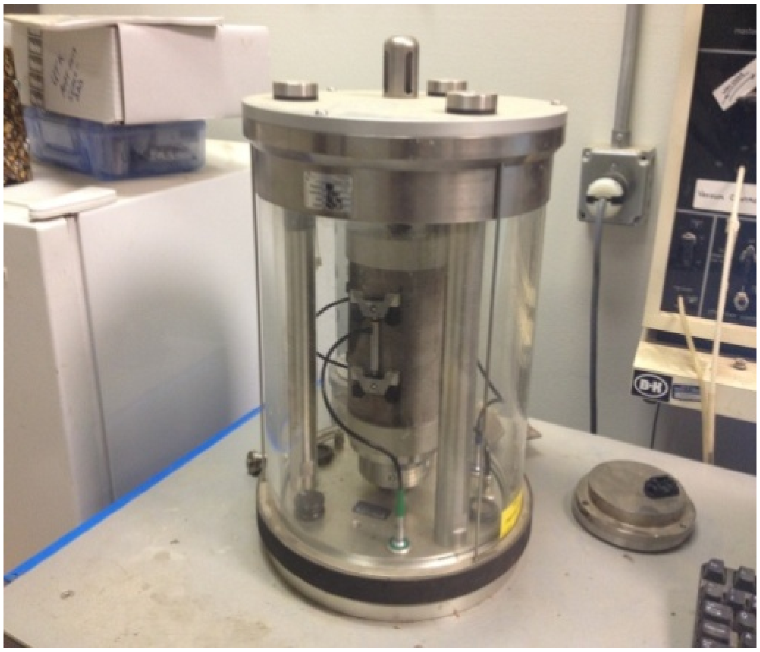


Figure 3.5 AMPT test setup for 100mm x 150mm cylinder samples.

3.7 Results and Discussion

3.7.1 UCS Results

Figures 3.6 and 3.7 show the UCS results for both type I and type II samples after 3, 7, and 28 days. As observed in a previous study performed by the authors, there was a significant reduction in strength development coinciding with the increase of asphalt binder. This is due to the asphalt binder having a retarding effect on the hydration of the cement particles and can be seen in both cationic and anionic samples (Rutherford *et al.* 2014). The loss of strength is greatest in type II samples where cement hydration contributes the largest amount to strength. As more asphalt binder is added to the mix design the reduction in strength begins to decay due to the asphalt bonding to the cement and aggregates. With the exception of the 1.16 B/C ratio specimens, which contained the largest amount of asphalt binder, cationic testing results proved to yield a higher strength for each B/C ratio for both type I and type II samples. Pouliot *et al.* (2003) studied the effects of strength development between SS-1 and CSS-1 emulsions and found similar results regarding the performance of cationic emulsions over anionic. They concluded that the interaction between the cationic emulsion and aggregates formed a tighter bond than with anionic emulsion. The positively charged cationic emulsion and negatively charged cement and sand aided in the breaking of the emulsion, whereas the anionic emulsion prolonged breaking.

The findings of the workability test demonstrated the effects of emulsion breakage time on performance. For each B/C ratio the cationic and anionic batches had comparable mix designs, however because the water/cement (W/C) ratio changed between the type I and type II samples there was an increase in workability between 0.57 and 0.73 B/C. The results in Table 3.2 show that the anionic emulsion mixtures had better workability for each B/C ratio. Based on these results it can be concluded that anionic emulsion is typically best suited for type II mix designs where strength development can afford to be reduced in order to produce better workability and a more uniform mixture (Wang and Liu 2012). It should be noted that the particle charge of both the cement and aggregates are important in determining which type of emulsion is best suited for strength development.

