

Laboratory Evaluation of Heat Exchange Between Superheated Virgin Aggregate and Reclaimed Asphalt Pavement Material

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
August 7, 2021

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ABSTRACT

The most common method of Reclaimed Asphalt Pavement (RAP) material processing in the production of Hot Mix Asphalt (HMA) in the United States is by using cold feed recycling. Superheating the virgin aggregates by hot gas to elevated temperatures above discharge temperature depends on the RAP content, RAP moisture content, and target discharge temperature. The superheated virgin aggregate is mixed with cold-wet RAP material in the dry mixing zone during HMA production. Drying and heating of the RAP material occur through heat transfer between virgin aggregate and RAP material before adding hot virgin binder. There are existing recommendations for superheated temperatures required for virgin aggregate in Asphalt Institute MS-20, National Asphalt Pavement Association IS-71, and ASTEC T-127. However, no research studies were found that validated these recommendations either in the field or in a controlled laboratory environment. Several research studies emphasize the importance of the thermal process during the dry blending stage. However, limited research has been conducted to understand the heat transfer process between superheated virgin aggregate and RAP. A better understanding of the heat transfer between virgin aggregate and RAP would be helpful in producing high-quality asphalt mixtures.

The primary objective of this study was to characterize and investigate the heat transfer between virgin aggregate and RAP material as it relates to variations in RAP content, RAP moisture content, virgin aggregate gradation, RAP gradation, and virgin aggregate thermal properties. Another objective of the study was to validate current recommendations for superheated virgin aggregate temperatures needed. A heat transfer testing protocol was developed in this study for the laboratory evaluation of heat transfer. A laboratory blending chamber with minimal heat losses was fabricated to have a uniform and continuous mixing of virgin aggregate

and RAP particles inside the chamber. An infrared camera was selected that is capable of measuring a representative sample size of the mixture in the chamber. Analysis methodologies to determine the time required for heat transfer completion and heat conductance between virgin aggregate and RAP were developed as part of the study. Discrete Element Model (DEM) simulation results were used to validate the assumptions made as part of the new test method.

On all combinations of the experimental design, heat transfer between virgin aggregate and RAP was measured. For each of these combinations, heat transport parameters (T_{equi} and H_C) developed as part of the study were determined. The developed test method was able to produce repeatable results with three replicates. Discharge temperatures obtained from experimental results were utilized to verify the existing superheated temperature recommendations. The existing equation was overestimating the superheated temperatures required; a modified equation is recommended. The time required for thermal equilibrium is affected by RAP size; T_{equi} was determined to be 45 sec for 10% dry, fine RAP compared to 116 sec for 10% dry, coarse RAP. The time required for thermal equilibrium was observed to take up to 5.0 times for mixtures with high RAP and moisture content (40% RAP and 5% moisture) compared to 10% dry RAP mixtures. Analysis of variance (ANOVA) test results showed that RAP content, RAP size, RAP moisture, virgin aggregate size, and virgin aggregate source affect heat transfer between virgin aggregate and RAP.

A hypothesis was tested to check whether preheating RAP before adding to virgin aggregate would reduce the time required for thermal equilibrium or not. Based on the results, preheating RAP would help in asphalt mixtures to attain thermal equilibrium quickly compared to the cold feed recycling method. Preheat RAP temperatures for different RAP contents, and RAP moisture contents are recommended. Heat energy consumption analysis shows that both cold and warm feed

methods of recycling would consume nearly the same amount of heat energy to process RAP during production.

The outcomes of the study, including a new test protocol for heat transfer characterization, analysis frameworks to calculate heat transfer parameters, the modified equation for superheated temperature determination, and recommended RAP preheat temperatures, are expected to be useful tools for HMA production and future research on this topic.

ACKNOWLEDGMENT

I would like to thank my major professor and committee chair, Dr. Fabricio Leiva-Villacorta, for his continuous guidance and motivation towards my dissertation work. I am grateful for the opportunity to achieve my doctoral degree under his supervision. I would like to express my sincere gratitude for the opportunity Dr. Michael Heitzman provided me to start my doctoral studies at the National Center for Asphalt Technology. I want to thank him for his continuous advice, guidance, and mentorship all these years. Further, I would like to thank my committee, Dr. Thomas Burch, Dr. Benjamin F. Bowers, and Dr. Adriana Vargas Nordbeck, for their time in reviewing my dissertation and contributing towards the completion of my Ph.D. program at Auburn University. I want to thank Dr. April Simons for serving as the university reader.

I would like to thank ASTEC industries for sponsoring this project and Andrew Hobbs for his support towards completing the study. Andrew's knowledge of DEM simulation and heat transfer helped me in better shaping the dissertation and to answer some critical questions throughout the study.

This work would not be possible without the support of my colleagues at NCAT. Specifically, I would like to recognize Matt Sasser, Jason Moore, and Vickie Adams for their guidance and support during my time in the laboratory at NCAT. I want to thank my graduate friends at NCAT: David Allain, Danny Martinez, Towhid Rahman, Mostafa Nakhaei, Farhang Jalali, Mawazo Fortunatas, Anurag Anand, David Vivanco, Anthony Bernes, and Josue Garita for their support and friendship all these years.

Next, I want to thank Dr. Kusam Sudhakar Reddy, Dr. Vishnu Radhakrishnan, and Dr. Bharath Gottumukkala at the Indian Institute of Technology, Kharagpur, for their mentorship and motivation to pursue a Ph.D. and for believing in my research abilities all these years.

Finally, I would like to thank my parents: Venkatrao and Manga Tayararu Gatiganti, my sister and brother-in-law: Ramalinga Swamy and Adhi Lakshmi Arumilli, for shaping my life. I want to thank my girlfriend for being on my side at the crucial time of my life.

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CHAPTER 1 INTRODUCTION

1.1 Background and Problem Statement

Reclaimed Asphalt Pavement (RAP) material contains good quality aggregates, aged asphalt binder, and is widely used as a recycling material in asphalt concrete production because of its economic and environmental benefits (Copeland, 2011; Kandhal and Mallick, 1997; Horvath, 2003; Aurangzeb, 2014). The average percentage of RAP used in Hot Mix Asphalt (HMA) increased from 15.6 percent in 2009 to 21.1 percent in 2018 in the United States, with a total of 82.2 million tons produced (Williams et al., 2019). Figure 1.1 shows the average percentage of RAP used in HMA in 2018 in the United States.

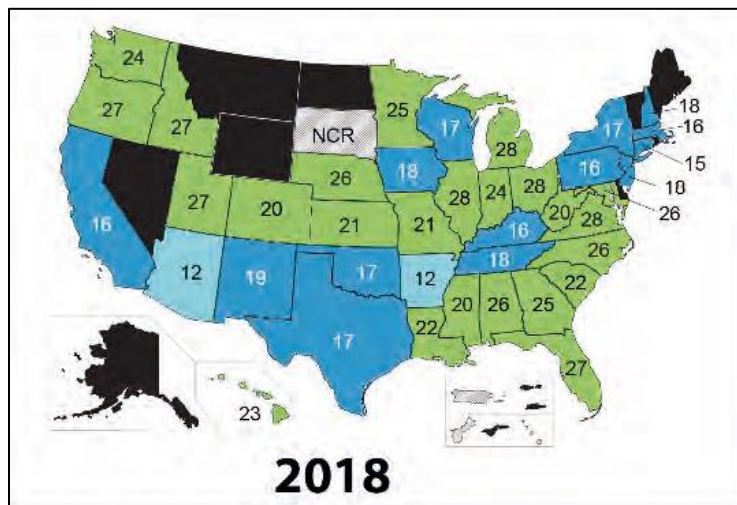


Figure 1.1: Average percentage of RAP used by states in HMA in 2018 (Williams et al., 2019).

The most common method of RAP processing in the production of HMA in the United States is by using cold feed recycling (Liu et al., 2017; Zhang et al., 2019). Production of asphalt concrete (AC) mixtures with RAP involves superheating the virgin aggregates by hot gas to elevated temperatures above the discharge temperature before the RAP is introduced in the mixing process. The recommended superheated temperatures depend on the RAP content, RAP moisture content, and target discharge temperature (NAPA IS-71, 1985; MS-20, 1981; Brock and

Richmond, 2007). Then, the superheated virgin aggregate is mixed with wet, cold RAP material in the blending chamber (continuous drum plant) or pug mill (batch plant), or outer drum (double barrel drum plant) to dry and heat the RAP material through heat transfer between virgin aggregate and RAP material before adding hot virgin asphalt.

Asphalt Institute's MS-20 (1981) and National Asphalt Pavement Association's IS-71 (1985) reported virgin aggregate temperatures required to dry and heat RAP material in a batch mix plant for various RAP moisture contents and RAP percentages. However, no published documentation or details are available about the method and the assumptions made in the analysis to establish the reported values. A similar table for required virgin aggregate temperatures in a batch plant was proposed by ASTEC Industries (Brock and Richmond, 2007) using an empirical formula (Equation 1.1) developed in France by Baroux (1980). This equation is based on two assumptions: 1) energy from the superheated virgin aggregate will be absorbed only by the RAP material and RAP moisture, and 2) the specific heat capacity of both virgin aggregate and RAP are equal (Baroux, 1980). These tables are currently being used in the industry to select virgin aggregate temperatures for a given AC mixture with RAP based on the target mixture discharge temperature, RAP content, and RAP moisture content. However, no research studies have validated these tables either in the field or in a controlled laboratory environment.

$$T_{v.a.} = \frac{T_{RHMA} - S_{RAP} \cdot T_{RAP}}{1 - S_{RAP}} + \frac{4 \cdot S_{RAP} \cdot W_{RAP}}{1 - S_{RAP}} (637 - T_{RAP}) \quad (1.1)$$

Where,

- $T_{v.a.}$ = Superheated temperature of virgin aggregates used for the test, °C
- T_{RHMA} = Required temperature of recycled hot mix asphalt, °C
- S_{RAP} = Percentage of RAP by weight of dry mixture (without virgin binder), as a decimal
- T_{RAP} = Initial temperature of RAP, °C
- W_{RAP} = Percentage of Moisture by weight of dry RAP, as a decimal

During the mechanical mixing stage (dry and wet), it is expected that the superheated virgin aggregate will transfer heat to the RAP material. The heat transfer process is responsible to heat the RAP material and activate the RAP binder (Zhang et al., 2015; Pérez Madrigal et al., 2017), and break lumps of RAP into fine particles to form a homogeneous asphalt mixture (DeDene et al., 2014; Nyugen, 2013; Johnson et al., 2013; Sivilevičius et al., 2017). However, insufficient heat transfer will result in several problems in the final mixture, including inadequate heating of RAP material and moisture in the final asphalt mixture. Additionally, spraying virgin asphalt onto superheated virgin aggregate at relatively higher temperatures can result in unwanted aging of the virgin asphalt.

When high RAP contents are used in a cold feed recycling method, extended mixing times are recommended to allow drying and heating of RAP (Brock and Richmond, 2007; Zaumanis and Mallick 2015). Further, higher superheated temperatures will also be used during production. The difference in superheated temperatures between a low RAP mixture and a high RAP mixture may or may not allow complete heat transfer with the same amount of mixing time.

Zhang (2016) investigated the heat transfer between virgin aggregate and RAP using coupled CFD-DEM modeling. As part of the study, the effect of RAP content and RAP moisture on optimum mixing time needed were studied. The major limitation of the study is the definition used for optimum dry mixing time for an asphalt mixture. The optimum mixing times are determined based on the target average temperature of the mixture. However, both virgin aggregate and RAP particles could be at very distinct temperatures at the target average temperature. Therefore, a more accurate characterization of heat transfer between superheated virgin aggregate and RAP is required. Also, quantification of the effect of mixture composition (RAP content, RAP size, and RAP moisture content) and material properties (aggregate thermal properties) on the heat transfer

process will assist asphalt producers in altering plant production parameters such as mixing time, for different mixtures to ensure sufficient heat transfer. This would, in turn, allow to produce high-quality mixtures. The objectives of this study were based on this background and the unaddressed issues.

1.2 Objectives

The primary objective of this study is to characterize and investigate the heat transfer between virgin aggregate and RAP material in terms of final discharge temperature and time required for heat transfer completion, as it relates to variations in RAP content, RAP moisture content, virgin aggregate gradation, RAP gradation, and virgin aggregate thermal properties. Another objective of the study is to validate existing recommendations for superheated virgin aggregate temperatures.

1.3 Scope of the Work

A laboratory blending chamber, insulated to minimize heat loss, was designed and fabricated to continuously mix both virgin aggregate and RAP to achieve the proposed research objectives. In addition, the temperature of the mixture was recorded using a measuring system capable of monitoring the temperatures of both virgin aggregate and RAP over the mixing time.

A consistent laboratory testing procedure was established to study the effect of mixture composition and material thermal properties on the heat transfer process. Testing was conducted at: (1) four RAP contents (10%, 20%, 30%, and 40%), (2) four RAP moisture contents (0%, 1%, 3%, and 5%), (3) four RAP sizes, (4) four virgin aggregate sizes, (5) four virgin aggregate sources, and (6) three superheated temperatures for every mixture combination. Heat transfer testing was conducted at three different temperatures for a given mixture combination to validate superheated temperature tables. The final mixture discharge temperature yielded by each superheated temperature was used to establish a relationship between superheated temperature and discharge temperature for different material combinations and determine the superheated temperature

required for a target discharge temperature of 300°F by either interpolation or extrapolation. The determined superheated temperatures required from the study were then used to validate the existing recommendations.

This study is a fundamental evaluation of heat transfer through heat conduction between virgin aggregate and RAP in a laboratory setting. This study does not account for hot gases and high wall temperatures present in an asphalt plant.

1.4 Organization of the Dissertation

The dissertation is organized into six chapters as follows:

Chapter 1: Introduction Introduces the increased use of RAP in asphalt mixtures, current methods of processing RAP in asphalt production. Then, it explains the existing methods available for asphalt producers to determine the superheated temperatures needed for producing asphalt mixtures that target discharge temperature and discusses the need for experimental validation of the existing methods. Next, this chapter reviews the importance of understanding heat transfer between virgin aggregate and RAP when RAP is processed using the cold feed recycling method. Finally, based on the problem statement established, the objectives and scope of the dissertation work are discussed in detail.

Chapter 2: Literature Review Presents background on existing technologies for asphalt mixtures with RAP production and methods of determining superheated temperatures required. Also, it presents research studies conducted on the effect of the thermal process between virgin aggregate and RAP on the performance of asphalt mixtures. At last, it discusses studies that investigated cold feed recycling heat transfer.

Chapter 3: Development of Heat Transfer Test Protocol Discusses the development of a new test method for investigating heat transfer between virgin aggregate and RAP in the laboratory. This chapter also discusses new calculation methods developed as part of the study to determine heat

transfer parameters based on the data obtained from the new test protocol. DEM simulations were used to validate primary assumptions made during the test method development.

Chapter 4: Laboratory Investigation of Heat Transfer Provides heat transfer test results tested as part of the experimental design. This chapter also presents a validation analysis of existing superheated temperature recommendations using the experimental results of the study. It also discusses the effect of mixture variables on heat transfer between virgin aggregate and RAP.

Chapter 5: Concept of Preheating Reclaimed Asphalt Pavement during HMA Production Presents results of analytical procedure used to understand the benefits of preheating RAP in attaining thermal equilibrium quickly for high RAP mixtures. This chapter also presents a comparative analysis of the energy required to produce asphalt mixtures with conventional cold feed recycling and warm feed recycling.

Chapter 6: Conclusions and Recommendations Summarizes the conclusions and recommendations obtained from the laboratory study and further research needed on the topic.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The key findings of the literature review are documented in this chapter. In the following sections, studies based on the usage of RAP are discussed, followed by conventional methods of processing RAP in the plant production asphalt mixtures. Next, studies that revealed the importance of the thermal process between aggregate and RAP on the performance of asphalt mixtures are presented. Previous studies on the laboratory investigation of heat transfer in asphalt mixtures and granular materials are reviewed and presented. Finally, available RAP heating technologies for plant production of asphalt mixtures are presented in this chapter.

2.2 RAP Usage in Asphalt Mixture Production

Overall, there is a growing interest in the pavement community to increase the usage of RAP in HMA production. Figure 2.1 shows the average percentage of RAP use from the results of the annual survey conducted by NAPA in 2009 and 2018. The average percentage of RAP used in HMA production nationwide increased from 15.6 percent in 2009 to 21.1 percent, with a total of 82.2 million tons of RAP in 2018 (Williams et al., 2019).

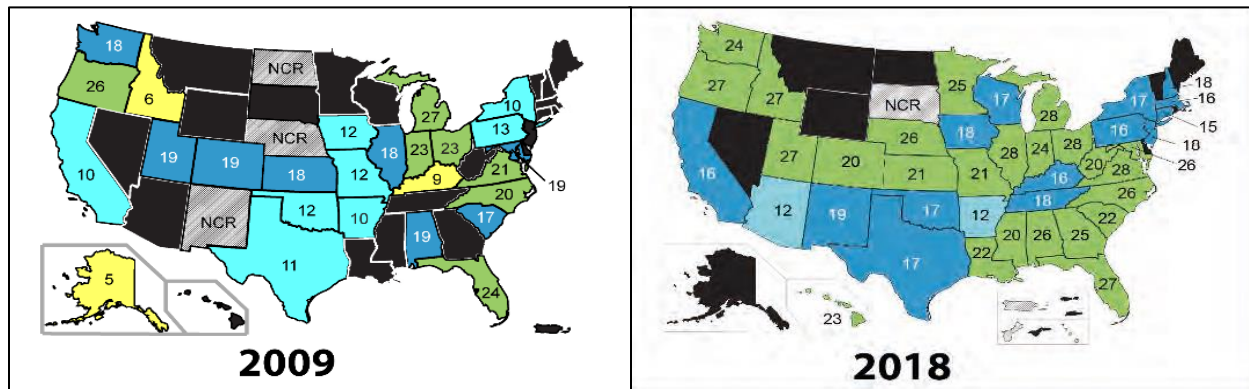


Figure 2.1: Average percentage of RAP used by states in AC from 2009 to 2018 (Williams et al., 2019): NCR=no companies responded and black=less than three companies responded.

2.3 Processing of RAP During the Plant Production of HMA

Direct heating of RAP using the burner flame will result in hydrocarbon emission from the RAP material, known as the blue smoke effect, and burn off RAP binder. Cold feed recycling is the most commonly used method of drying and heating RAP material in a hot mix asphalt plant (Kandhal and Mallick, 1997; NAPA IS-123, 1996). In the cold feed recycling method, wet RAP at an ambient temperature is mixed with superheated virgin aggregate in a dry blending chamber to heat the RAP material. Various types and configurations of mixing plants have been introduced and are being used to produce recycled mixtures with high amounts of RAP with reduced plant emissions. These plants can be broadly classified into two types: batch plants and drum plants.

In a batch mix plant, virgin aggregate is superheated in a drum dryer before screening and weighing. Then, the heated virgin aggregate is mixed with the cold-wet RAP in the pugmill. Thus, the primary heating source for RAP material is the superheated virgin aggregate temperature. Heat conduction between virgin aggregate and RAP is the key heat transfer mechanism responsible for heating and drying RAP material before adding virgin binder.

As shown in Figure 2.2, there are three primary ways in which RAP is introduced in the drum plant mixing process: (a) adding mixer after the drum mixer to mix RAP with superheated aggregates, (b) center entry in a parallel flow mixing drum (typically using a RAP collar), (c) center entry in a counter flow mixing drum at the back of the burner zone, and (d) adding the RAP into the outer shell of a double-barrel drum configuration. According to the Federal Highway Administration (FHWA), the most efficient system, the double-barrel drum mixer, allows for 90 seconds of mixing time in the external shell. By comparison, using a RAP collar provides significantly less mixing time, around 10–12 seconds (Kandhal and Mallick, 1997). Most of the existing hot-mix drum plants utilize the center entry with the RAP collar method to manufacture mixtures containing RAP, and available mixing times vary by plant configuration.

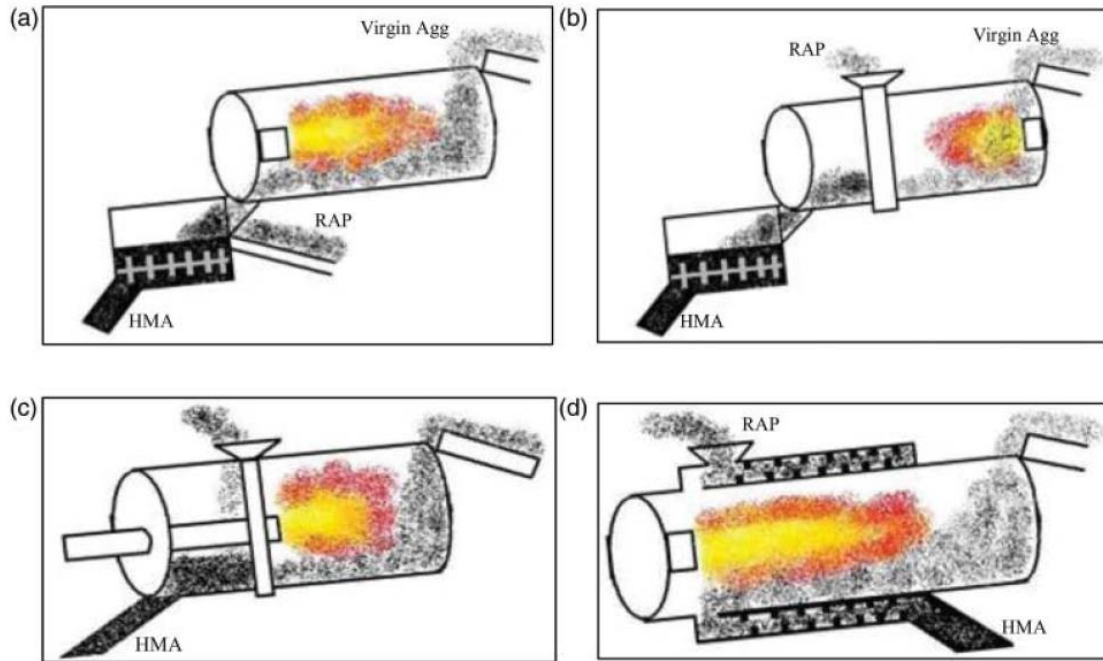


Figure 2.2: Different mixing drum configurations for use with RAP (Brock and Richmond, 2007): (a) Counterflow with no RAP collar. (b) Parallel flow with RAP collar. (c) Counterflow with RAP collar. (d) Double-Barrel drum mixer.

2.3.1 Existing Recommendations on Superheated Temperatures

Asphalt Institute's MS-20 (1981) and National Asphalt Pavement Association's IS-71 (1985) recommend virgin aggregate temperatures required to dry and heat RAP material in a batch mix plant. Required superheated virgin aggregate temperature is dependent on the RAP content, RAP moisture content, and target mixture discharge temperature of the asphalt mixture. Heat conduction from superheated virgin aggregate is considered the only heating source for RAP. No information was found on the methodology and background followed and the assumptions considered for this analysis.

ASTEC T-117 recommends the virgin aggregate temperatures required in a standard counterflow drum plant based on the RAP content, RAP moisture content, and the desired temperature of the final mixture (Brock and Richmond, 2007). An empirical equation (Equation 1.1) was used to produce these recommendations (Baroux, 1980). This equation was developed

using the thermal energy balance between virgin aggregate and RAP material, based on the assumption that heat conduction is the only heat source to dry and heat RAP material.

Both recommended tables considered heat conduction from superheated virgin aggregate as the only source to heat the RAP. Superheated temperatures recommended by NAPA and Asphalt Institute are higher for a given RAP content, RAP moisture content, and discharge temperature when compared to ASTEC recommendations. The difference is as low as 1°F for low RAP and moisture contents and as high as 90°F for high RAP and moisture contents, as shown in Figure 2.3. However, no research studies were found that validated these tables either in the field or in a controlled laboratory environment.

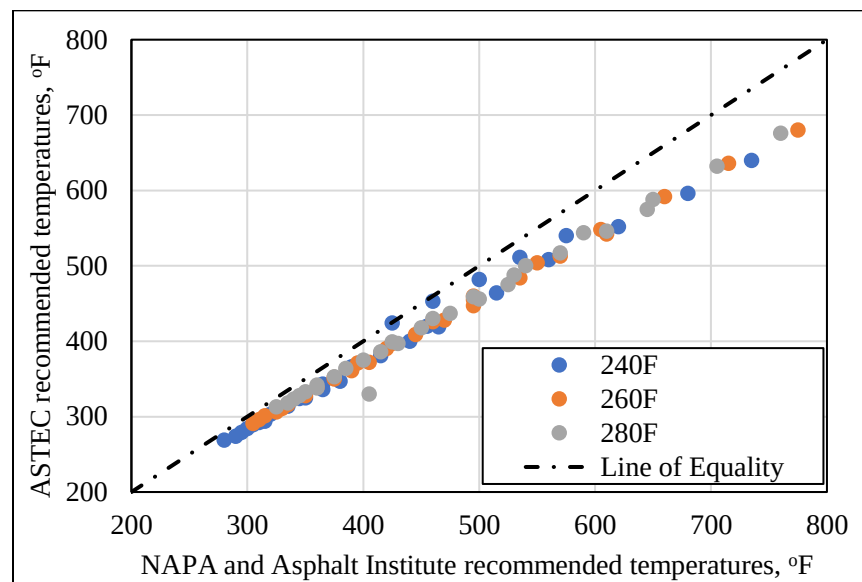


Figure 2.3: Comparison of NAPA and ASTEC recommended virgin aggregate temperatures.

2.4 Effect of Thermal Process on the Performance of HMA mixtures

Several studies based on the laboratory performance of HMA mixtures with RAP have noted the importance of understanding the thermal process in the dry mixing stage, especially RAP temperature and dry mixing time, in producing high-quality asphalt mixtures (Zhang et al., 2019).

Nguyen (2013) developed a study to understand the impact of dry mixing time on the homogeneity of AC produced with two different sizes of RAP (10 mm and 20 mm). Mixtures were prepared by mixing 40% RAP at ambient temperature with superheated virgin aggregate (215°C) at different dry mixing times (2, 4, 6, and 8 minutes) and at a constant wet mixing time of 2 minutes. Mixed AC was compacted into one slab specimen for each dry mixing time, and five samples were cored from the slab and tested for indirect tensile stiffness test (ITST) in four directions per cored sample. Variation in the 20 measured ITST values was used to evaluate the homogeneity of the AC. It was concluded that longer dry mixing times resulted in high average stiffness values with low variation between tested replicates for both sizes of RAP used. A decrease in stiffness variability was attributed to the breakage of RAP agglomerates and better dispersion in the AC at longer mixing times due to improved heat transfer. Increased stiffness with longer dry mixing time was attributed to better blending efficiency between RAP and virgin binders because of RAP binder activation.

Heneash (2013) prepared AC mixtures with 45% RAP using RAP at initial temperatures of 20, 40, and 80°C and dry mixing times of 2, 8, and 16 minutes. Virgin aggregates were heated to required superheated temperatures to yield constant discharge temperatures. Stiffness modulus of the asphalt concrete prepared at different initial RAP temperatures and dry mixing times were conducted, and concluded that stiffness of AC increased with an increase in RAP initial temperature and dry mixing time. Increased stiffness was attributed to better activation of RAP binder and breaking of RAP agglomerates in the asphalt mix, which results in increased blending efficiency and more homogeneous mixtures compared to mixtures produced at lower RAP temperatures and shorter mixing times.

Ma et al. (2016) conducted a series of triaxial tests on 100% RAP specimens compacted by preheating RAP at different preheating temperatures (60, 90, 100, 110, 120, 130, 140, 150, and 160°C) to understand the dispersion ability of RAP agglomerates. Triaxial test specimens were prepared by compacting RAP at the above-mentioned preheating temperatures, and cohesive strength and internal friction of compacted RAP specimens were determined. The cohesive strength of RAP was increased, and internal friction decreased with an increase in RAP preheat temperature. Based on this observation. It was concluded that an increase in RAP temperature during mixing could activate the RAP binder and results in the dispersion of RAP agglomerates into the final mixture.

Pérez Madrigal et al. (2016) prepared several AC mixtures with varying RAP contents, RAP preheat temperatures, virgin aggregate superheated temperatures, and mixing times. Based on the moisture damage (TSR) and cracking potential (Fenix test) results conducted on these specimens, it was concluded that extended mixing times improved the resistance to moisture susceptibility and cracking potential of AC with RAP. The effect of longer mixing times could be due to sufficient heat transfer between RAP and virgin aggregate to activate the RAP binder for better blending efficiency.

In summary, the heat transfer between superheated virgin aggregate and RAP during the dry mixing stage could result in (a) activation of RAP binder and (b) breakdown of RAP agglomerates, both of which result in higher cracking resistance and more homogenous mixtures. Therefore, a better understanding of the heat transfer between virgin aggregate and RAP would help to produce high-quality asphalt mixtures.

2.5 Laboratory Investigation of Heat Transfer

2.5.1 *Heat Transfer in HMA Mixtures*

Very few research studies have been conducted to evaluate the heat transfer process between superheated virgin aggregate and RAP material. Denene et al. (2014) developed a finite-difference spherical particle model to assess the heat transfer between virgin aggregate and RAP. The study proposed a theoretical model to calculate the minimum time required for a spherical RAP particle at ambient temperature to reach a desired internal temperature of 150°C, assuming the surface of the RAP particle is at drum temperature (default of 315°C). The proposed model was used to calculate the minimum amount of time required to reach the desired temperature at the core of the RAP particle for various conditions of initial temperature of particle, thermal diffusivity, particle diameter, and drum temperatures. The estimated heating times required for various combinations considered vary from 20 to 72 seconds. However, the practical use of the proposed model is questionable as it does not consider the kinematic of the mixing process and RAP moisture drying (Zhang et al., 2019).

Mohajeri (2015) made an effort to understand the heat transfer between virgin aggregate and RAP using a laboratory mixing chamber and an infrared camera. Asphalt concrete mixtures with 60% RAP (0% and 4% moisture) were used in the study, and four different combinations of RAP and virgin aggregate temperatures were used, as shown in Table 2.1. Virgin aggregate and RAP were mixed in a 10-liter Hobart mixer. An infrared camera (FLIR A320) was used to measure the temperature of the virgin aggregate and RAP particles using 3 minutes of mixing time and a 4-minute rest period (for a total period of 7 minutes). Qualitative observation of the temperature histogram data of the mixture over time was used to determine the amount of time required for complete heat transfer between aggregate and RAP, which is defined as the time at which a

homogenous temperature histogram was visually observed. It was observed that a mixing time of 270 s and 135 s were required for SM60 and PW30 mixtures, respectively.

Table 2.1: Mixtures and temperature combinations used for the heat transfer evaluation in Mohajeri (2015)

	<i>RA content [%]</i>	<i>Moisture Content of RA [%]</i>	<i>Preheating Temperatures [°C]</i>	
			RA	Virgin aggregate
SM60	60	0	170	170
PW60	60	0	130	330
UPG060	60	0	25	430
UPG460	60	4	25	515

Zhang (2016) used the computational fluid dynamics (CFD) coupled with the Discrete Element Method (DEM) to simulate the heat exchange between superheated virgin aggregate and RAP in a plant sized pugmill, as shown in Figure 2.4. The DEM method was used to model the particle dynamics of granular particles in a pugmill with mixing time. The heat transfer process between virgin aggregate and RAP material was simulated using the coupled CFD model by coupling particle movement from the DEM model.

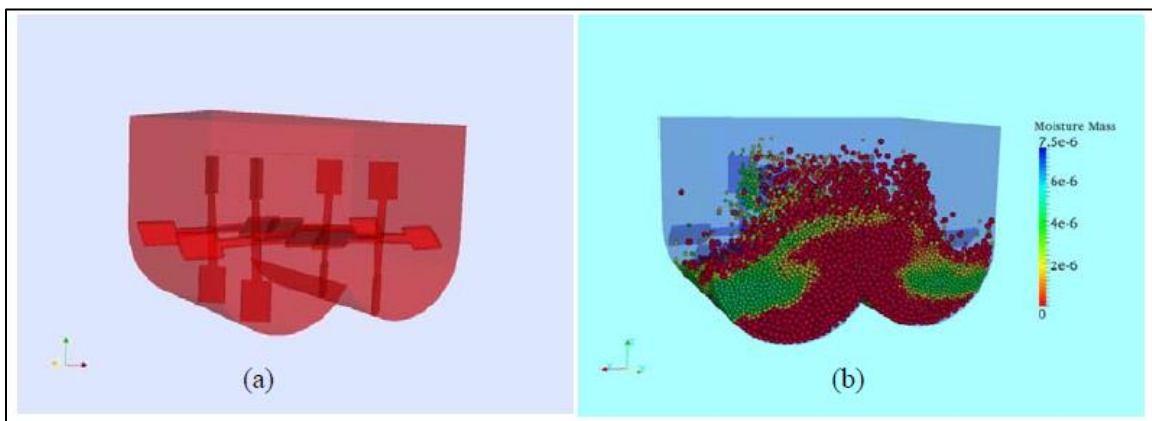


Figure 2.4: Heat transfer simulation using coupled CFD-DEM simulation in a pugmill model (Zhang, 2016).

Two mixtures with 20% and 40% RAP containing different moisture contents (0 to 5% RAP moisture at 1% increment) were modeled to evaluate the average temperature of the mixture. The average temperature evaluation with mixing time was used to determine the optimum dry mixing time required, defined as the time at which the average temperature of the mixture reaches a target discharge temperature, shown in Figure 2.5. The study concluded that higher dry mixing times were needed for high RAP contents, and lower dry mixing times are needed for high moisture contents to reach a target discharge temperature. It should be noted that these conclusions were based on the average temperature of the mixture to reach a target discharge temperature.

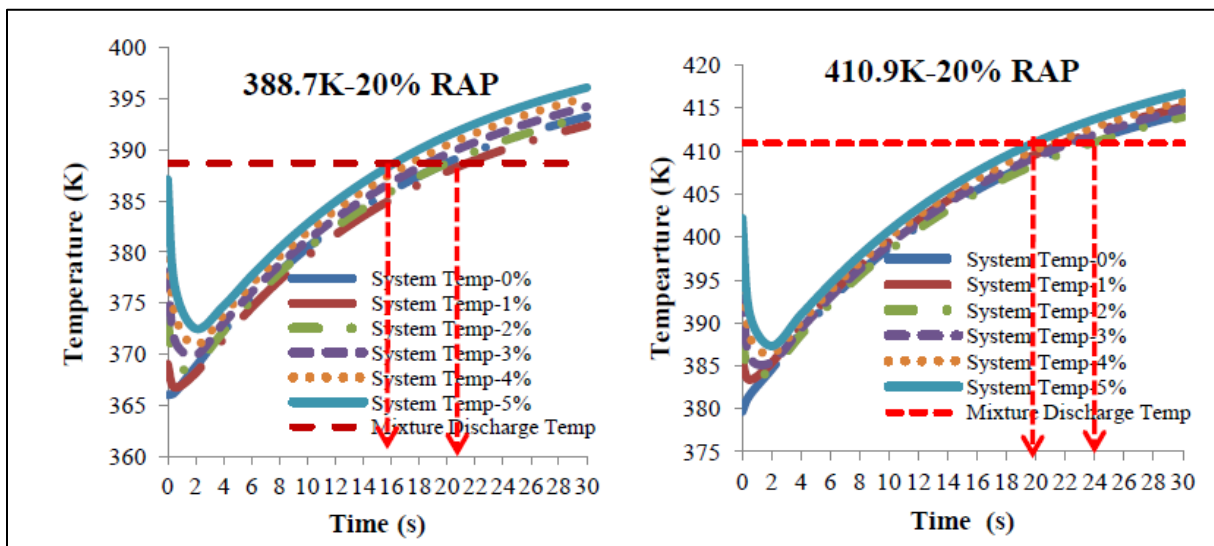


Figure 2.5: Simulated average temperature of the mixture with different moisture contents (Zhang, 2016).

To verify the DEM models used in the study, temperatures of RAP and virgin aggregate particles were measured over 5 minutes in a laboratory experiment using a laboratory drum mixture with an infrared camera. The author concluded that DEM models used in the study worked well to simulate the heat transfer between RAP and virgin aggregate. However, no statistical analysis of results was shown to prove the validity of DEM models in simulating experimental results.

2.5.2 Heat Transfer in Granular Materials

Even though very few studies were conducted on heat transfer in asphalt mixtures, several studies investigated the heat transfer in granular material in rotary drums (Chaudhuri et al., 2010; Nafsun et al., 2018; Boepple, 2019). This section summarizes the testing and calculation methods utilized in these studies to characterize heat transfer experimentally.

Chaudhuri et al. (2010) experimentally characterized heat transfer between heated wall and alumina powder (200 μm) and cylindrical silica pellets (2 mm diameter and 3 mm long) rolling in rotary calciners. A cylindrical calciner shown in Figure 2.6 was used. The calciner was loaded with a material of interest at room temperature, and the exterior wall was heated with an industrial heat gun to maintain the temperature of the wall at 100°C. Ten thermocouples were used to measure the radial temperature of the material rolling inside the calciner. As measuring continuous monitoring was not possible, the temperature readings of the materials were taken at multiple intervals by stopping the calciner and inserting the thermocouples into the holes provided.

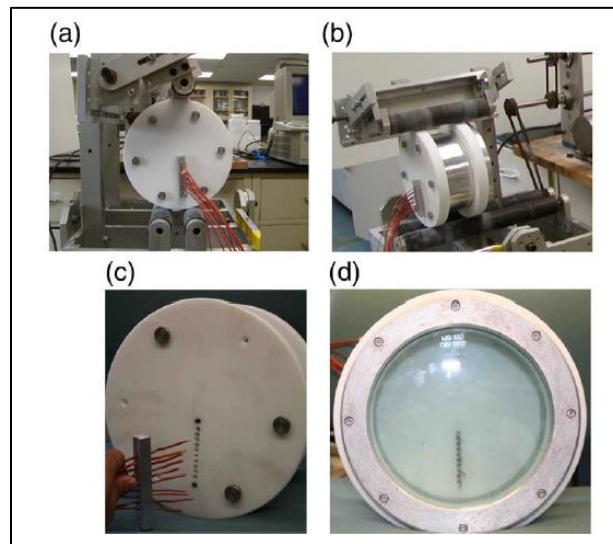


Figure 2.6: Laboratory calciner used by Chaudhuri et al. (2010) for heat transfer characterization: (a) back view of the calciner, (b) side view of the calciner, (c) series of thermocouples used for temperature measurement, and (d) front end of the calciners (Courtesy Chaudhuri et al., 2010).

This study proposed a method to determine the heat transfer coefficient between the wall and particles inside the calciner using Equation 2.1.

$$\ln\left(\frac{T_w - T_s}{T_w - T_s^o}\right) = -\frac{\alpha_s e_s A_s L}{M_s C_{ps}} \quad (2.1)$$

Where,

- M_s = Mass of alumina
- A_s = Drum circumference
- C_{ps} = Heat capacity of alumina
- e_s = The fraction of the drum circumference touched by alumina
- T_s = Temperature of alumina
- T_w = Temperature of the wall
- α_s = Heat transfer coefficient
- L = Length of the drum

The slope of the fitted straight line, as shown in Figure 2.7 along with Equation 2.1, was used to calculate the heat transfer coefficient between the heated wall and the material rolling in the calciner.