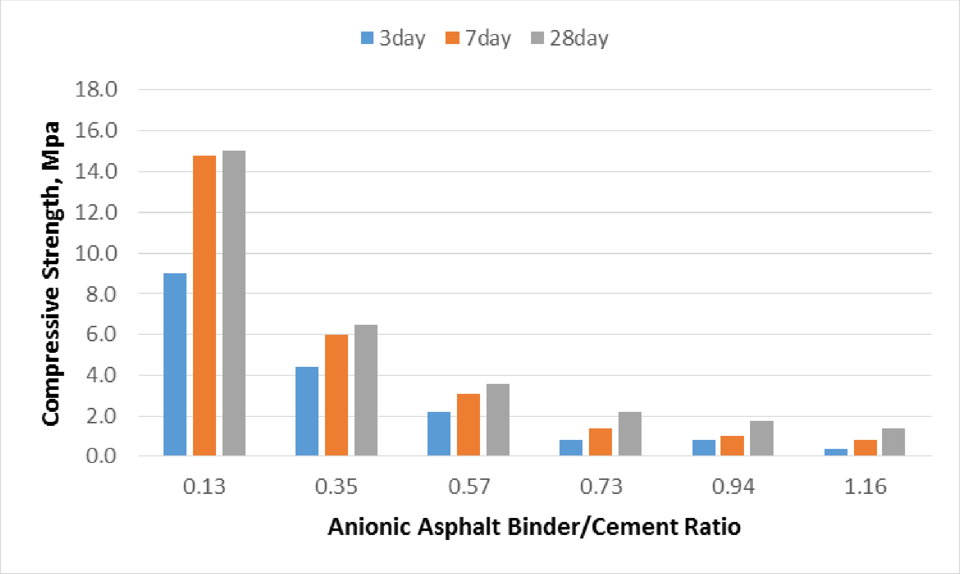


Figure 3.6 Anionic compressive strength results.

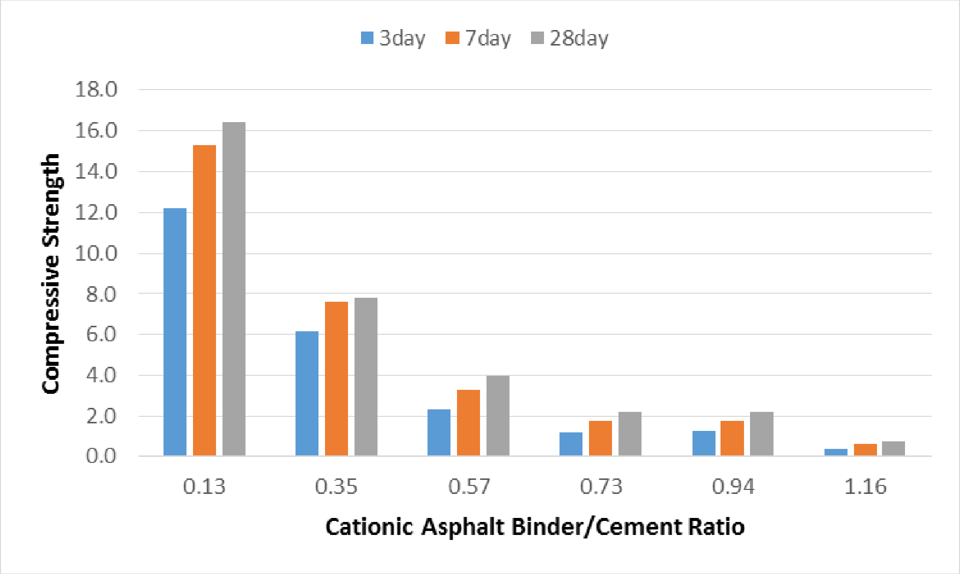


Figure 3.7 Cationic compressive strength results.

Table 3.2 Precent increase in diameter workability results.

B/C Ratio	**0.13**	**0.34**	**0.57**	**0.73**	**0.94**	**1.16**
Cationic **Emulsion**	137.5%	100%	6.25%	93.75%	56.25%	0%
Anionic **Emulsion**	150%	125%	12.5%	143.75%	125%	0%

3.7.2 IDT Strength Results

Figure 3.8 shows the results of the IDT testing for both moisture induced and non-conditioned samples. Based on the results from the compressive strength testing it is concluded that the difference in strength between 0.57 and 0.73 B/C ratios is due to the change in mix design where anionic emulsion was used for the type II and cationic emulsion for the type I. In each case the addition of asphalt binder reduced the IDT strength of the samples, with the reduction of strength greater in the type II samples than in type I. The reduction in IDT strength between 0.13 to 0.35 and 0.35 to 0.57 is upwards of 36% and 66% respectively. The total loss of strength between 0.13 and 0.57 is around 80%. In contrast the total strength loss between 0.73 and 1.16 was roughly 50%. Similar results are seen in the compressive strength testing as type I mortar benefits more from the asphalt binder than cement hydration.