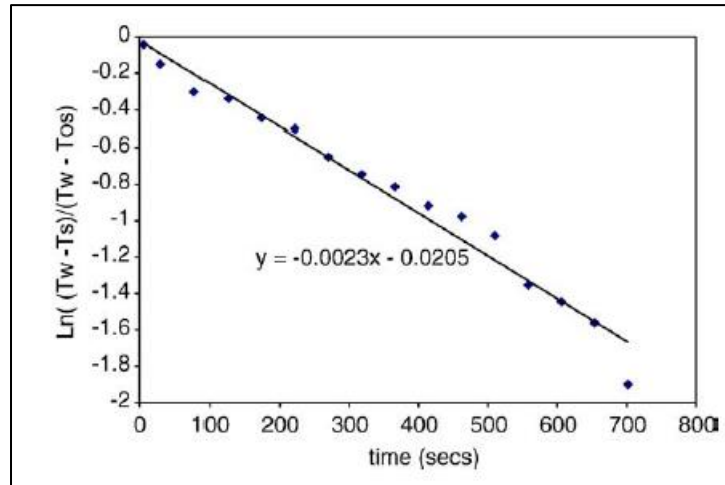


Figure 2.7: Variation of scaled temperature difference with time (Chaudhuri et al., 2010).

The major drawback of the testing method used by Choudhari et al. (2010) was that the material mixing profile was interrupted to collect the temperature readings by stopping the calciner at multiple intervals.

Boeapple (2019) fabricated a similar calciner with an additional hot air valve to add hot air into the calciner chamber, as shown in Figure 2.8. In addition, an infrared camera was used for continuous measurement of material and wall temperatures in the chamber, as shown in Figure 2.9. A sapphire window was used for the front end of the calciner to allow IR camera measurements.

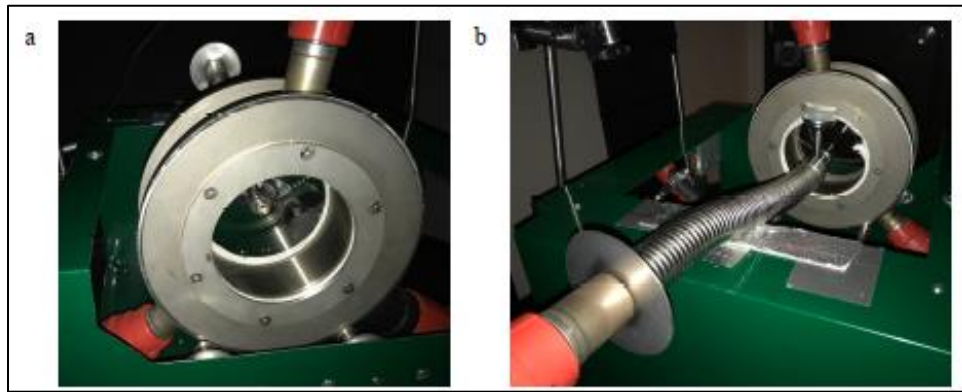


Figure 2.8: Modified Calciner used in the study by Boeapple, 2009: Front view of empty drum with sapphire window. b) Rear view of empty drum with air inlet duct and quartz window (Boeapple, 2019).

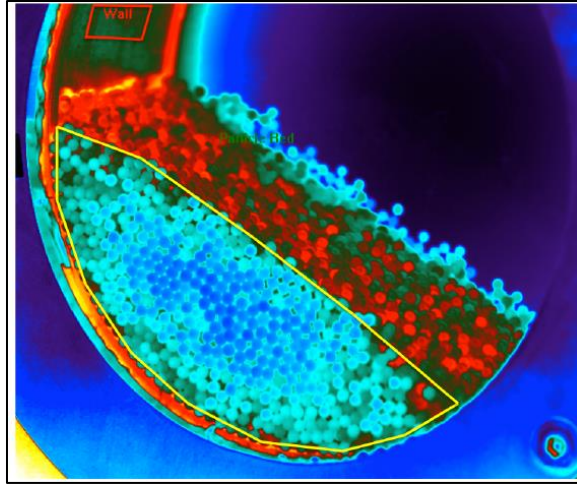


Figure 2.9: Infrared measurement taken by Boeapple, 2019 (Boeapple, 2019).

Boeapple (2019) used the same approach proposed in Equation 2.1 by Chaudhari et al. (2019) to determine the heat transfer coefficient between the heated wall and soda-lime-silica glass beads at room temperature.

Nafsun et al. (2018) conducted a study to investigate the transversal thermal bed mixing behavior for various materials, including quartz sand, glass beads, expanded clay, and steel spheres in a batch rotary drum. A stainless-steel rotary drum with 600 mm diameter, 450 mm length with 2 mm wall thickness was used for the study. The drum was heated externally using three electrical heaters to maintain wall temperature at 200°C. The study's overall objective was to determine the time required for thermal mixing two material beds started at two temperatures. At first, hot particles were placed at the bottom of the drum, followed by cold particles, as shown in Figure 2.10. The drum was rotated to allow the thermal mixing of two layers with distinct temperatures until they reached thermal equilibrium.

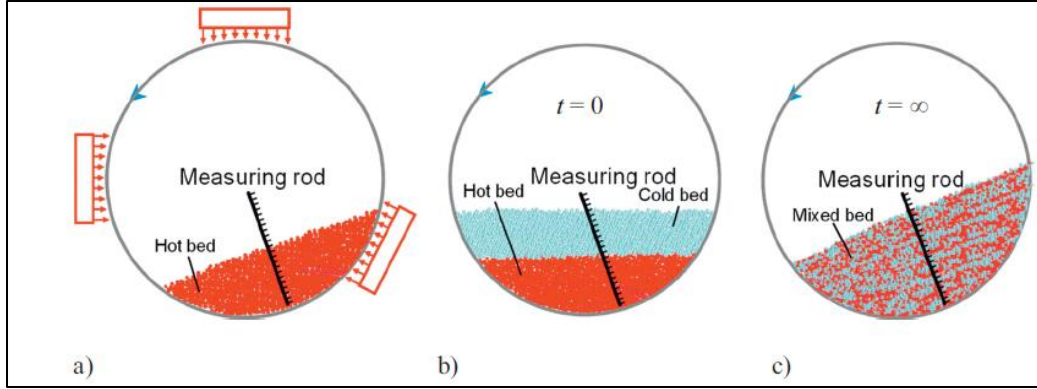


Figure 2.10: Schematic of the experimental method used by Nafsun et al., 2018 (Nafsun et al., 2018).

The temperature of the two material beds was measured using a measuring rod with 16 thermocouples attached at equal intervals. The temperature measuring rod position was fixed at 130° angle with the circumference to measure the temperature profile in the radial direction. Minimum and maximum temperatures of the 16 thermocouples were considered to represent temperatures of cold and hot particles, respectively, as shown in Figure 2.11.

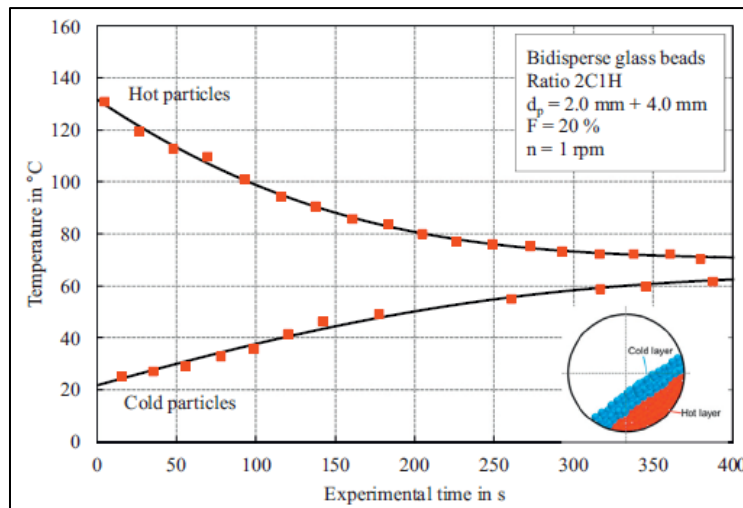


Figure 2.11: Change in temperature of hot and cold particles towards thermal equilibrium (Nafsun et al., 2018).

The thermal mixing time required for equilibrium was calculated using a mixing index. The mixing index is a measure of thermal mixing quality inside the drum bed; calculated as follows:

$$M(t) = \frac{\Delta T(t) - \Delta T_0}{\Delta T_\infty - \Delta T_0} \quad (2.2)$$

Where,

- $\Delta T(t)$ = Temperature difference with respect to time, °C
- ΔT_0 = Initial temperature difference, °C
- ΔT_∞ = equilibrium temperature difference inside the bed, °C
- $M(t)$ = Thermal mixing index at time t

The time required for thermal equilibrium was calculated when the mixing index reached 0.9. It was assumed that the 90% thermal mixing index was good enough. However, this assumption is highly subjective.

2.6 Available Technologies for Heating RAP

One of the many reasons for limiting usage of higher RAP contents in HMA is conventional HMA production technology. The cold feed recycling method of processing RAP in HMA production requires very high unrealistic superheated temperatures of virgin aggregate for high RAP content mixtures (Zaumanis et al., 2014). Preheating RAP before adding to virgin aggregate would reduce the temperatures required for virgin aggregate. Zaumanis et al. (2014) visited several asphalt plants producing 100% RAP mixtures and documented several technologies available for heating RAP. Table 2.1 presents a summary of several available technologies for preheating RAP during HMA production.

Table 2.1: Summary of available technologies for RAP heating during production

Technology	RAP Temp.	Production rate	Method of heating
All-RAP process	up to 300°F	-	Uses conventional HMA plant components with a special blue smoke filtration system
Ammann RAH100	up to 330-356°F	-	This system uses a counterflow dryer, hot air from the combustion zone dry, and heat RAP. Heated RAP is discharged before getting in direct contact with the flame
Alex-Sin Manufacturing, Inc	up to 176°F	-	RAP is heated in a drum dryer indirectly. Seven burners heat the exterior wall of the drum dryer in a heating chamber. Heat is transferred from the heated metal drum shell to the RAP rolling inside through heat conduction.
Rapmaster	up to 320°F	-	RAP is heated indirectly using hot gases around the rotating drum. Hot gases enter heat transfer tubes that run around the rotating drum throughout the length of the drum in the counterflow direction to the RAP material.
RATech	-	80-180 ton/hr.	RAP is heated in an originally designed triangle profile drier. RAP is indirectly heated first with the hot air of 200-400°C and then exposed directly to the hot air of 120-200°C; thereby, there is less additional aging to the RAP binder.
RapSaver	up to 165-185°F	80-100 ton/hr.	RAP is heated in a continuously fed sealed conductive heating system. This system allows RAP to heat and dry using a slow-moving hollow screw heating auger. Hot heat exchange fluid is pumped through the hollow jacket and hollow auger flights that heat RAP indirectly through conduction.

2.7 Summary of the Literature Review

Cold feed recycling is the most common method of RAP processing in the production of HMA mixtures. There is a great amount of discrepancy among existing superheated temperature recommendations, and experimental validation is needed. Several research studies showed that the thermal process between virgin aggregate and RAP affects the performance of the HMA mixtures. However, no experimental studies were conducted to characterize the heat transfer between virgin aggregate and RAP. Experimental investigation of heat transfer in rotary drums was researched

extensively in granular materials. The infrared thermal imaging technology was successfully used in several research studies to measure the temperature of moving granular materials and in asphalt mixtures.

CHAPTER 3 DEVELOPMENT OF HEAT TRANSFER TEST PROTOCOL

Possible modes of heat transfer that can occur in an HMA plant to dry and heat RAP material are; (a) heat conduction, (b) heat convection, and (c) radiation, shown in Figure 3.1. However, it was reported by NAPA (NAPA IS-123, 1996) that heat conduction between virgin aggregate and RAP is the primary mode of heat transfer in a batch plant, counter flow drum plant, and double barrel drum plant. Though heat conduction and heat convection were stated as primary modes of heat transfer in a parallel flow drum plant, several researchers estimated that 90% of the heat transfer occurs by heat conduction and 10% by heat convection between RAP and hot gases in the drum (Brock, 1998; DeDene et al., 2014). It is not realistic to continuously monitor virgin aggregate and RAP material temperatures over mixing time in a full-size HMA plant (Zhang, 2016). As heat conduction between virgin aggregate and RAP is believed to be the primary mode of heat transfer in an HMA plant, an experimental laboratory study based on heat conduction is expected to provide the necessary understanding of heat transfer between these two materials.

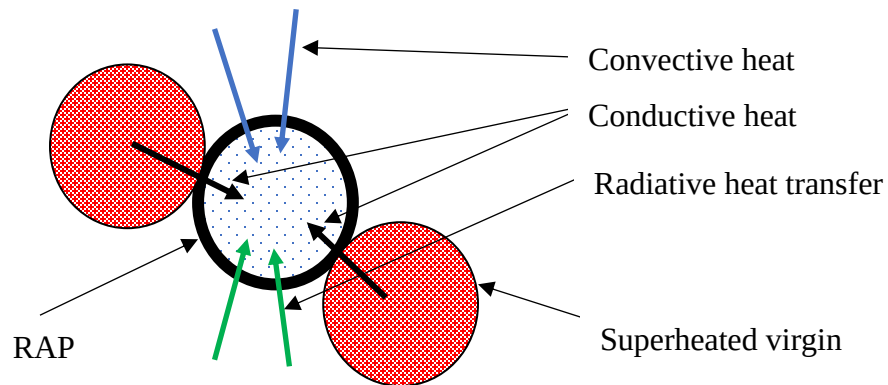


Figure 3.1: Schematic of the heat transfer between virgin aggregate and RAP material.

The following key steps were involved in the development of a new test method for investigating the heat transfer between virgin aggregate and RAP in a laboratory setup:

- Development of a blending chamber,
- Selection of a temperature measuring device,
- Development of testing sequence,
- Development of analysis framework to calculate heat transfer parameters.

Each step is discussed in detail in the following sections of the chapter.

3.1 Development of the Blending Chamber

It was necessary to develop and fabricate a blending chamber that could provide continuous mixing with minimal heat losses to investigate the heat transfer process between superheated virgin aggregate and RAP material. A schematic of the fabricated blending chamber and temperature measuring system is shown in Figure 3.2. As shown in Figure 3.3 (a), a 9 in diameter by 10.75 in high steel drum was inserted into an 11 in diameter by 13.5 in high laboratory asphalt bucket mixture. The gap between these two steel drums was filled with a glass fiber insulating material to reduce heat loss from the blending chamber. The internal flight assembly (Figure 3.3(b)), the rotational speed, and the inclination of the blending chamber were designed by ASTEC Industries, Inc. using a Discrete Element Modelling (DEM) simulation method for uniform and continuous blending of virgin aggregate and RAP material.

A speed of 6 rpm was recommended by ASTEC Inc; however, due to the limitations of the speed controller attached to the blending chamber, a speed of 8 rpm was used. An angle of inclination of 15° for the blending chamber was recommended based on the DEM simulations, but due to practical reasons, an angle of 21.5° was used during heat transfer testing. A wooden plank was used as a lid to the front end of the chamber, and circular insulation was attached to the mixer lid to control heat losses from the front end of the mixer. A 3x3 in. opening was provided to record the temperature of materials inside the blending chamber during testing and allow access to add

RAP to the blending chamber. Continuous airflow across the opening of the front lid provided an air curtain to control heat losses and protected the camera lens. The developed heat transfer test setup is shown in Figure 3.3(c).

A removable spiral flight assembly was designed for the internal flight system of the blending chamber. The flight assembly divided into two halves in length, faced in a counter direction to each other. The bottom half of the flights was designed to move the material at the bottom of the blending chamber to the front end of the drum. The top half of the flights in a counter direction were designed to move material from the front end of the blending chamber to the back to have a uniform and continuous mixing of particles in the chamber.

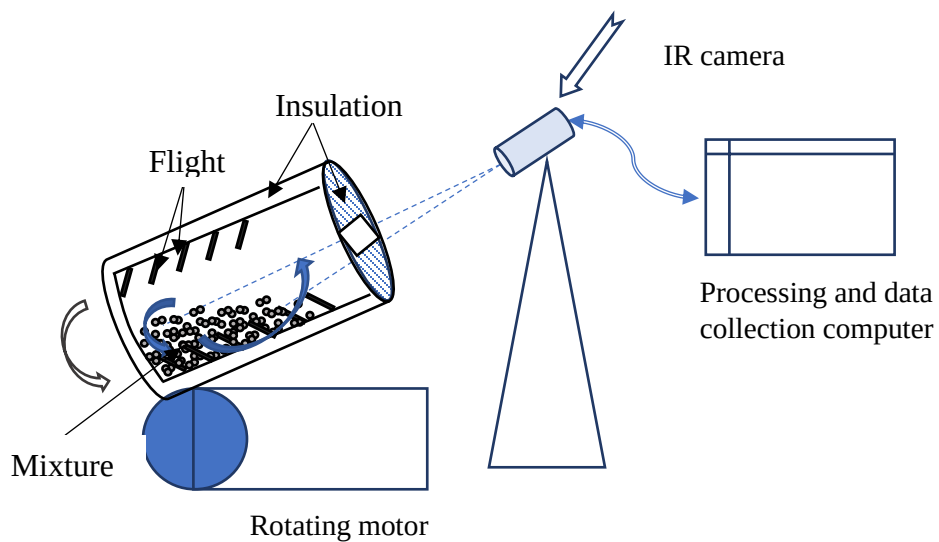


Figure 3.2: Schematic of the blending chamber and temperature measuring system.

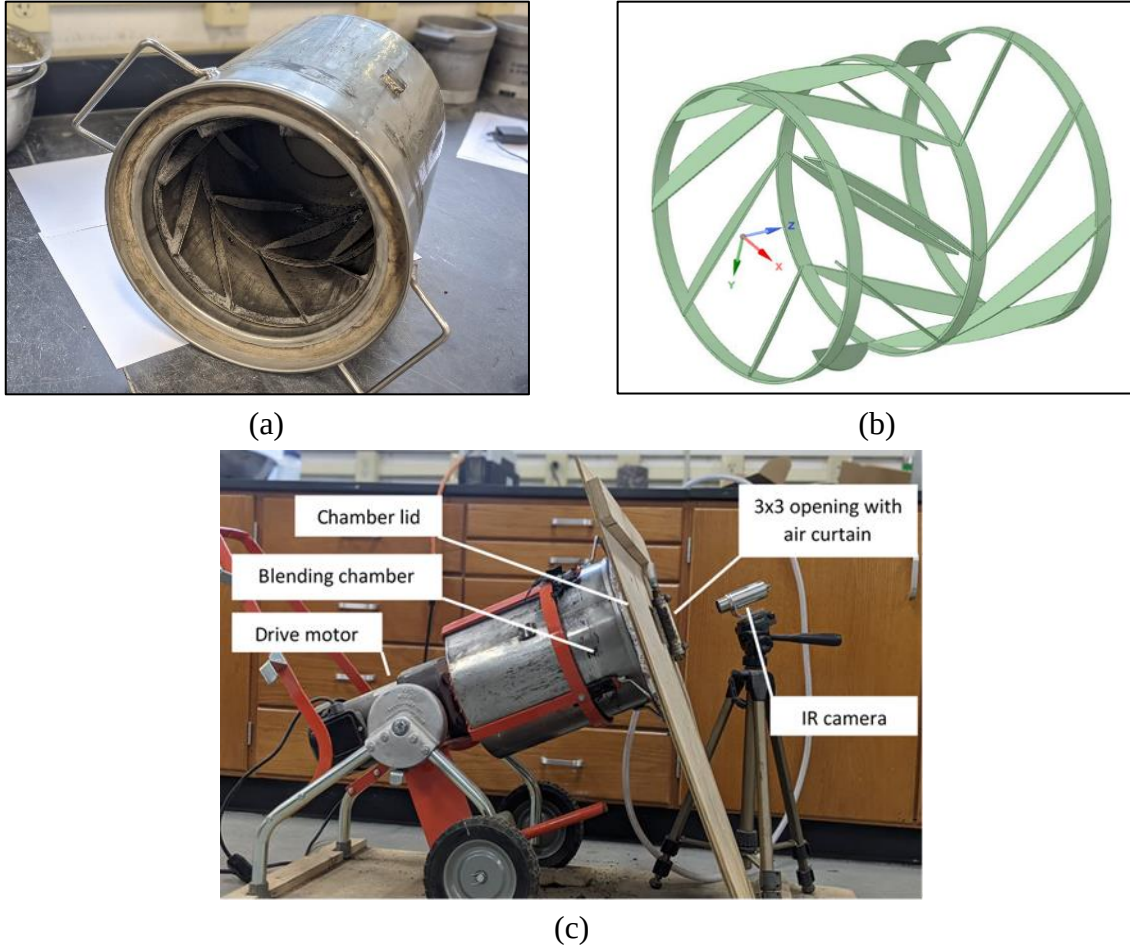


Figure 3.3: Developed heat transfer test setup: (a) insulated blending drum, (b) designed flight assembly, and (c) assembled blending chamber.