Moisture conditioning results proved inconclusive as the samples seemed to be unaffected after 1000 cycles. It is concluded that the additional strength of the concrete mixed with the resilience of asphalt binder produced a moisture resistance material. Further moisture conditioning and durability testing is recommended in order to fully assess the durability properties of this material.

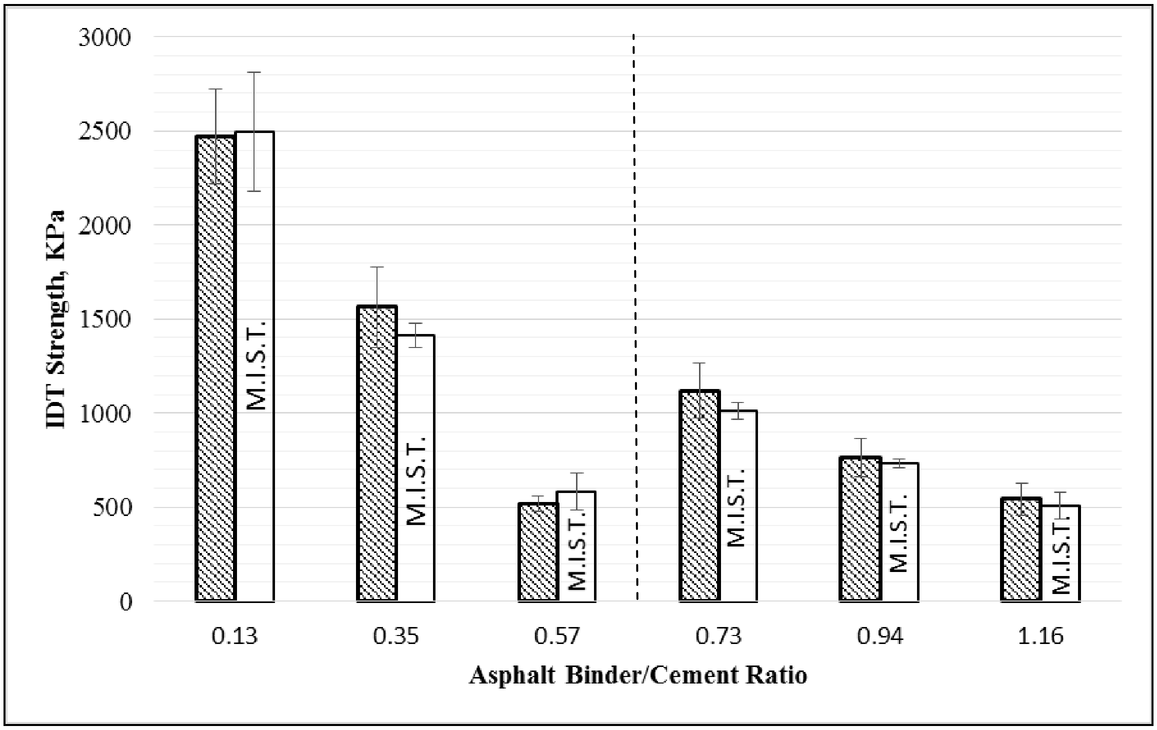


Figure 3.8 IDT testing results.

3.7.3 Dynamic Modulus and Damping Ratio Results

The results of the dynamic modulus testing can be seen in Figure 3.9. Both type I and type II CEAM showed typical loading rate dependent viscoelastic properties. The dynamic modulus of each material increased with the increase in loading frequency. As seen in the UCS and IDT tests, the high modulus of elasticity type II CEAM experienced a greater reduction in performance as the increase in B/C significantly reduced the stiffness of the material. In addition the 0.57 B/C samples proved to have a lower E* than both the type I 0.73 and 0.94 samples. For typical slab track design that uses the Chinese specifications for emulsion types, the use of anionic emulsion for type II and cationic for type I may create overlapping performance characteristics.