3.2 Temperature Measuring Device

Infrared thermography is a non-contact surface temperature measuring technique where an infrared (IR) camera measures the infrared energy emitted from the surface of an object and converts it to surface temperature. Infrared thermography technology has been successfully used in other research (Mohajeri, 2013; Zhang, 2016; Boeapple, 2019) to study heat transfer in a rotary drum in the powder industry and measure thermal segregation during HMA mixing in the laboratory. A commercially available high-resolution IR camera, Micro-Epsilon TIM40 (Figure 3.4), was used in this study to measure the temperature of aggregate and RAP particles in the blending chamber. The camera was controlled by external computer software (TIM connect) to set temperature

measuring frequency and recording interval. The camera was placed at a distance of 0.4 m from the surface of the mixture in the blending chamber to provide a Field of View (FOV) of 5.3 x 4.0 in (temperature measuring area of the material surface). It was measured that the obtained FOV of 5.3 x 4.0 in. covered 38% of the surface of the mixture in the chamber, and this is assumed to be a representative sample size of the material surface to explain the temperature behavior of the entire mixture. At the set distance from the surface of the mixture, the IR camera can accurately measure the temperature of particles with a minimum size of 1.04 mm. The camera divides this entire FOV into 110,016 (382 x 288) pixels, measures the temperature of each pixel (0.35 mm), and stores the data into the computer at a defined measuring interval. For accurate temperature measurement, the recommended minimum particle size is a 3x3 pixel matrix that is 1.04 mm.



Figure 3.4: Micro-Epsilon TIM 40 infrared camera (source: Micro-Epsilon).

For this study, temperature readings of the mixture were measured at 1-second intervals from the point of introduction of RAP material at ambient temperatures to the superheated virgin aggregate for 15 minutes of mixing. A 15-minute test time was selected to gather enough temperature data and determine the mixing time required for heat transfer completion between virgin aggregate and RAP.

3.2.1 Calibration of the IR camera

The selected IR camera can be operated in two temperature ranges: range-1: 32 to 482°F & range-2: 302 to 1652°F. A proper measuring range must be selected based on the measuring temperatures

while operating the camera, as the measuring range cannot be changed during testing. The camera was calibrated by the manufacturer for two measuring ranges. However, the IR camera measuring temperatures had to be calibrated for the materials used in the study. A calibration study was conducted to accurately measure the temperatures of materials selected. In this study, four aggregate types: Limestone, Basalt, Dolomite, Quartzite, and one RAP source were used for testing. Therefore, the IR camera calibration process was conducted on these five types of materials.

These materials were placed in an oven set at the calibration temperature for three hours to allow temperature stabilization in the material. A calibrated thermocouple was used to measure the temperature of each material type at the set temperature. Exhaust opening available at the top of the oven was utilized as shown in Figure 3.5(a) to measure the material temperature under the IR camera view (Figure 3.5(b)). The IR camera readings were taken for 20 seconds for each material at the set temperature (Figure 3.5(c)).

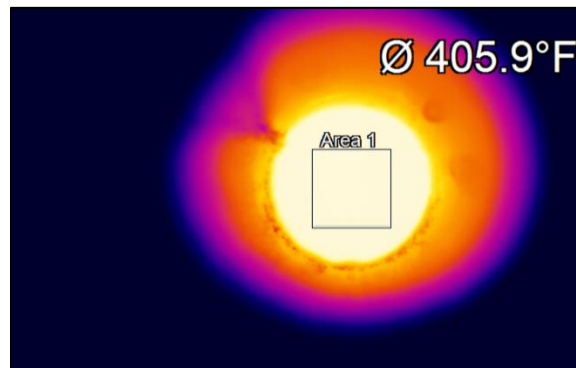
The same process of measuring temperatures with thermocouple and IR camera was repeated for all material types and over a range of temperatures. Figure 3.6 shows the comparison of thermocouple and IR camera measurements using the two operating ranges available for the camera. It can be observed that the temperature data for all materials considered were overlapping. Therefore, one calibration equation for an operating range is sufficient for all materials. The calibration equations presented in Figure 3.6 were used to correct all temperatures in this study.



(a)

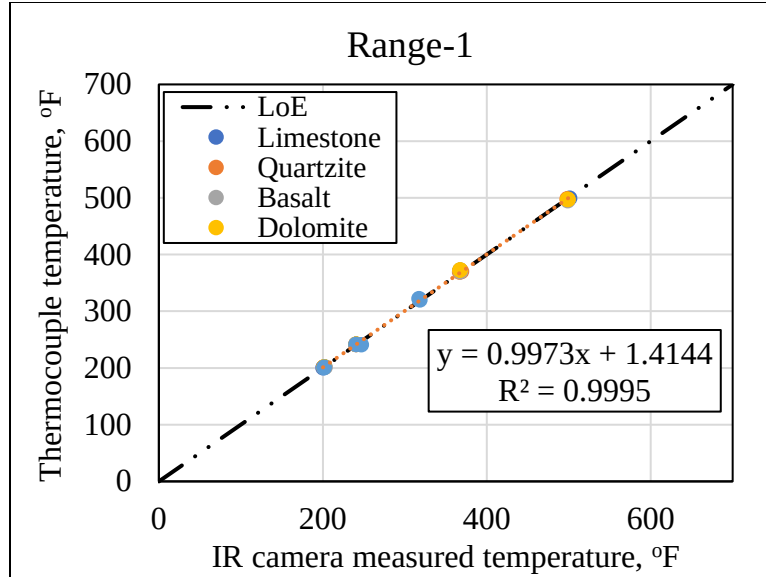


(b)

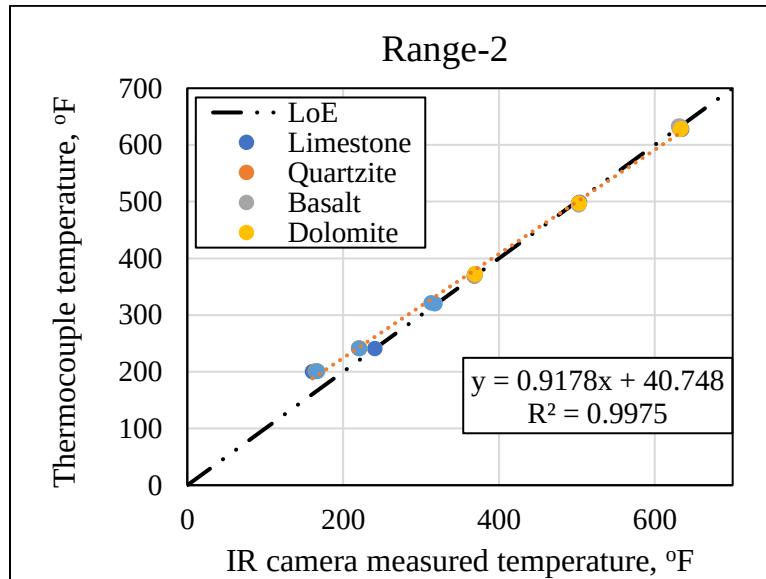


(c)

Figure 3.5: IR camera calibration setup: (a) IR camera looking inside the oven, (b) material of interest placed under the IR camera view, and (c) temperature profile captured by the IR camera (Area1).



(a)



(b)

Figure 3.6: IR camera calibration for: (a) Range-1, and (b) Range-2 operating ranges.

3.3 Heat Transfer Testing Procedure

The following sequential steps were followed for heat transfer testing:

- Virgin aggregate and RAP material were air-dried and screened to required sizes based on the experimental matrix.
- 4,000 grams of the total mixture (RAP + virgin aggregate) were used for the testing. The entire testing was based on a dry mixture without an additional virgin binder. For wet RAP

cases, the required amount of water was added to the dried RAP at least 12 hours prior to testing, and the wet RAP was stored in a zip lock bag to allow water absorption into the RAP.

- The blending chamber was inserted into the rotating frame in the vertical position with the open end on top. The chamber was loaded with 4,000 grams of aggregate material to preheat the chamber. The chamber was lowered to the required inclination, and the lid was placed on the chamber. The motor was turned on for 5 minutes to begin the rotation cycle and preheat the blending chamber.
- The motor was turned off, the lid was removed, the assembly was brought back to the vertical position, and the preheated blending chamber was removed from the rotating frame. It was placed back into the rotating frame after transferring the preheated aggregate to a cool pan for reuse.
- Superheated virgin aggregate materials were heated to excessive temperatures to make sure they were reduced to the required superheated temperature after 200 seconds of mixing in the chamber. This step was performed to account for the heat losses from the drum between unloading preheating material and loading superheated aggregate material.
- Superheated virgin aggregate was introduced to the blending chamber, the chamber was lowered to the required inclination, and the top lid was placed. Loading the preheated chamber was accomplished quickly.
- The blending chamber motor was started, and the virgin aggregate temperature was monitored. The infrared camera was set to recording, and focus and field of view were re-confirmed and adjusted accordingly.

- RAP was introduced into the blending chamber through the lid opening while the superheated aggregate was in motion. The RAP material was added when the virgin aggregate material reached the required superheated temperature, which took around 200 seconds from the time of loading the superheated aggregate into the preheated blending chamber.
- IR camera readings were collected at 1-second intervals for analysis. The heat transfer testing was continued for a mixing time of 15 minutes.
- The motor was turned off, the lid was removed, and the blending chamber was brought back to the vertical position. The blending chamber was removed from the frame to transfer the tested material into a cool pan. Internal flight assembly was removed to clean any material remaining in the chamber.
- After cleaning, the internal flight assembly was inserted back to the chamber, and the blending chamber was placed into the rotating frame for further testing.

The test method used in the study for heat transfer testing is presented as a standard in Appendix A.

3.4 Heat Transfer Test Hypothesis

3.4.1 Test Hypothesis

Figure 3.7 shows expected changes in the temperature data of virgin aggregate, RAP material, and the average temperature of the mixture in the blending chamber over mixing time. Right after the incorporation of RAP into the blending chamber (At time $t=0$ second), both RAP and virgin aggregate are at two distinct temperatures: RAP is at ambient temperature, and virgin aggregate is at selected superheated temperature. With mixing, heat transfer occurs between these two materials, the temperature of the virgin aggregate reduces, and the temperature of RAP increases until a uniform temperature is achieved, defined in this study as the time required for equilibrium

(T_{equi}). At time $t=0$ second, the average temperature of the entire mixture can be lower or higher than the temperature at equilibrium, depending on the RAP/virgin aggregate proportioning. With mixing time and heat exchange, the average temperature of the mixture stabilizes to a final discharge temperature once the heat transfer between these two materials is complete at T_{equi} .

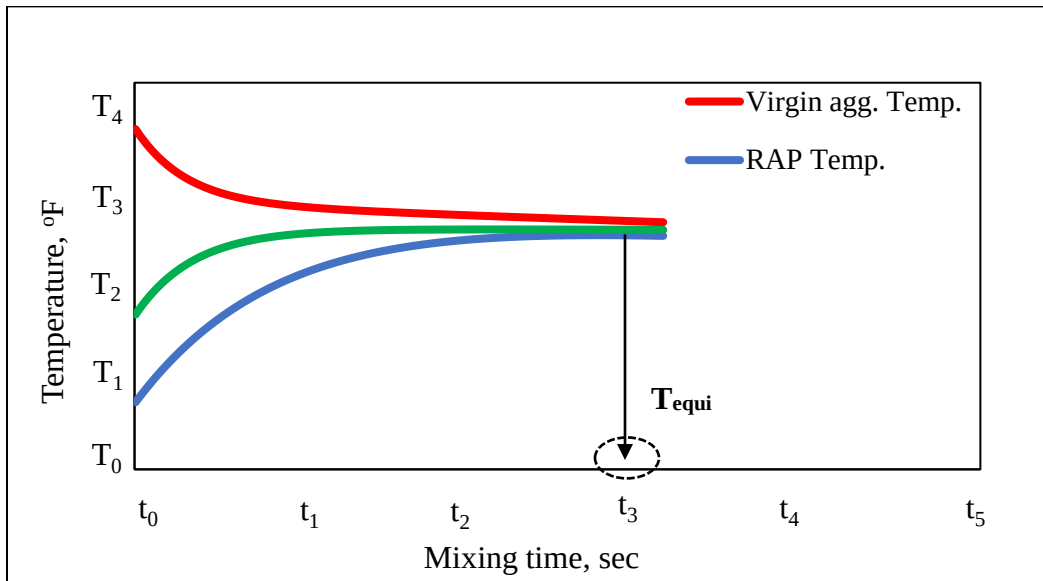


Figure 3.7: Schematic of the expected changes in temperatures of different components of the mixture over mixing time.

3.4.2 Visualization of Raw Data

After the development of the test blending chamber, temperature measuring device, and testing procedure for the heat transfer testing, preliminary tests were carried out at 10% and 40% RAP contents with dry fine RAP (passing through #4 sieve) and coarse RAP (retained on the #4 sieve), virgin aggregate gradations obtained from the blending exercise were used. These preliminary tests were used to explain the data that was generated by the developed heat transfer testing protocol. The superheated virgin aggregate temperatures were selected from the ASTEC recommended table (ASTEC T-127) for a target discharge temperature of 300°F. Superheated virgin aggregate temperatures of 335°F and 465°F were used for the 10% and 40% cases, respectively.

Figure 3.8 presents thermal images showing complete FOV recorded by the IR camera at different times during testing for the 40% coarse RAP case. It can be observed from Figure 3.8 that RAP and virgin aggregate were at very different temperatures at the start of the test and started to converge to a uniform temperature over the period of mixing due to heat transfer.

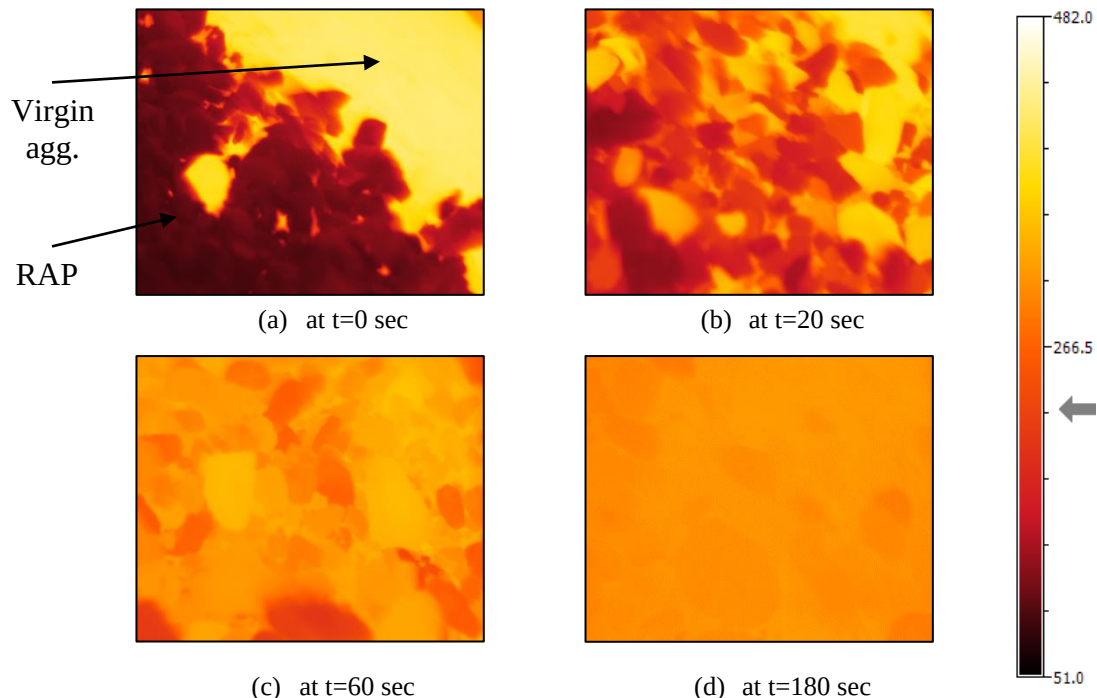


Figure 3.8: Visualization of IR camera measurements over time: for 40% Coarse RAP at 465°F superheated aggregate temperature.

Figure 3.9 and Figure 3.10 show ridgeline plots of temperature histograms of the FOV over mixing time for the 10% RAP case and 40% RAP case, respectively, with both fine and coarse RAP at 10 second mixing time intervals. It can be noted from Figure 3.10 that the temperature histogram of the FOV initially had a wide base (high standard deviation) with two distinct peaks, one at a higher temperature range and the other at a lower temperature range. These two peaks represent temperatures of virgin aggregate and RAP, respectively. Over the mixing time, the width of the temperature histogram was reduced (lower standard deviation) and became constant, and two peaks of the histograms converged to a single peak. The convergence of the two peaks was

more evident in the 40% RAP case (Figure 3.10) compared to the 10% RAP case (Figure 3.9), as the former case had more data points (pixels) that represent RAP material. Thus, it can be concluded that the devised test method, the blending chamber, and the temperature measuring device generated a reasonable dataset that can be used with appropriate analysis techniques to investigate the heat transfer process between superheated virgin aggregate and RAP material.

As it was assumed the blending chamber resulted in a uniform and continuous blending of the mixture, the temperature distribution of surface particles that the IR camera could measure was assumed to represent the entire mixture.

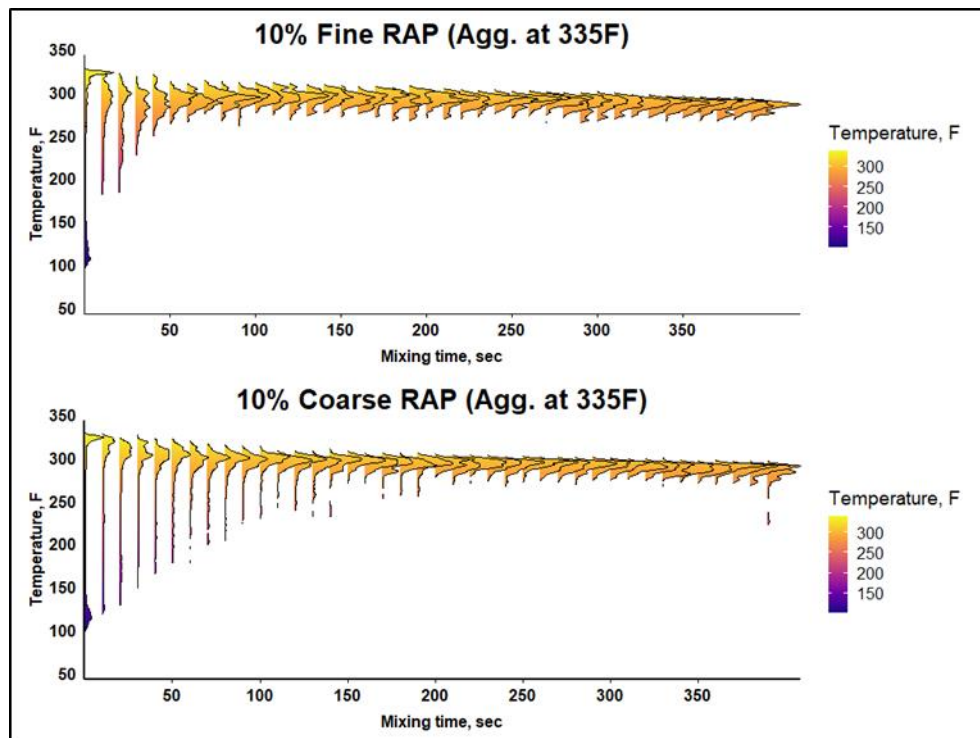


Figure 3.9: Ridgeline plot of temperature histogram of the FOV for the (a) 10% fine RAP, and (b) 10% Coarse RAP.

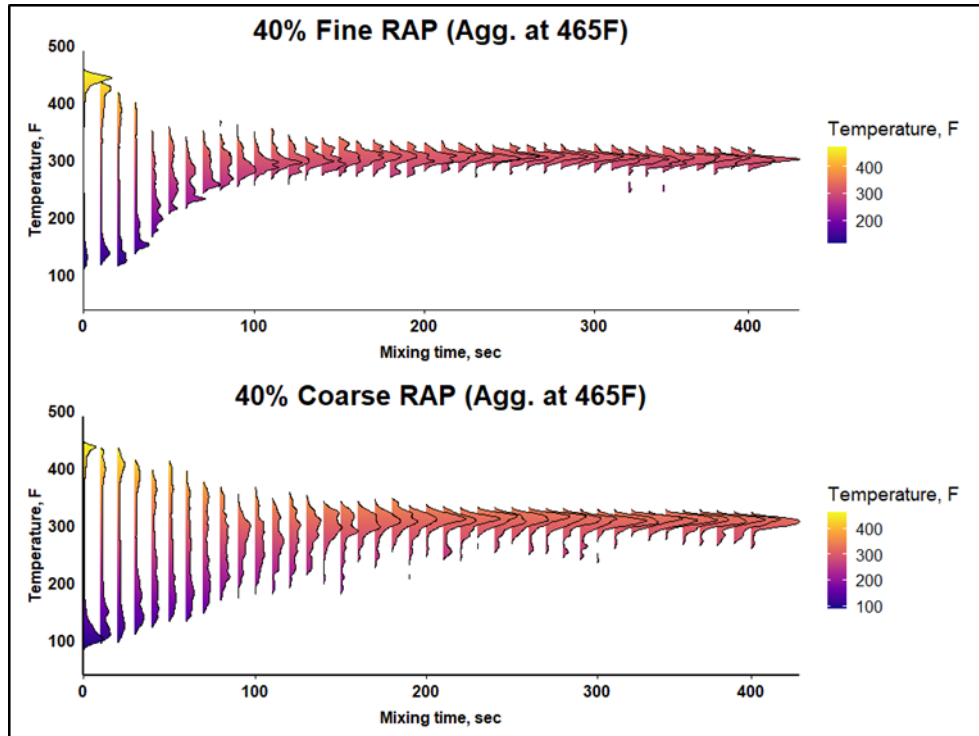


Figure 3.10: Ridgeline plot of temperature histogram of the FOV for the (a) 40% fine RAP, and (b) 40% Coarse RAP.

3.5 Analysis Framework for Heat Transfer Process

To investigate the effect of selected variables on the heat transfer process between superheated virgin aggregate and RAP material, the following two parameters were considered:

- Time required for heat transfer completion (T_{equi})
- Heat conductance between virgin aggregate and RAP (H_C)

Analysis frameworks developed to determine these three parameters using the data obtained from the above heat transfer test protocol are explained in the following sections.

3.5.1 Determination of Time Required for Heat Transfer Completion (T_{equi})

As shown in Figure 3.9 and Figure 3.10, the width of the temperature histogram was reduced with mixing time due to heat transfer. This data was used to define the time of heat transfer completion. The standard deviation of the mixture temperature (standard deviation of all pixels in the FOV at a given time) was a computed parameter representing the width of the histogram. The standard deviation of the mixture temperature was plotted against mixing time and is shown in Figure

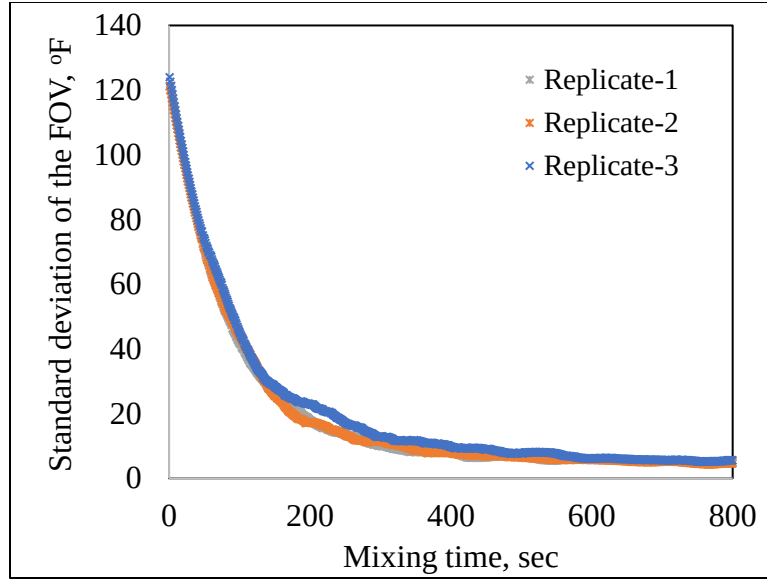
3.11(a) for the 40% coarse RAP case as an example. From Figure 3.11(a), it can be seen that the standard deviation of the temperature data reduced at an exponential rate and became asymptotic. As the blending chamber developed in this study had heat losses from the system, the later portion of the standard deviation curve acted as an asymptote. It was anticipated that the initial exponential drop in standard deviation was due to the heat transfer between RAP and virgin aggregate. The early length of the asymptotic part was due to a very slow rate of heat transfer, while the final length was due to heat losses from the blending chamber after the completion of heat transfer between virgin aggregate and RAP. A mathematical analysis framework was developed to define the completion of heat transfer.

Figure 3.11(b) shows the standard deviation curve on a semi-logarithmic scale. The form of the curve represents a sigmoidal function with a negative rate. The standard deviation data with time was fitted as a negative growth sigmoidal function in the form of Equation 3.1, as shown in Figure 3.11(b).

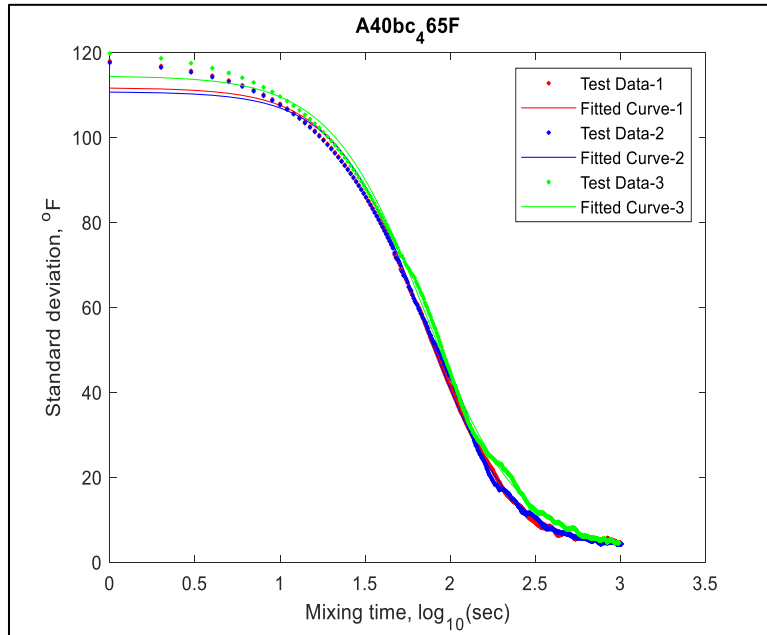
$$SD(t) = f(t) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log_{10}(t)}} \quad (3.1)$$

Where,

$$\begin{aligned} t &= \text{Mixing time, sec} \\ SD(t) &= \text{Standard deviation of FOV at mixing time } t, ^\circ F \\ \alpha, \beta, \gamma, \delta &= \text{Curve fitting coefficients} \end{aligned}$$



(a)



(b)

Figure 3.11: Change in the standard deviation of the FOV data (experimental data): (a) on the arithmetic time scale, and (b) on logarithmic time scale with a fitted negative sigmoidal curve.

For sigmoidal functions, as shown in Equation 3.1, the asymptote will converge to the value α when time (t) equals infinity. However, defining completion of heat transfer as infinity is not practical. Therefore, heat transfer completion should be the point beyond which change in standard deviation is negligible (change in slope of the SD curve in Figure 3.11(a) equals zero).

As this is a negative sigmoidal function, the slope of this curve will never become zero but converges to zero instead. Hence, T_{equi} is a point beyond which the rate of change in slope (second derivative) converges to zero. Change in the slope of a negative sigmoidal curve (second derivative) will start to converge to zero after the third inflection point of the second derivative of the function, as shown in Figure 3.12. This inflection point can be calculated by equating fourth-order derivative of $f(t)$ to zero (T_{equi}). T_{equi} can be determined by solving Equation 3.2. This analysis procedure was used to determine the T_{equi} for all of the heat transfer testing conducted as part of the experimental matrix.

$$\frac{d^4(f(t))}{dt^4} = 0 \quad (3.2)$$

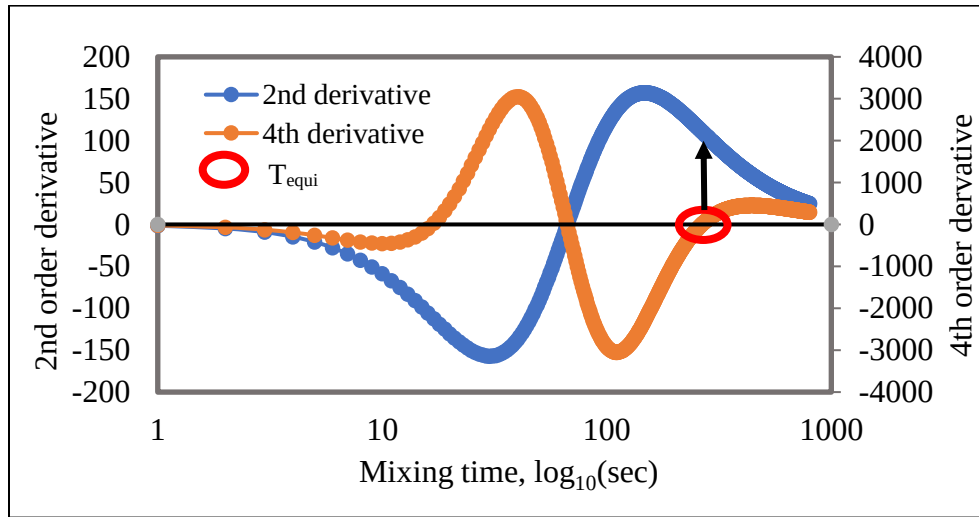


Figure 3.12: Illustration of the second and fourth-order derivative of negative growth sigmoidal function.

3.5.2 Determination of Heat Conductance between Virgin aggregate and RAP

The thermal contact conductance coefficient, H_C , is a property indicating the thermal conductivity, or ability to conduct heat, between two bodies in contact. To determine H_C , the energy-balanced equation of the proposed test method was used (Equation 3.3).

$$-m_{va}C_{va} \frac{dT_{va}}{dt} = Q_{VR} + Q_{WR} + Q_{VFR} + Q_{HL} \quad (3.3)$$

Where,

- m_{va} = Mass of virgin aggregate, kg
- C_{va} = Specific heat capacity of virgin aggregate, J/kg-°C
- T_{va} = Temperature of virgin aggregate, °C
- t = Mixing time, sec
- Q_{VR} = Rate of heat transfer from virgin aggregate to RAP, J/sec
- Q_{WR} = Rate of heat transfer from wall to RAP, J/sec
- Q_{VFR} = Rate of heat transfer from virgin aggregate to air to RAP, J/sec
- Q_{HL} = Rate of heat loss from the wall through the insulated chamber, J/sec

If the three heat transfer scenarios are neglected: heat transfer from the chamber wall to the RAP, heat transfer from the virgin aggregate to air, and the heat loss from the wall through the insulated chamber, then, Equation 3.3 is reduced to:

$$Q_{VR} = -m_{va}C_{va} \frac{dT_{va}}{dt} \quad (3.4)$$

The conductive heat transfer from virgin aggregate to RAP can also be written as:

$$Q_{VR} = m_{rap}C_{rap} \frac{dT_{rap}}{dt} \quad (3.5)$$

$$Q_{VR} = H_C(T_{va} - T_{Rap}) \quad (3.6)$$

Connecting Equations 3.4 and 3.5 results in:

$$\frac{dT_{rap}}{dt} = \left[\frac{-m_{va}C_{va}}{m_{rap}C_{rap}} \right] \frac{dT_{va}}{dt} \quad (3.7)$$

Connecting Equations 3.4 and 3.6 results in:

$$-m_{va}C_{va} \frac{dT_{va}}{dt} = H_C(T_{va} - T_{Rap}) \quad (3.8)$$

By substituting Equation 3.7, Equation 3.8 can be solved into the following form.

$$\ln \left[\frac{T_{va} - T_{rap}}{T_{va}^0 - T_{rap}^0} \right] = H_C * \left[\frac{1 + \frac{m_{va}C_{va}}{m_{rap}C_{rap}}}{m_{va}C_{va}} \right] \times t \quad (3.9)$$

Where,

- T_{rap} = Temperature of RAP, °C
- T_{rap}^0 = Initial temperature of RAP, °C
- T_{va} = Temperature of virgin aggregate, °C

T_{va}^0	=	Initial superheated virgin aggregate temperature, °C
t	=	Mixing time, sec
H_C	=	Heat conductance between virgin aggregate and RAP, J/sec-°C
m_{rap}	=	Mass of RAP, kg
C_{rap}	=	Specific heat capacity of RAP, J/kg-°C
m_{va}	=	Mass of virgin aggregate, kg
C_{va}	=	Specific heat capacity of virgin aggregate, J/kg-°C

The slope of the line between $\ln \left[\frac{T_{va} - T_{rap}}{T_{va}^0 - T_{rap}^0} \right]$ and mixing time, along with material properties such as the mass of RAP and virgin aggregate and heat capacity of RAP and virgin aggregate, can be used to calculate a heat conductance value for a given material combination at a selected superheated temperature. However, to determine the slope between $\ln \left[\frac{T_{va} - T_{rap}}{T_{va}^0 - T_{rap}^0} \right]$ and mixing time, and eventually, heat conductance, the temperature of RAP material, and virgin aggregate over the mixing time needs to be extracted from the IR camera measurements.

The IR camera used in this study measures the temperature of the entire mixture in the FOV and cannot distinguish between virgin aggregate particles and RAP particles. However, as seen in Figure 3.9 and Figure 3.10, the RAP started at lower temperatures, and the virgin aggregate started at higher temperatures. Therefore, a histogram of the temperature data measured by the IR camera (382 x 288 pixels) at a given time frame could define the temperatures of RAP and virgin aggregate temperatures at that time. Based on the assumption that the temperature of RAP is always lower than the temperature of virgin aggregate, the 5th percentile of the temperature histogram was defined as the RAP temperature, and the 95th percentile of the temperature histogram was considered as virgin aggregate temperature for this study. This use of the test data to extract virgin aggregate temperature and RAP temperature can be supported by the early period

of mixing when two distinct peaks appear in the pixel temperature distribution, as shown in Figure 3.9 and Figure 3.10.

Figure 3.13 presents a temperature progression of RAP and virgin aggregate for 40% RAP content with fine and coarse RAP. The above-mentioned definitions of RAP temperature and virgin aggregate temperature were used to calculate temperature progression over mixing time.

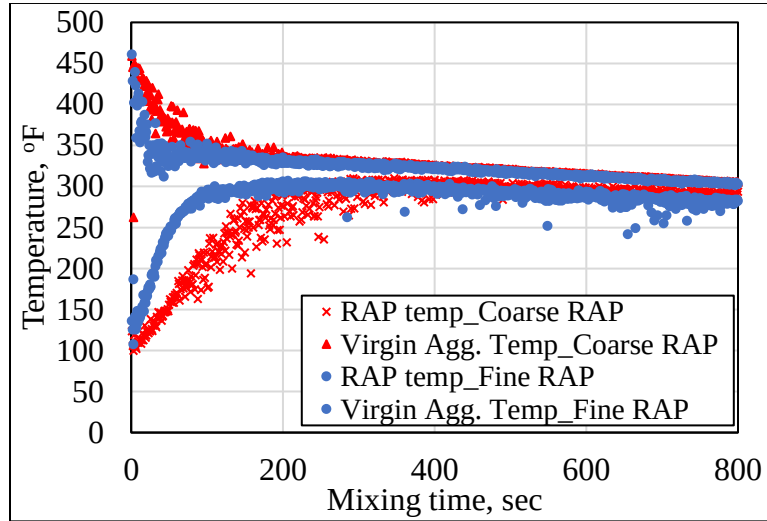
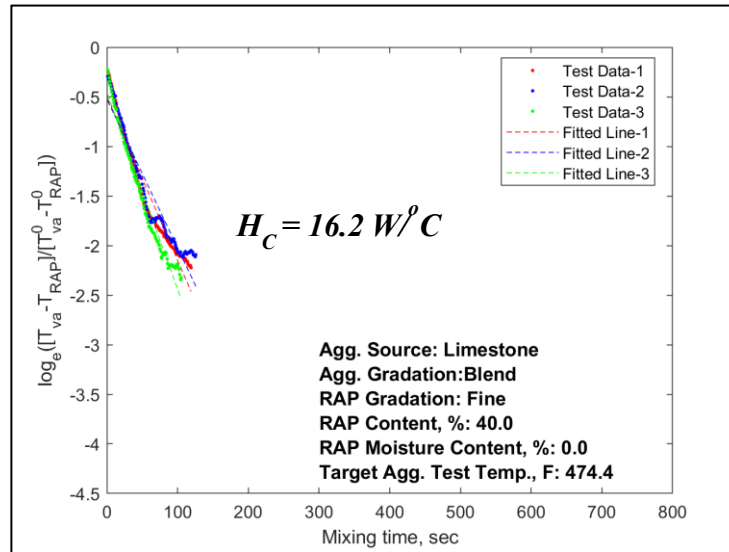


Figure 3.13: Temperature progression of RAP and virgin aggregate for fine and coarse RAP.

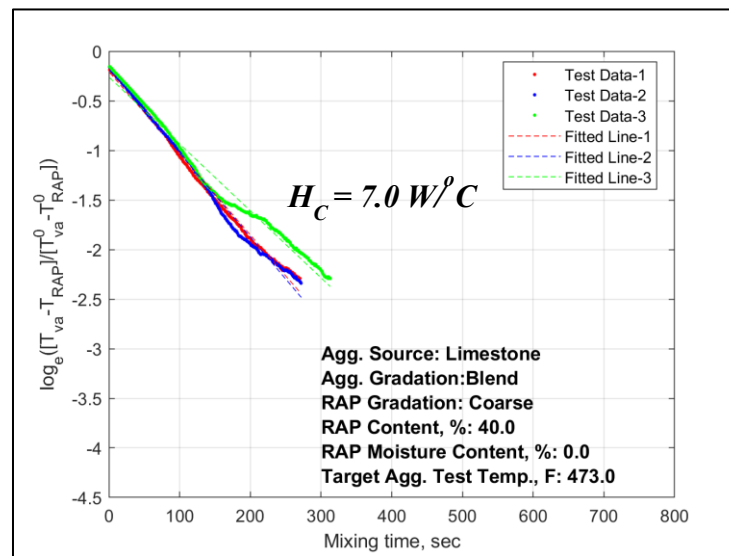
The temperature progression of RAP and virgin aggregate over mixing time, along with initial temperatures of RAP and virgin aggregate, were used to plot $\ln \left[\frac{T_{va} - T_{rap}}{T_{va}^0 - T_{rap}^0} \right]$ against mixing time, as shown in Figure 3.14. The slope of this plot until T_{equi} was used to calculate heat conductance for a given combination, shown in Equation 3.10. Heat transfer between the virgin aggregate and RAP was negligible after T_{equi} . Consequently, there was no measurable exchange of heat between virgin aggregate and RAP.

$$H_c = \frac{Slope}{\left[1 + \frac{m_{va} C_{va}}{m_{rap} C_{rap}} \right] \frac{m_{va} C_{va}}{m_{va} C_{va}}} \quad (3.10)$$

The mentioned analysis procedure for heat conductance computation was used to determine heat conductance values for all of the heat transfer testing conducted as part of the experimental matrix.