In addition to the dynamic modulus the phase angle for each sample was measure using the AMPT. For a perfectly elastic material, the applied cyclic stress is always in phase with the resulting strain, resulting in a zero phase angle. For a purely viscous material, the strain always lags the stress by 90°. The ordinary viscoelastic materials have a phase angle between 0 and 90°. Although low, both types of CEAM demonstrated viscoelastic properties seen in Figure 3.10. The phase angles were averaged and a damping ratio was calculated. Table 3.3 compares the averaged damping ratios with the B/C ratios and emulsion types used for the mix. The use of different emulsions for type I and type II demonstrates the versatility of the material. Higher B/C type II and lower B/C type I can demonstrate comparable damping ratios but with varying stiffness and compressive strengths.

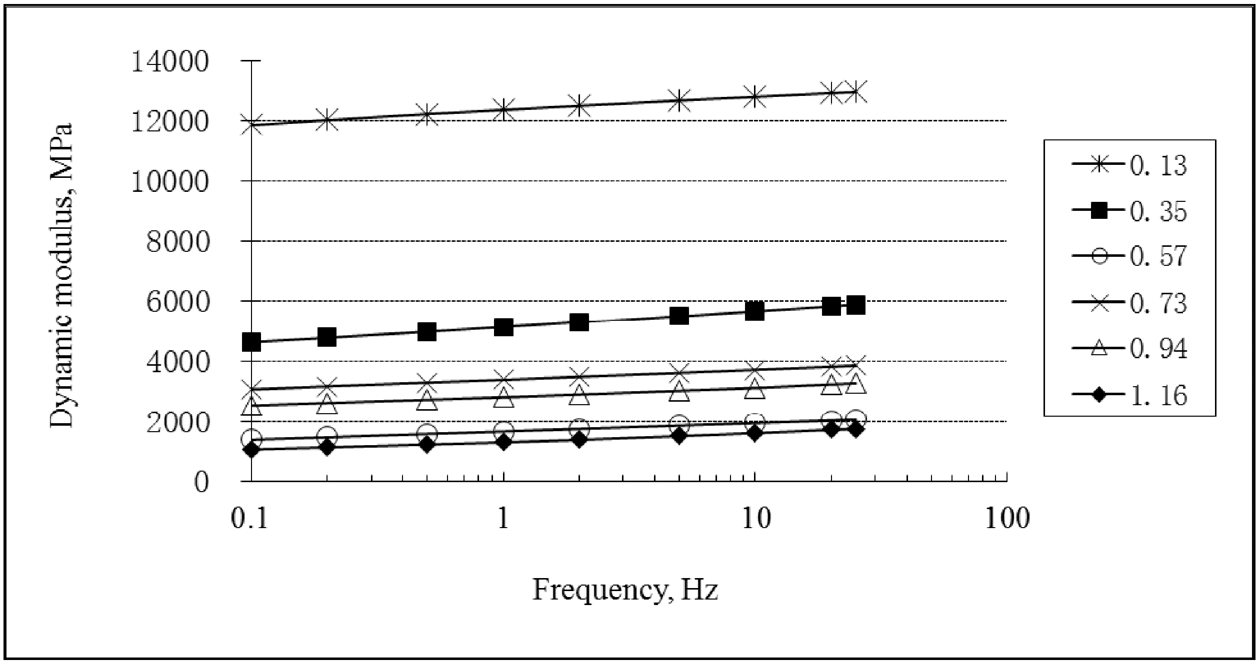


Figure 3.9 Dynamic Modulus testing results.