(a)



(b)

Figure 3.14: Heat Conductance Calculation for (a) fine RAP, and (b) coarse RAP.

3.6 Validation of Assumptions During Development of the Test

From the blending chamber development to the analysis framework, the following are the primary assumptions made during the process:

- The fabricated blending chamber can produce uniform and continuous mixing of RAP and virgin aggregate.
- Temperature characteristics within the surface FOV represent the behavior of the entire mixture in the drum.
- The assumption of the 5th and the 95th percentile of the FOV as RAP and virgin aggregate temperatures are reasonable.

As validating these assumptions with physical experiments is practically difficult, DEM simulations were used to verify these assumptions. All the DEM simulations and the associated data presented in this section belong to Andrew Hobbs with ASTEC industries. The simulation data was used only as a complement to validate the assumptions made in the test method development.

The DEM method simulates the movement of particles during the mixing and heat transfer process based on particle dynamics. DEM simulation method with the soft contact particle model was used for thermal exchange by following the approach proposed by Hobbs et al. (2020). Two binary mixtures were simulated to replicate the heat transfer testing process used in this study. The simulated particle temperatures of the mixtures are shown in Figure 3.15.

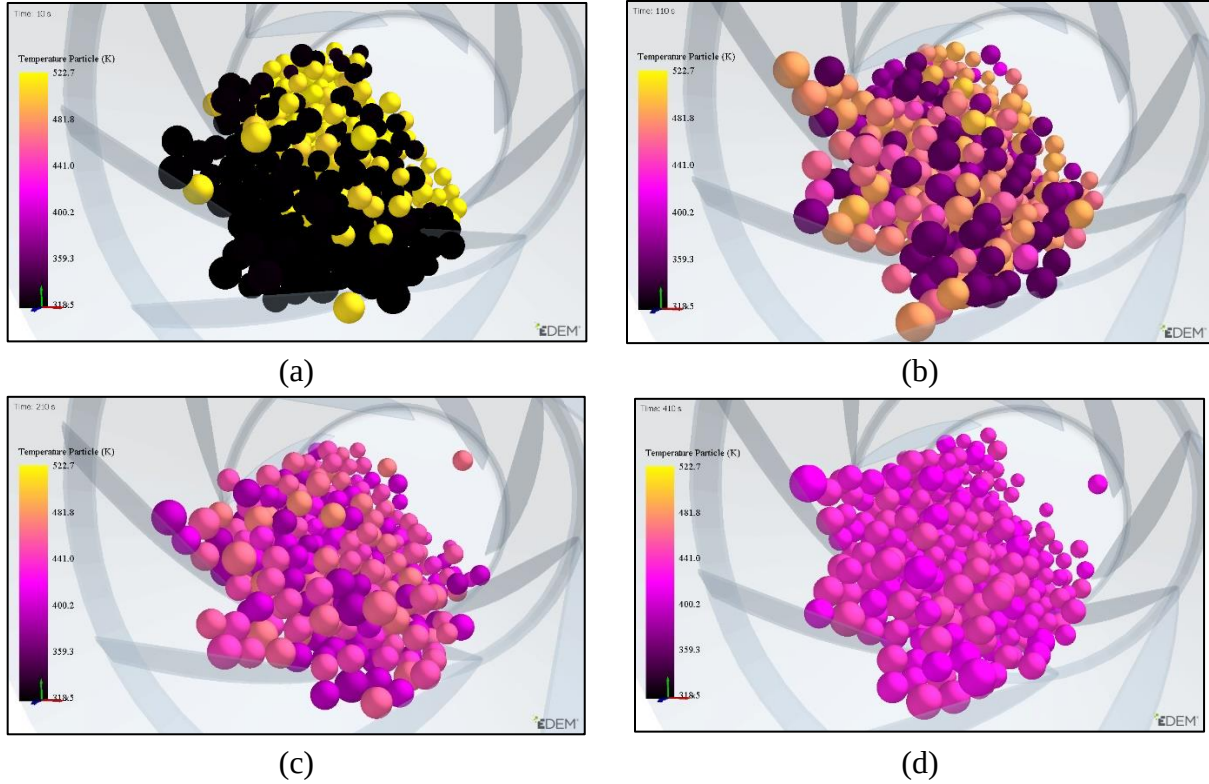


Figure 3.15: DEM simulated particle temperature values at: (a) 10, (b) 110, (c) 210, and (d) 410 sec after RAP addition.

Two mixtures with 10% and 40% RAP were selected to include low and high RAP contents. As dense-graded mixtures are computationally expensive and take several days for simulation, single-sized gradations were used for both RAP and virgin aggregate. Both RAP and virgin aggregate used had the following gradation: 100% of the particles pass through the 1-in. screen (25.4 mm) while 35% of the particle mass retained on a 3/4-in. screen (19 mm), and the remaining 65% retained on a 1/2-in. screen (12.5mm).

3.6.1 Mixing Capability of the bending chamber

An image analysis technique was used to evaluate the uniform and continuous mixing capability of the blending chamber using both DEM and experimental testing data. A segregation index proposed by Xiau et al. (2017) was incorporated to investigate the time required before RAP and virgin aggregate are blended into a homogenous mixture.

In the DEM analysis, RAP particles were colored as black spheres, and virgin aggregate particles were colored as white. The images were extracted from the simulation every second and converted to a greyscale image, as depicted in Figure 3.16.

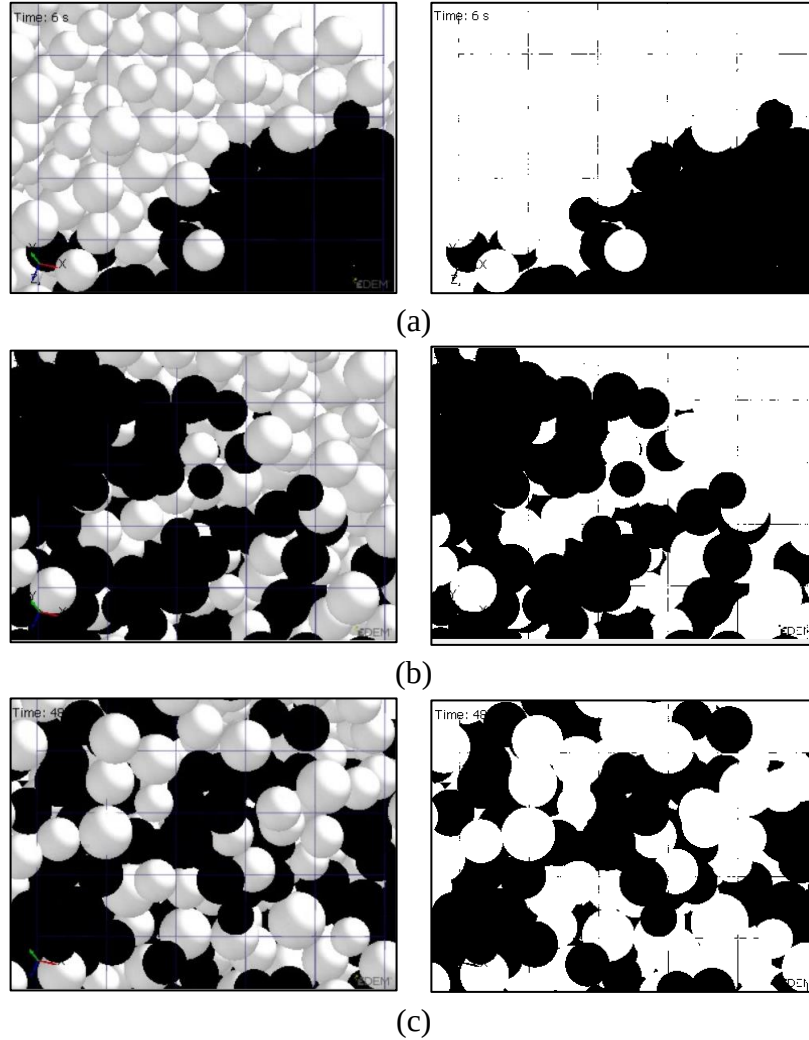


Figure 3.16: Screenshots from DEM simulation and converted greyscale picture at (a)1, (b) 3, and (c) 42 sec after RAP addition.

Each greyscale screenshot was divided into 100 squares blocks to calculate the segregation index at each second of mixing for 60 seconds after addition of RAP to virgin aggregate, as follows:

$$\varphi_i = \frac{a_i}{a_i + b_i} \quad (3.11)$$

$$\varphi = \frac{\sum_{i=1}^N a_i}{\sum_{i=1}^N (a_i + b_i)} \quad (3.12)$$

$$S = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (X_i - \bar{X})^2} \quad (3.13)$$

Where,

a_i and b_i = Number of black and white pixels respectively within square block i.

S = Segregation Index

X_i = φ_i / φ

$\bar{X}$ = Mean of X_i .

When RAP and virgin particles are not mixed, the segregation index is high, and it is low when uniform mixing happens between RAP and virgin aggregate.

Heat transfer experiment was conducted on 10% and 40% RAP mixtures with limestone using the same gradations as the simulation for RAP and virgin aggregate. Thermal images after the addition of RAP were extracted for every 1-second interval for 60 seconds. These thermal images were converted to a greyscale image, as shown in Figure 3.17. It should be noted that Figure 3.17(a) and Figure 3.17(b) are only examples and do not belong to the same testing. The fore-mentioned segregation index calculation procedure was followed even for the experimental data.

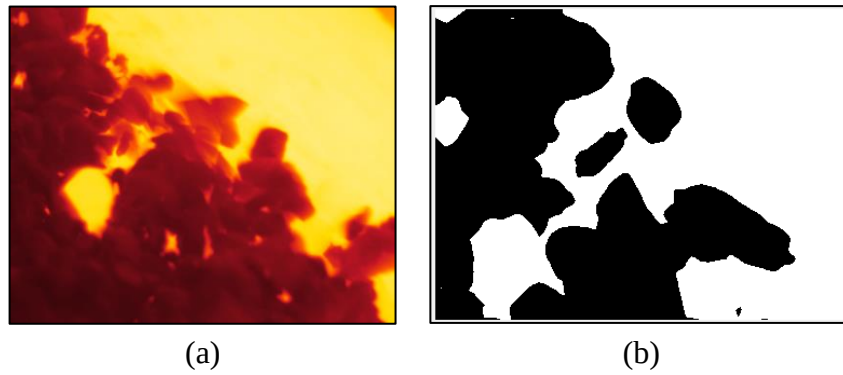


Figure 3.17: Thermal image from experiment and converted greyscale picture.

Figure 3.18 presents the change in the segregation index of 10% and 40% RAP binary mixtures. With mixing time, the segregation index dropped rapidly and eventually stabilized to a plateau value. The steep drop in the segregation index was due to the dispersion of added RAP particles into the mixture to form a uniform mixture. The segregation index for both low-and high-RAP contents stabilized at around 8-12 seconds, which is reasonably quick dispersion of RAP particles into the mixture. The segregation index calculated from experimental data was matching with the value calculated using DEM simulation data. This reveals the fact that DEM simulation was able to recreate the particle mixing dynamics of the experimentation.

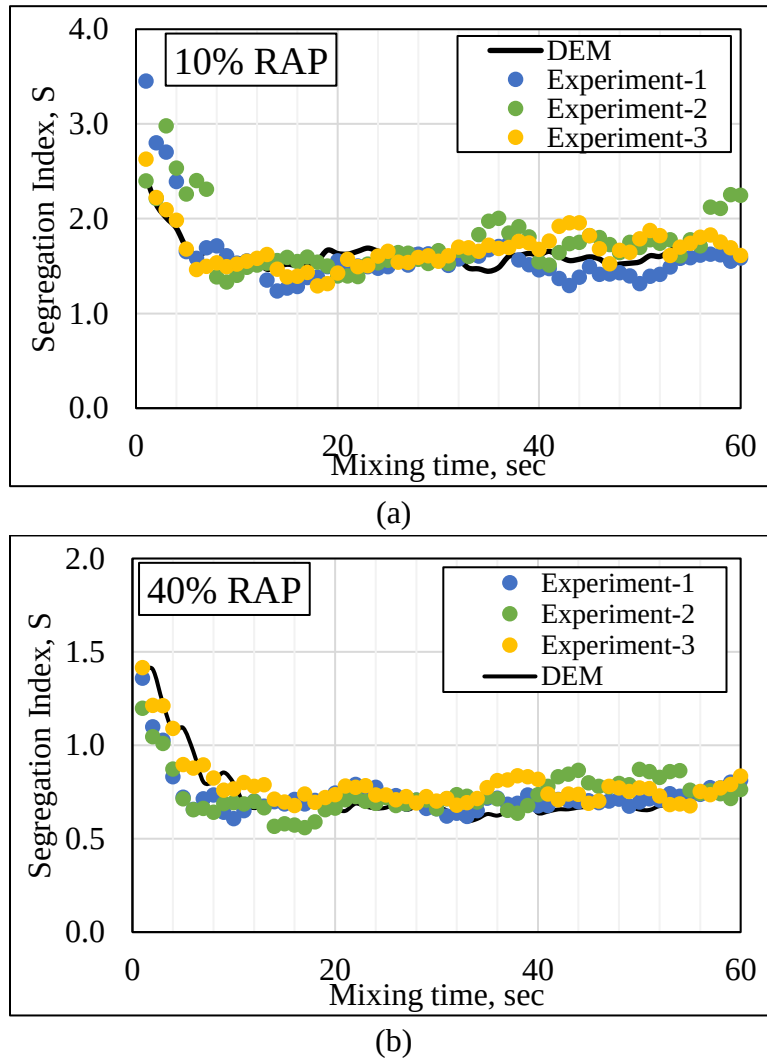
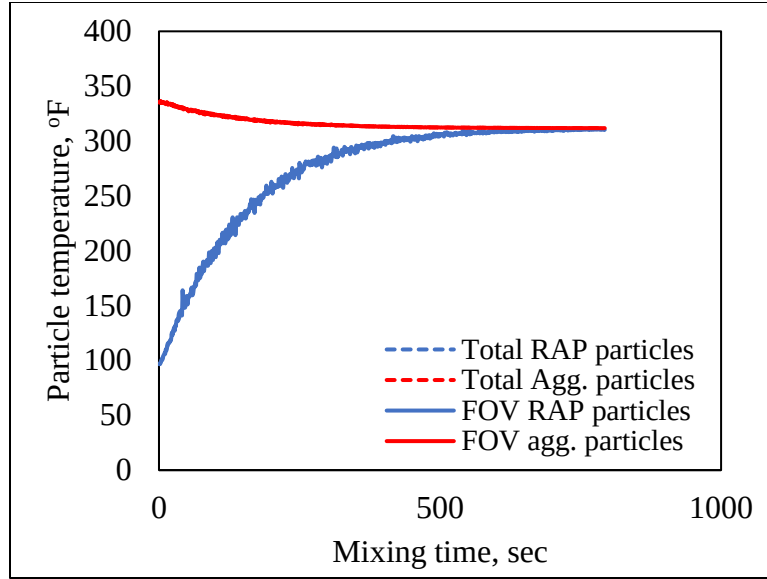


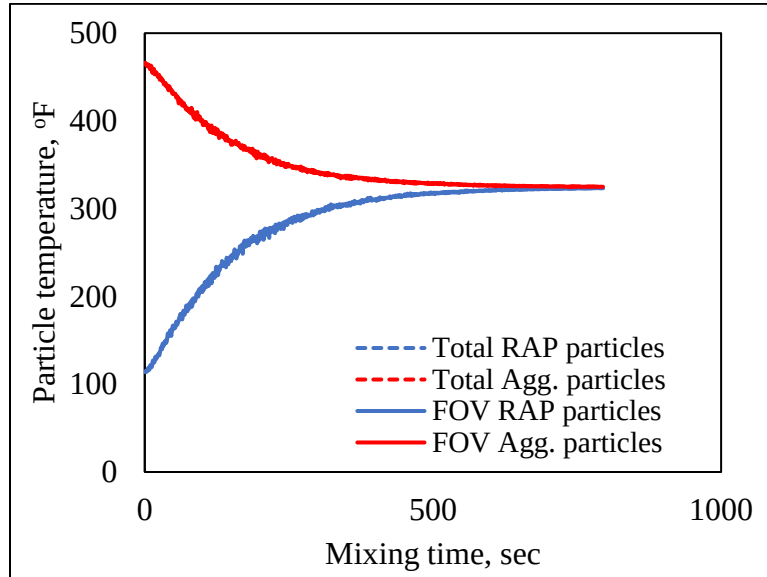
Figure 3.18: Segregation index for both DEM simulation and experimental data for (a) 10%, and (b) 40% RAP mixtures.

3.6.2 Surface Particles Vs. Total Mixture Temperature Characteristics

As mentioned in section 3.2, the selected IR camera at 0.4 m distance was able to measure the temperature of the 5.3 x 4.0 in FOV on the surface of the mixture, mixing in the chamber. It is important to understand how well the 5.3 x 4.0 in surface particle temperature characteristics would represent the entire mixture temperature profile. But experimental confirmation of which is practically difficult. Therefore, DEM simulation data for 10% and 40% RAP were used and temperature profiles from the DEM simulation are shown in Figure 3.19. Average particle temperatures of RAP and virgin aggregate of the entire mixture were extracted for 10% and 40% RAP mixtures. A sample area of 5.3 x 4.0 in was set on the surface, average particle temperature of RAP and virgin aggregate in the surface sample area were extracted. Figure 3.19 presents a comparison of entire particle temperature characteristics and particles in the surface sample area from the DEM simulations. It can be concluded that the surface sample area similar to IR camera measurement is a good representative sample of the entire mixture to understand the temperature characteristics of the RAP and virgin aggregate particles.



(a)



(b)

Figure 3.19: Particle temperature of the entire particles in the blending chamber Vs. Particles on the surface sample area: (a) 10% RAP, and (b) 40% RAP mixtures

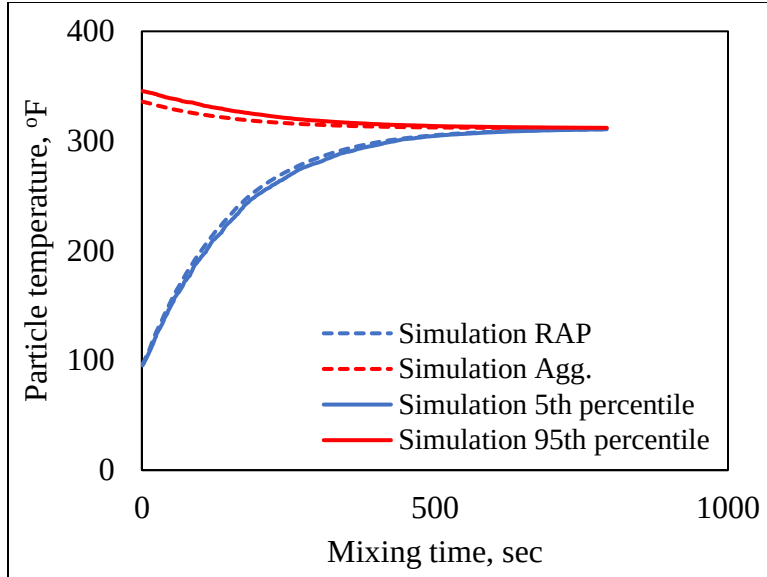
3.6.3 Mixing Capability of the bending chamber

One of the primary assumptions of the study is the definition of RAP and virgin aggregate temperatures from IR camera measurements. As the IR camera cannot distinguish between virgin aggregate particles and RAP particles, this assumption needs to be validated. The DEM analysis is capable of labeling RAP and virgin aggregate particles and can keep track of RAP and virgin

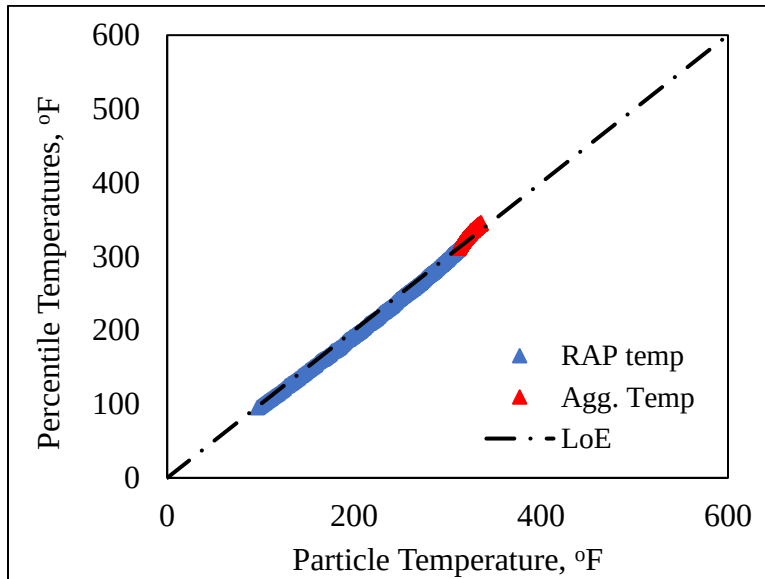
particle temperatures over time. Therefore, DEM simulation data was used to validate this assumption.

Average RAP particle temperature, average virgin particle temperature, 5th percentile of all particle temperature, and 95th percentile of all particle temperature in the blending chamber were extracted for 10% and 40% RAP simulations. Both RAP and virgin aggregate temperatures were compared over mixing time for 10% and 40% RAP cases.

Figure 3.20 presents a comparison between the 5th percentile and RAP temperature, and the 95th percentile and virgin aggregate temperature. Based on Figure 3.20 and Figure 3.21, it can be concluded that the definition for RAP and virgin aggregate temperatures made in this study is reasonable. It should be noted that these assumptions were validated using single-sized coarse RAP and virgin aggregate gradation. So, the change in gradations would change particle dynamics and may affect the validation process.

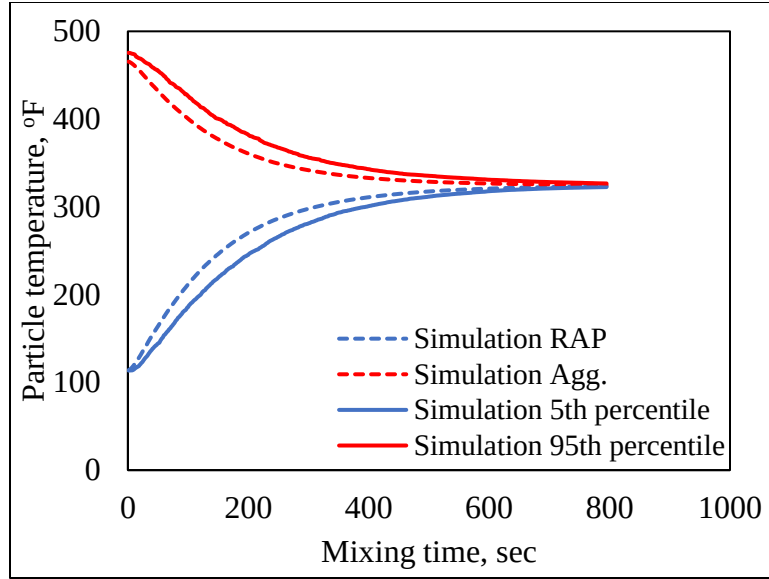


(a)

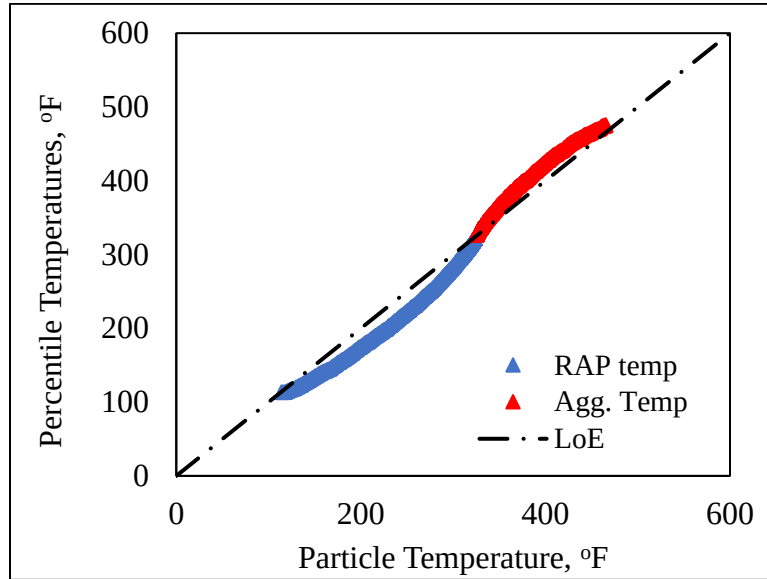


(b)

Figure 3.20: Comparison of average RAP, virgin aggregate, 5th percentile, and 95th percentile of all particles in the DEM simulation for 10% RAP mixture.



(a)



(b)

Figure 3.21: Comparison of average RAP, virgin aggregate, 5th percentile, and 95th percentile of all particles in the DEM simulation for 40% RAP mixture.

3.7 Repeatability of Developed Heat Transfer Test Method

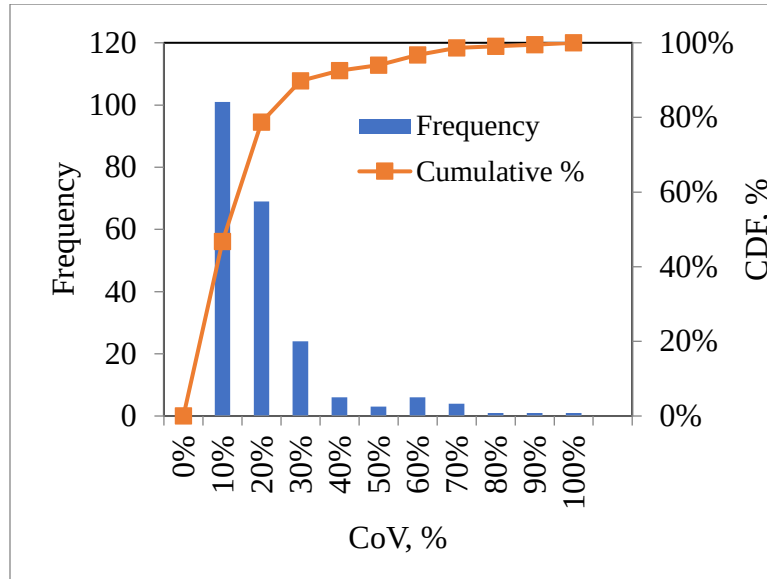
A total of 216 heat transfer test combinations were tested with three replicates each, and the results of T_{equi} and heat conductance are presented in Appendix B. Details of the experimental matrix are discussed in detail in the next chapter. An attempt was made in this section to understand the

variability of the calculated heat transfer parameters: (a) time required for completion of heat transfer, T_{equi} , and (b) heat conductance, H_C .

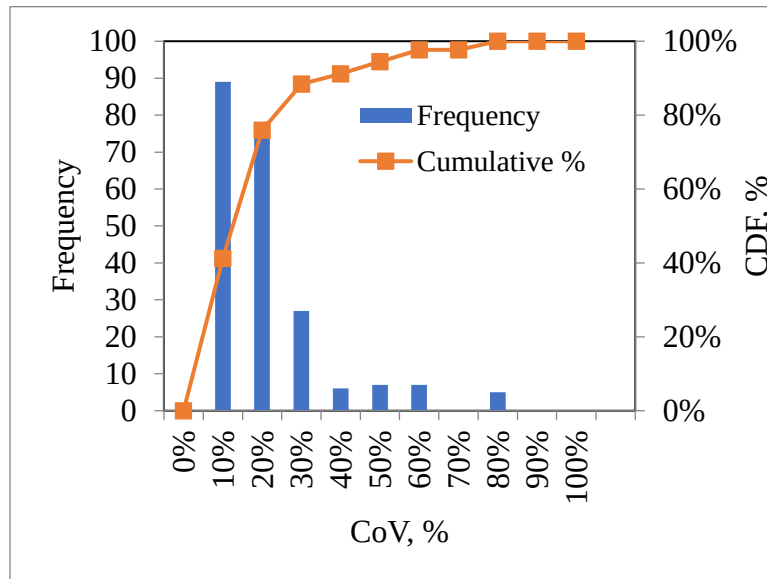
Most of the dataset produced repeatable results with three replicates for both T_{equi} and H_C . However, few combinations produced highly variable data with coefficients of variability (COV) over 30% (Figure 3.22). With only three replicates, an interquartile range or z-test analyses were not feasible to determine outliers. Therefore, the following analytical method based on T_{equi} data was adopted to identify the outliers:

- The 216 computed values of COV for T_{equi} were used as a data set. The mean COV value plus three times the standard deviation was determined and used as a threshold value to detect test combinations responsible for high variability (COV values higher than the threshold).
- For a material combination, heat transfer testing was conducted at three different superheated temperatures. As three replicates were tested at a superheated temperature, in total, there were nine T_{equi} values for a material combination. It was expected that all nine data points fall in the same range.
- The detected test combinations with high variability were analyzed to identify the existence of replicate values not in the common range of the remaining data points; that data point was identified as an outlier.
- Any test combined with a detected outlier was omitted from further analysis, as it was difficult to represent deviations in a dataset having two or one replicate data for a test combination.

- The process was repeated four times until no outliers were identified. In the end, the mean COV for T_{equi} changed from 15.3%, to 13.6%, to 12.3%, to 12.0%. And the standard deviation of COV for T_{equi} reduced from 15.1% to 11.5%, to 8.9%, to 8.4%.



(a)

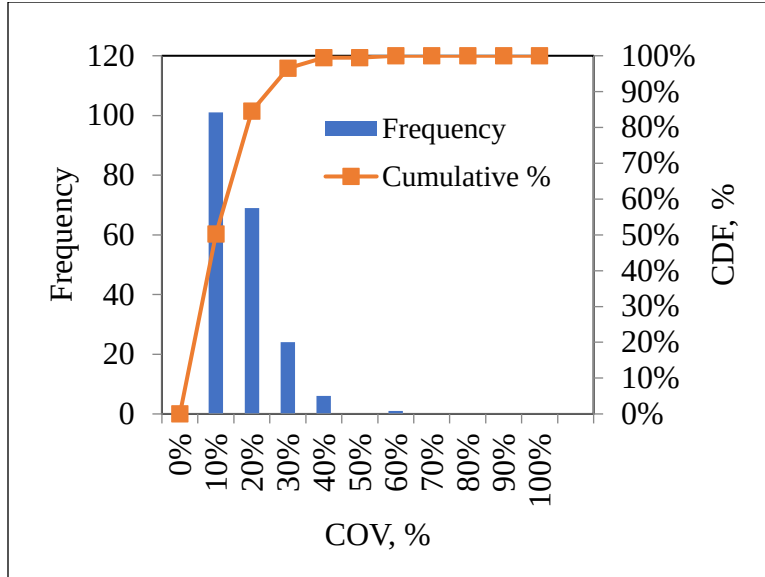


(b)

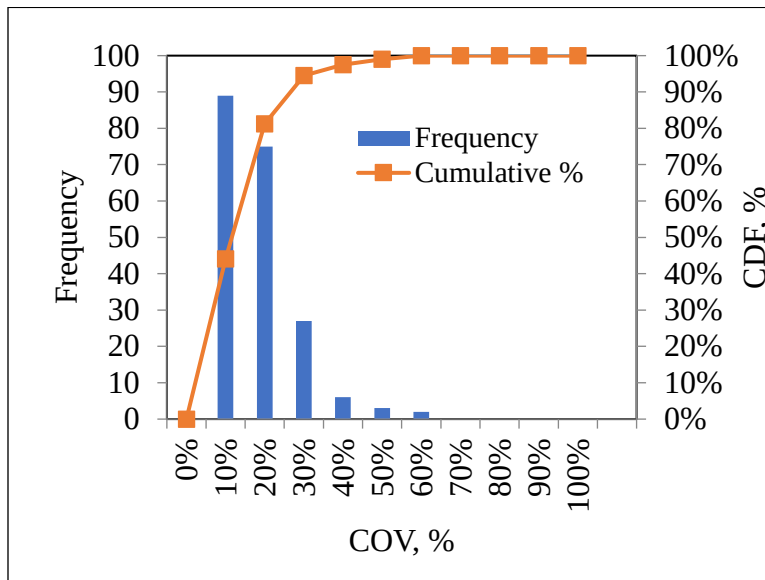
Figure 3.22: Coefficient of variation histograms using the original database (216 combinations) for (a) T_{equi} , and (b) H_c .

A total of 13 test combinations were identified and removed from the data set for further analysis. All the datasets identified as outliers belong to test combinations with single-sized (passing #8 and retained on #32 sieve) fine RAP and single-sized (passing #8 and retained on #32 sieve) virgin aggregate gradations. Therefore, it can be concluded that the developed heat transfer test method may not be suitable for fine RAP-fine virgin aggregate gradation combinations.

Figure 3.23 presents the histogram of COV of T_{equi} and H_C after removing the omitted test combinations. The 98th percentile COV of T_{equi} and H_C was 66.1% and 70.5% for the original data. They decreased to 32.3% and 41.7%, respectively, after removing the outliers. Concisely, the developed heat transfer test method was capable of producing repeatable results with three replicates.



(a)



(b)

Figure 3.23: Coefficient of variation histograms after removing outlier test combinations from the original database (200 combinations) for (a) T_{equi} , and (b) H_c .

3.8 Summary

The following observations and conclusions are extracted from the efforts of this chapter:

- A new heat transfer test method was developed, which included the establishment of (a) blending chamber with uniform and continuous mixing of particles, (b) IR camera, and (c) consistent step-by-step test procedure.
- A mathematical analysis framework was built to calculate the time required for thermal equilibrium between virgin aggregate and RAP using raw data from heat transfer testing.
- A theoretical solution was developed to calculate heat conductance between virgin aggregate and RAP using raw data from heat transfer testing.
- DEM simulation data was used to validate the assumptions made in the study for testing, extracting, and analyzing the heat transfer test data:
 - Segregation index analysis based on image analysis of DEM and experimental data confirmed that the blending chamber achieves uniform and continuous mixing of particles within the first 8-12 seconds of mixing.
 - Temperature characteristics of particles rolling on the surface of the mixtures are a representative sample of the entire mixture.
 - Assumption of 5th percentile and 95th percentile as RAP and virgin aggregate temperature is reasonable.
- The developed heat transfer test method and analysis framework produced repeatable results with three replicates.

CHAPTER 4 LABORATORY INVESTIGATION OF HEAT TRANSFER

The flow chart (Figure 4.1) presents the research methodology used to investigate the heat transfer process between virgin aggregate and RAP in this chapter.

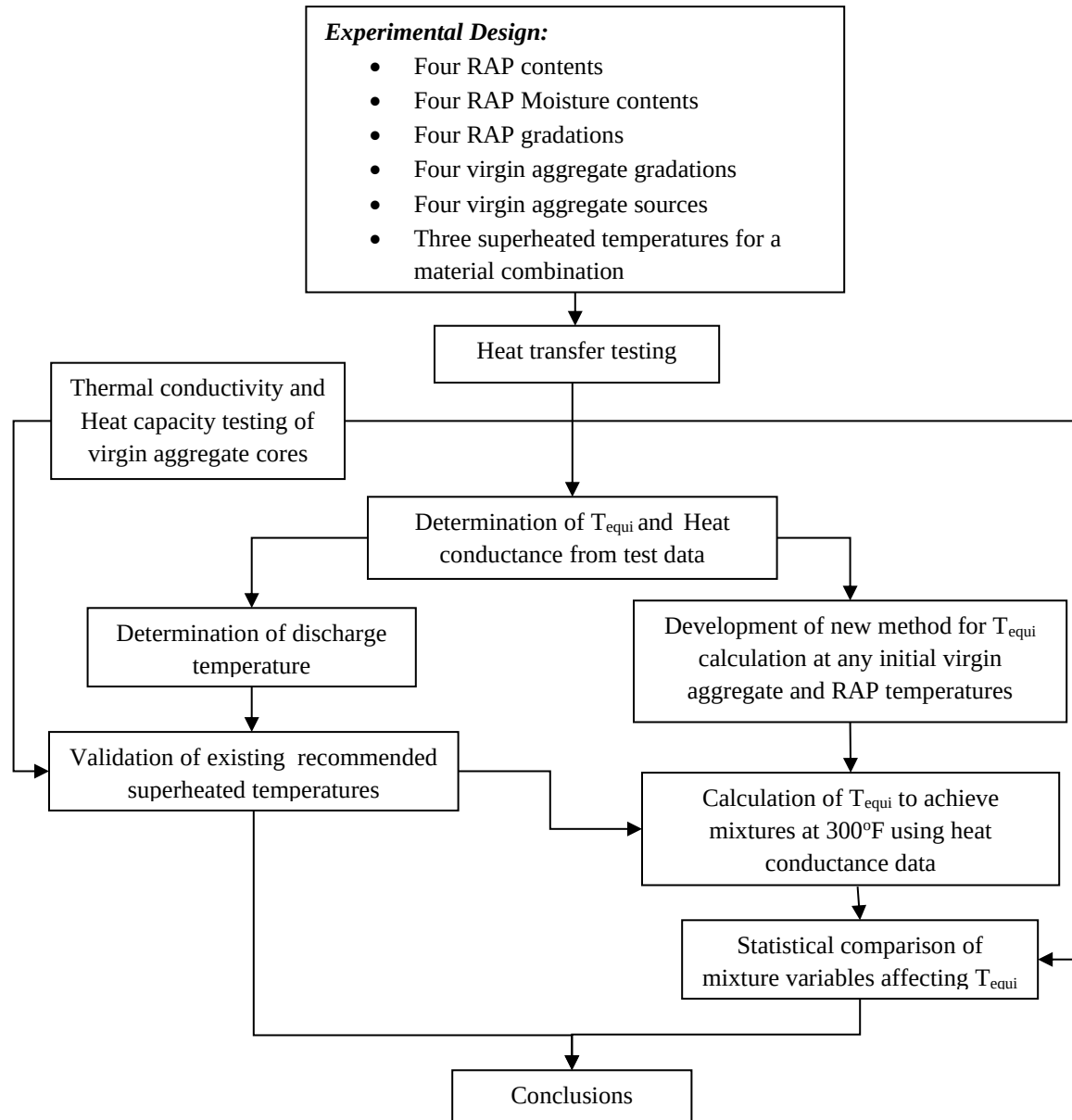


Figure 4.1: Methodology flow chart used to investigate heat transfer.

4.1 Experimental Design

The experimental matrix presented in Table 4.1 was designed to understand the effect of RAP gradation, virgin aggregate gradation, virgin aggregate thermal properties, RAP content, and RAP moisture content on heat transfer time and final discharge temperature of asphalt mixtures.