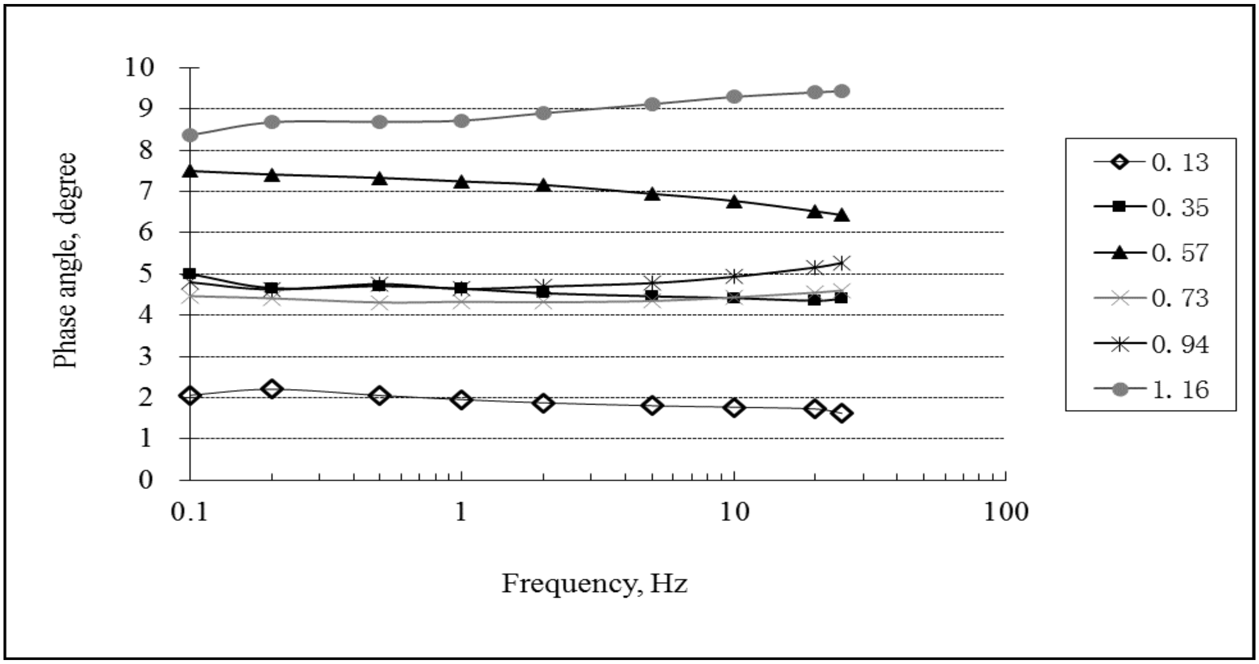


Figure 3.10 Phase angle testing results.

Table 3.3 Calculated average damping ratios.

B/C Ratio	0.13	0.35	0.57	0.73	0.94	1.16
Emulsion Type	Anionic	Anionic	Anionic	Cationic	Cationic	Cationic
Average Damping Ratio	1.7%	4.0%	6.2%	3.9%	4.2%	7.9%

3.7.4 SEM Observations

CEAM functions using two separate binders to develop its strength and viscoelastic properties. SEM pictures of hardened CEAM were taken after 28days of curing to examine the interaction between the portland cement and asphalt binder. The strength of hardened portland cement paste depends in part on the ability of the calcium silicate hydrates (C-S-H) to effectively bind other products of hydration, such as ettringite, and aggregates (Richardson 1999). C-S-H is the main binding component in all portland cement-based materials and reduction of this development can critically hinder strength development. In CEAM, an asphalt film coats the cement particles and hydration products, and hydration products pierce the asphalt film (Du 2013). Figure 3.11 shows typical development of C-S-H and ettringite within an asphalt mastic. However, as seen in Figure 3.12 and 3.13 the higher asphalt binder content of type I CEAM begins to prevent hydration products from piercing the asphalt mastic. This indicates that while cement hydration may still occur within the asphalt mastic, higher B/C ratios reduce the ability for the cement to hydrate and function. For type II CEAM the hydration products of cement make contribution to the elasticity of CA mortar while the asphalt, attaching on the surface of hydration products of cement, makes contribution to the viscosity of CA mortar (Wang *et al.* 2011). For type I CEAM the large amounts of asphalt reduce the amount of hydration products and reduce strength development from the portland cement.

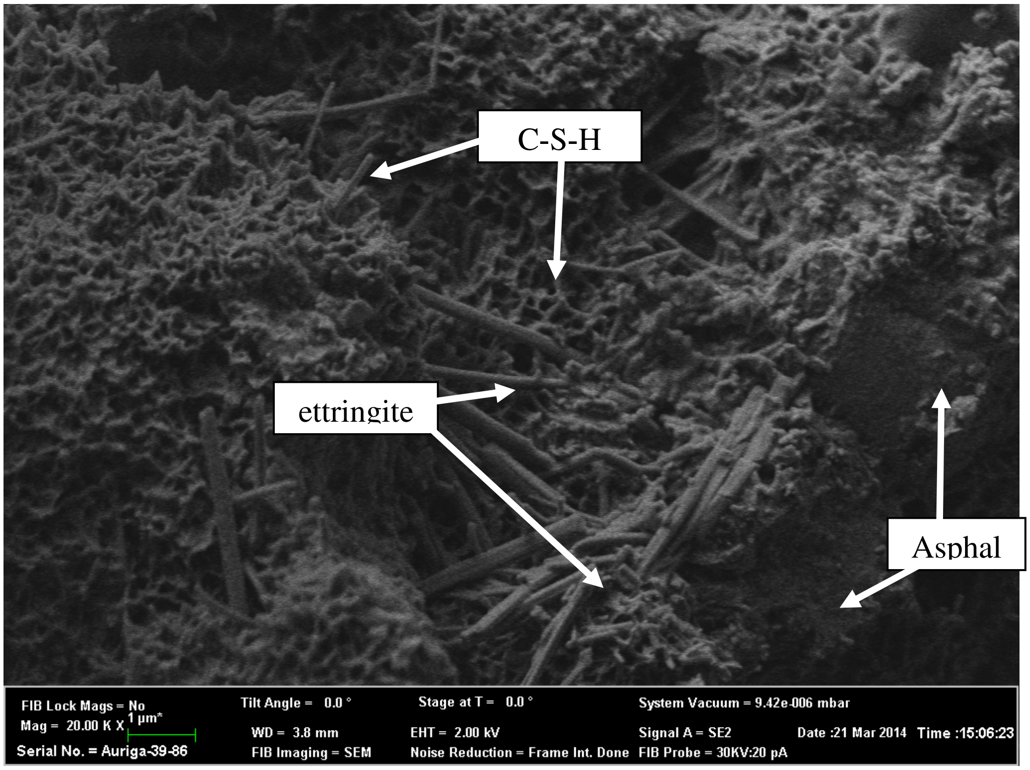


Figure 3.11 SEM pictures of 0.57 B/C ratio CEAM.

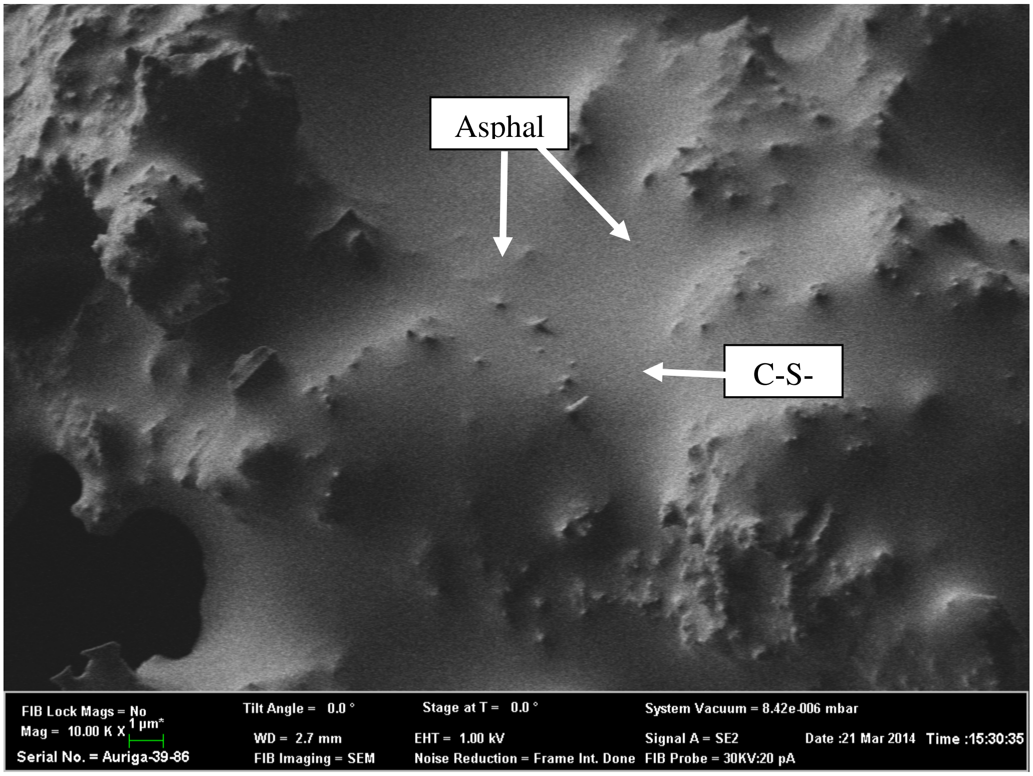


Figure 3.12 SEM pictures of 0.73 B/C ratio CEAM.

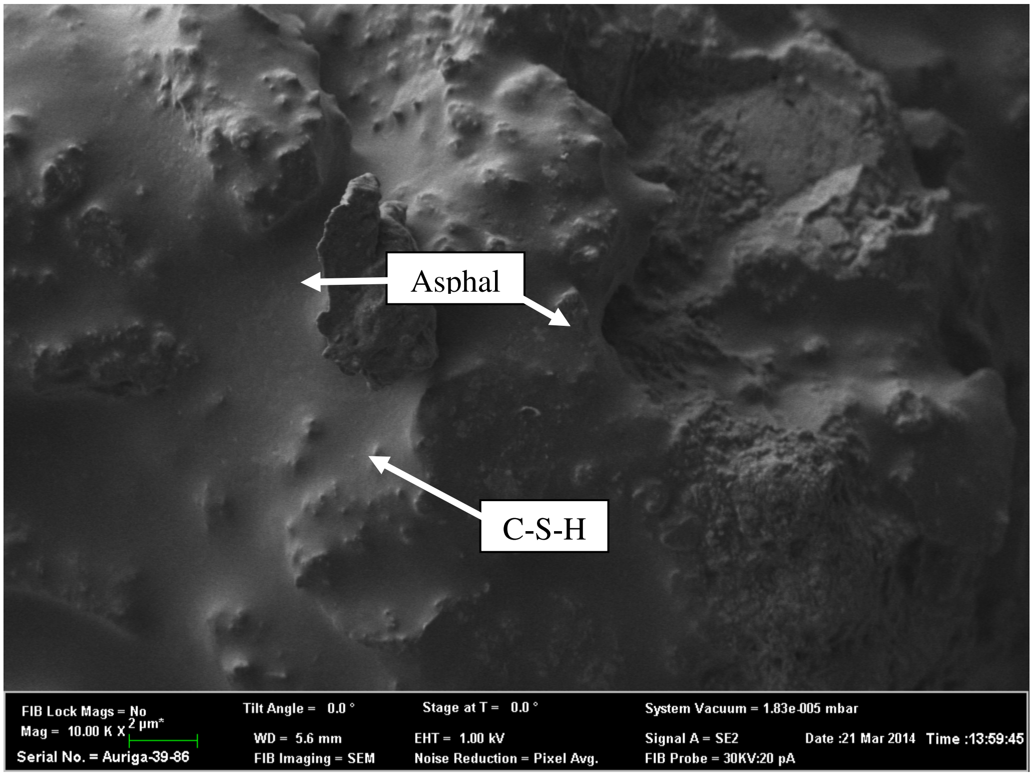


Figure 3.13 SEM pictures of 0.94 B/C ratio CEAM.

3.8 Summary and Conclusions

A laboratory study was conducted to investigate the mechanical and viscoelastic properties of low and high modulus of elasticity of hardened CEAM. The UCS, IDT strength, dynamic modulus and damping ratios were tested for the hardened CEAM at different B/C ratios. Based on the results from the study, the following conclusions can be obtained:

- Both types of hardened CEAM exhibited the properties of a hybrid material, combining the high strength of portland cement mortar and the energy dissipation capability of asphalt.
- The increase of asphalt binder had a negative effect on the UCS, IDT strength, and E* of the material while having a positive effect on the viscoelastic damping properties.
- The use of cationic emulsion provides greater compressive strength for both type I and type II CEAM at the cost of workability due to the breaking rate of the emulsion and the tighter bond formed by the binder.
- Type I hardened CEAM using cationic emulsion proved to have more viscoelastic properties at the highest B/C ratios than type II while being a softer material and having a lower E*
- Type II hardened CEAM using anionic emulsion proved to be a stiffer, stronger material at lower B/C ratios type I.
- IDT samples were unaffected by 1000 cycles of moisture induced stress testing. Further studies into the durability may require alternate testing methods or longer testing cycles in order to properly test the properties of the material.
- By using anionic emulsion for type II construction and cationic for type I, overlapping of certain viscoelastic and mechanical properties can be seen showing the versatility of hardened CEAM as a construction building material.

3.9 Acknowledgements

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CHAPTER IV
CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Two laboratory studies were conducted to investigate the properties of CEAM. In the first round of testing the UCS, IDT strength, dynamic and phase angle, shrinkage, and cement hydration heat were tested for the CEAM with different levels of asphalt binder. The second round of testing built on the results of the previous work and investigated the mechanical and viscoelastic properties of both types, low and high modulus of elasticity, samples of hardened CEAM. The UCS, IDT strength, dynamic modulus and damping ratios were tested for the hardened CEAM at different B/C ratios. Based on the results from the studies, the following conclusions can be obtained:

1. CEAM exhibited the properties of a hybrid material, combining the high strength of portland cement mortar and the energy dissipation capability of asphalt.
2. The B/C ratio showed a significant effect on the mechanical properties of CEAM. As the B/C ratio increased, the UCS, IDT strength, TSR, and dynamic modulus of CEAM decreased and the shrinkage increased.
3. Asphalt had a significant retarding effect on the cement hydration of CEAM. With the increase in binder, the retarding effect became more significant. The reduction in strength and stiffness could be attributed to the retarding effect of asphalt.
4. The damping characteristics of CEAM were improved by the addition of asphalt. The damping ratio of CEAM was much lower than asphalt binder and

mixture, but greater than ordinary portland cement composites. Both asphalt binder content and temperature proved to be vital to determining the damping properties. The reduced damping properties of CEAM were attributed to the fact that asphalt component was constrained by stronger portland cement paste.

5. The cement in low B/C CEAM could hydrate in much the same manner as it does in normal cementitious composites, stiffening CEAM and improving its mechanical properties. The increase in B/C prevented formation of more cement hydration products.
6. The use of cationic emulsion provides greater compressive strength for both type I and type II CEAM at the cost of workability due to the breaking rate of the emulsion and the tighter bond formed by the binder.
7. Type I hardened CEAM using cationic emulsion proved to have more viscoelastic properties at the highest B/C ratios than type II while being a softer material and having a lower E*.
8. Type II hardened CEAM using anionic emulsion proved to be a stiffer, stronger material at lower B/C ratios type I.
9. After adjusting the mix design for the second round of testing the IDT samples were unaffected by 1000 cycles of moisture induced stress testing. Further studies into the durability may require alternate testing methods or longer testing cycles in order to properly test the properties of the material.

10. By using anionic emulsion for type II construction and cationic for type I, overlapping of certain viscoelastic and mechanical properties can be seen showing the versatility of hardened CEAM as a construction building material.

4.2 Recommendations

The work presented in this study investigates the mechanical and viscoelastic properties of two types of CEAM. However, many variables had to be removed in order to accurately observe the interactions between the B/C ratio and performance. On the basis of the research presented herein, some considerations for future work are recommended as follows:

1. Alternative mixing methods have recently made publication. The use and method of mixing the binders and aggregates was noted to be crucial to the overall performance of the specimen and were kept constant to compare results between papers. Further research into mixing method and equipment may produce better preforming mortars.
2. The use of a comparable anionic and cationic emulsion were utilized in order to show the effect of particle charge on the material. However, there are several types of emulsions with various breaking speeds that could impact results. Considerations of other types of emulsions may provide altered results.

3. Durability testing was briefly covered with the moisture-induced stress testing and shrinkage. Further study into the freeze-thaw performance, fatigue, higher and lower temperature susceptibility, and other various testing methods will prove useful in exploring other uses of CEAM.

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VITA

Tyler Everette Rutherford was born in 1988 in Knoxville, Tennessee. He began his academic studies at the University of Tennessee in Knoxville, Tennessee in 2008 where he attained his Bachelors of Science in Civil and Environmental Engineering in 2012. During his final year as an undergraduate student he began work as an undergraduate research assistant under Dr. Baoshan Huang. During this time he expanded his knowledge of asphalt and concrete pavement testing techniques. After completing his undergraduate work, he began to pursue his Masters of Science in Civil Engineering at the University of Tennessee in Knoxville under the guidance of Dr. Baoshan Huang. He will attain his Masters of Science in Civil Engineering with a focus in Geotechnical and Materials Engineering in December of 2014.