- Four virgin aggregate sources and one RAP source were used to study the effect of virgin aggregate thermal properties on final discharge temperature and heat transfer.
- Four different sizes of RAP were taken, which are RAP passing through No. 4 sieve (fine RAP), retained on No. 4 sieve (coarse RAP), and two uniform sizes (passing #4 and retaining on #16 sieve (FA*), and passing 1" and retaining on ½" sieve (CA*)).
- Four different virgin aggregate sizes were used. Two uniform virgin aggregate sizes (passing #4 and retaining on #16 sieve (FA*) and passing 1" and retaining on ½" sieve (CA*)) were used. For tests containing fine RAP and coarse RAP cases, a blending exercise was conducted to maintain the gradation of the final mixture (RAP + virgin aggregate) for all RAP contents as closely as possible (shown in Figure 4.2). Test combinations with blended virgin aggregate gradations are referred to as dense gradation combinations, and combinations with uniform size RAP and virgin aggregate are referred to as theoretical gradation combinations hereafter.
- Four RAP contents: 10%, 20%, 30%, and 40% by weight of the mixture and four RAP moisture contents: 0%, 1%, 3%, and 5% by weight of RAP were selected for dense gradations, and a moisture content of 3% by weight of RAP was used for theoretical gradations.

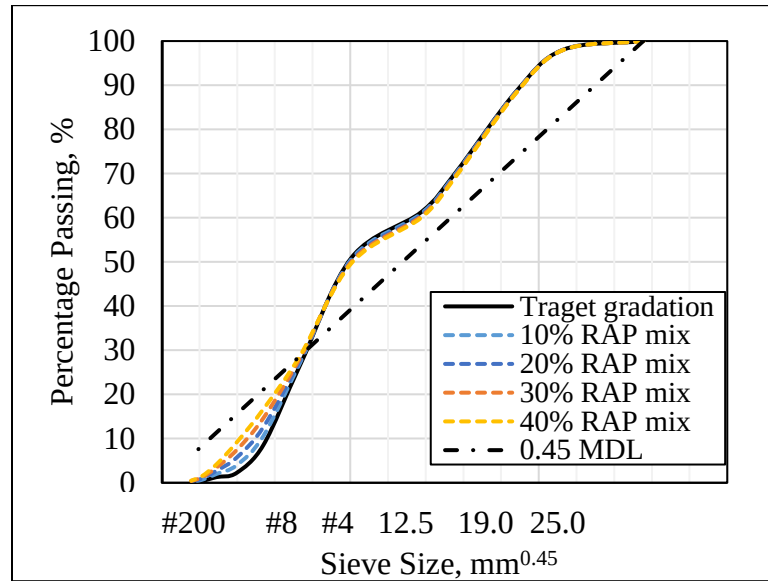
Table 4.1: Experimental design for the study.

Virgin Aggregate Gradation		FA*		Blend		CA*	
RAP Gradation		FA*	CA*	FA	CA	FA*	CA*
		Theoretical		Dense		Theoretical	
RAP content	RAP Moisture content						
10%	0%			A	A		
	1%			A	A		
	3%	ABCD	ABCD	A	A	ABCD	ABCD
	5%			A	A		
20%	0%			A	A		
	1%			A	A		
	3%	A	A	A	A	A	A
	5%			A	A		
30%	0%			A	A		
	1%			A	A		
	3%	A	A	A	A	A	A
	5%			A	A		
40%	0%			A	A		
	1%			A	A		
	3%	ABCD	ABCD	A	A	ABCD	ABCD
	5%			A	A		

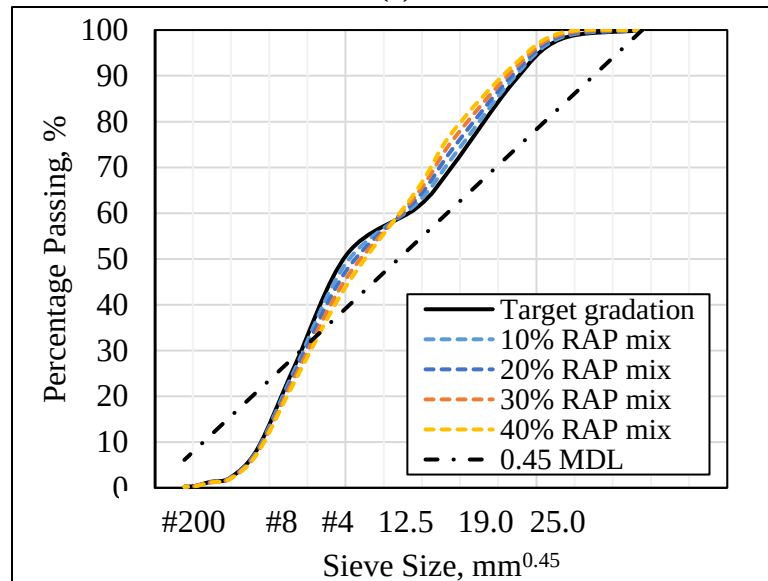
- FA** -Passing through #4 sieve
CA -Retaining on #4 sieve
FA* -Passing #8 and retaining on #16 sieve
CA* -Passing ¾" and retaining on ½" sieve
Blend -Blended gradation to meet the final target gradation
A -Limestone source in Alabama
B -Dolomite source in Iowa
C -Basalt source in Washington
D -Quartzite source in South Dakota

For analysis purposes, the experimental matrix was divided into two major datasets: (a) dense graded combinations and (b) theoretical gradation combinations. Dense graded combinations were designed to have a consistent final gradation for different RAP contents and RAP sizes. As described in the previous chapter, for dense gradation testing scenarios, four different RAP contents (0%, 10%, 20%, and 40%) were tested at four RAP moisture contents (0%,

1%, 3%, and 5%) with two RAP sizes: passing through #4 sieve (fine RAP) and retained on #4 sieve (coarse RAP).



(a)



(b)

Figure 4.2: Gradations of the mixture for blended combinations using: (a) RAP passing through #4, and (b) RAP retained on #4.

Theoretical gradation combinations are the material combinations with uniform particle sizes (FA* & CA*) for both RAP and virgin aggregate. Four different aggregate sources (limestone, dolomite, basalt, and quartzite) were tested at 10% and 40% RAP contents, and

limestone aggregate source was additionally used for 20% and 30% RAP. A RAP moisture content of 3% by weight of RAP was fixed for all theoretical gradation combinations.

One of the study objectives was laboratory validation of the recommended superheated temperatures for the virgin aggregate based on RAP content, RAP moisture content, and target mixture discharge temperature. It was expected that testing each material combination of the experimental matrix at three different superheated virgin aggregate temperatures would result in three final discharge temperatures. The relationship between superheated temperature and discharge temperature from the experimentation could be used to determine the virgin aggregate temperature required for any target discharge temperature of the mixture through interpolation or extrapolation. To select three virgin aggregate temperatures for a material combination, the ASTEC recommendation (ASTEC T-127) for the superheated temperature was used at a discharge temperature of 300°F. The three virgin aggregate temperatures used for testing each combination of RAP content and RAP moisture content are given in Table 4.2. The amount (ΔTemp) by which the lower and upper temperatures deviate from the reference temperature was not constant. Three replicates were tested for each combination at each virgin aggregate temperature and the temperatures were adjusted to maximize the number of tests conducted in a day.

Table 4.2: Superheated virgin aggregate temperatures used for testing.

RAP content (%)	Moisture content (%)	Superheated temperature (°F)		
		Low	Reference	High
10%	0%	305	335	360
	1%	305	340	360
	3%	325	350	385
	5%	335	360	385
20%	0%	342	367	402
	1%	355	375	410
	3%	365	400	420
	5%	385	420	445
30%	0%	385	410	430
	1%	392	427	462
	3%	430	465	490
	5%	490	505	530
40%	0%	445	465	490
	1%	465	490	505
	3%	530	550	575
	5%	575	610	635

4.1.1 Thermal Properties of Virgin Aggregate Material

Four virgin aggregate materials were selected for the study: Limestone (Alabama), Dolomite (Iowa), Basalt (Washington), and Quartzite (South Dakota), covering a range of thermal conductivity values to investigate the effect of virgin aggregate thermal properties on heat transfers. The thermal conductivity and heat capacity of virgin aggregate materials used were tested on virgin aggregate cores. Cylindrical specimens required for thermal property testing were cored from boulders of virgin aggregate quarries. Figure 4.3 shows the virgin aggregate cores used for thermal property testing. Due to existing geologic seams in the Basalt boulder, it was not possible to core a 4-in. diameter specimen; instead, a 2-in. core was taken for testing.

Only one core from each aggregate source was available for testing. Therefore, thermal conductivity and heat transfer tests were repeated three times on each sample. An improved and simplified test method developed at NCAT was used to measure the thermal conductivity of virgin

aggregate cores (Geng and Heitzman, 2016; Alleman and Heitzman, 2019). Further, a test method developed at NCAT was followed to measure the heat capacity of virgin aggregate cores (Alleman and Heitzman, 2019). An improved and simplified test method developed at NCAT was used to measure the thermal conductivity cores (Geng and Heitzman, 2016; Alleman and Heitzman, 2019) and heat capacity (Alleman and Heitzman, 2019) of virgin aggregate cores. The method requires a cylindrical sample 4 in. in diameter and 5 in. high. However, the samples used for testing deviate from the required dimensions (shown in Table 4.3), especially the Basalt specimen with a 2-in. diameter. Table 4.3 and Figure 4.4 summarize the measured thermal property values of selected virgin aggregates.

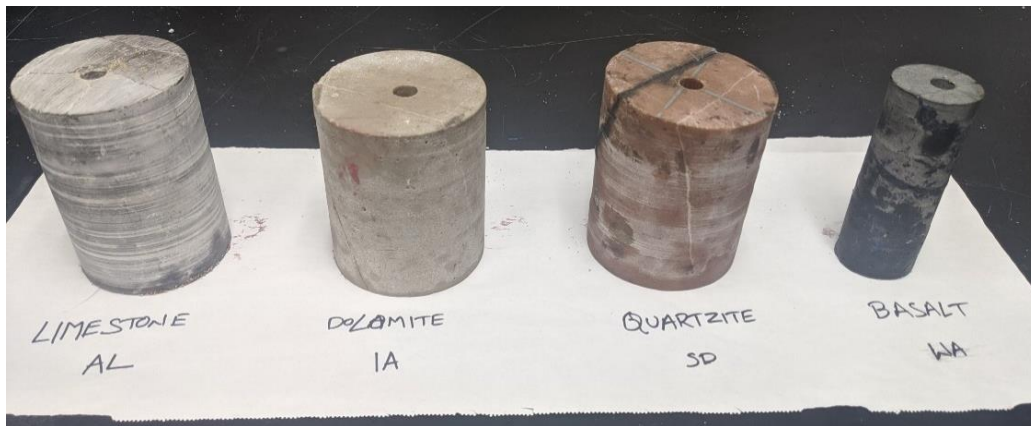
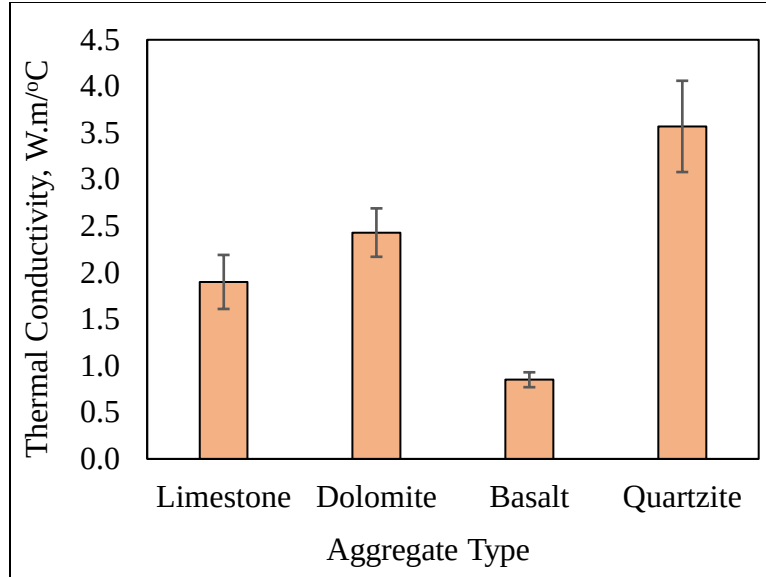


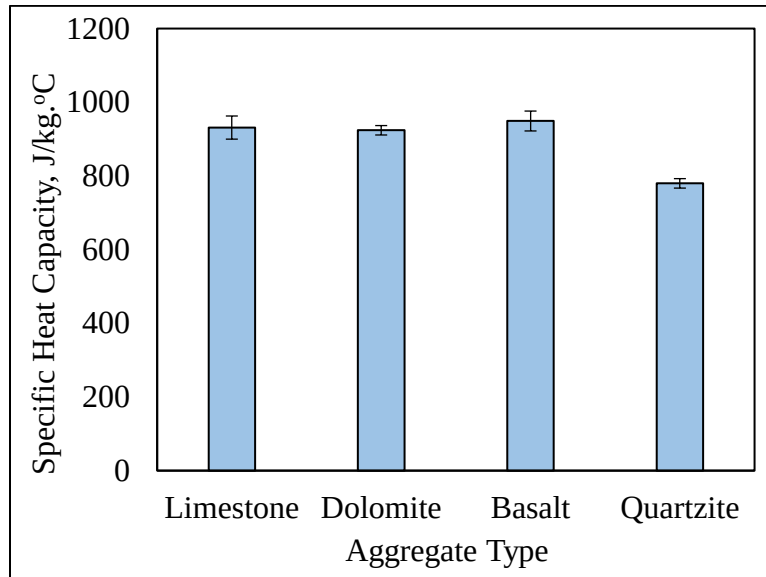
Figure 4.3: Virgin aggregate cores used for thermal property testing.

Table 4.3: Thermal Conductivity and Heat Capacity Values for the Aggregate Sources Used.

Aggregate Type	Location	Core Dimensions, mm		Thermal Conductivity, W.m/°C	Heat Capacity, J/kg.°C
		Height	Diameter		
Limestone	Alabama	129.7	93.8	1.90	931
Dolomite	Iowa	119.9	101.1	2.43	924
Basalt	Washington	131.4	50.2	0.85	949
Quartzite	South Dakota	126.2	101.5	3.57	780



(a)



(b)

Figure 4.4: (a) Thermal Conductivity, and (b) heat Capacity values for the aggregate sources used: error bars represent one standard deviation above and below mean.

4.2 Validation of Existing Superheated Temperature Recommendations

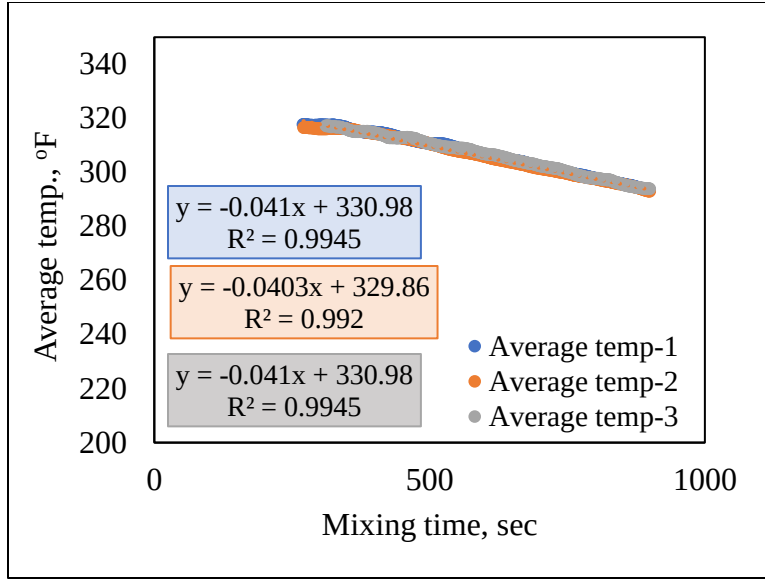
For the validation of exiting superheated temperatures, data corresponding to the dense-graded scenarios was used. As mentioned in the previous chapter, heat transfer testing for a material combination was performed at three superheated virgin aggregate temperatures. The three tested superheated temperatures yielded three final mixture discharge temperatures for a material

combination; this relation was used to interpolate superheated temperature corresponding to 300°F discharge temperature for a material combination. The exact process was repeated for all the dense-graded material combinations considered in this study.

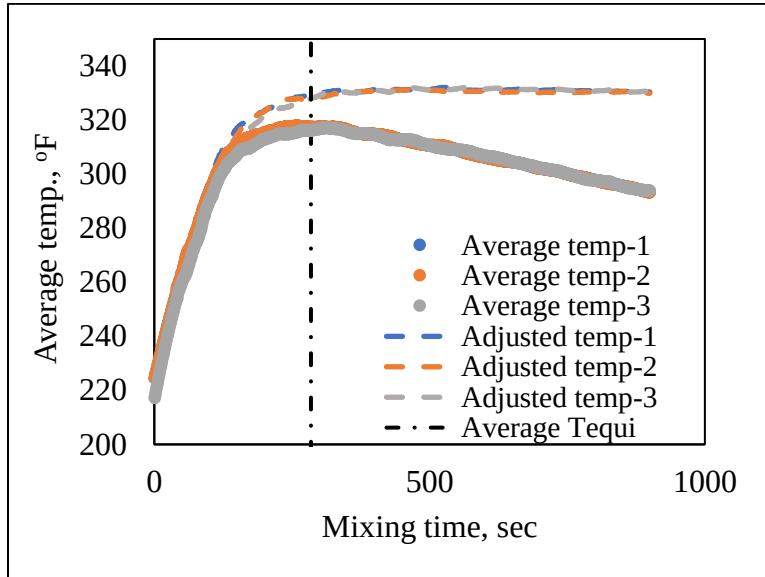
Final discharge temperature achieved during the heat transfer testing at a tested superheated temperature was extracted using the procedure explained below:

As mentioned in section 3.3.1, discharge temperature for a mixture is the average temperature of the mixture based on the entire FOV at T_{equi} . However, because of the heat losses from the blending chamber, the final discharge temperature from the IR camera measurements does not represent the true discharge temperature solely based on aggregate/RAP heat exchange. Therefore, an adjustment had to be made for the measured discharge temperature using the following framework for accounting for the blending chamber heat losses during the blending time.

An example of the measured average temperature of the mixture in the blending chamber is shown in Figure 4.5(b). The change in the measured average temperature of the mixture pre T_{equi} (calculated as per section 3.5.1) is due to the combination of aggregate/RAP heat transfer and heat losses from the blending chamber. And the change in average temperature post T_{equi} is solely due to heat losses from the chamber. Therefore, the slope of the average temperature curve post T_{equi} can be used to calculate the temperature loss per second of the average temperature. A linear regression equation was fitted for the measured temperature post T_{equi} . It is assumed that the slope of the linear regression equation represents the average heat loss per second (ΔT_{avg}) from the blending chamber for the material combination tested, shown in Figure 4.5(a). This average heat loss per second was used to adjust the average temperature of the mixture for the chamber heat losses, as shown in Figure 4.5-(b).



(a)



(b)

Figure 4.5: Illustration of heat loss correction for the average temperature of the mixture: (a) determination of heat loss per second ($\Delta Temp_{avg}$), and (b) actual versus adjusted average temperatures.

The true discharge temperature for a material combination tested can be determined using Equation 4.1.

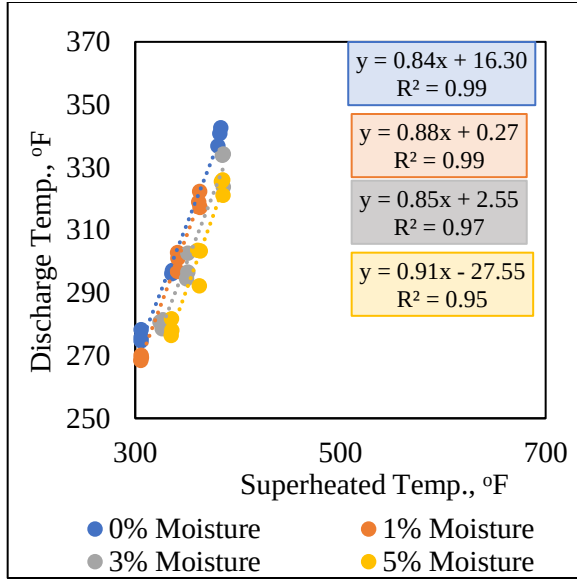
$$Temp_{Discharge} = Temp_{avg}(T_{equi}) + \Delta Temp_{avg} \times T_{equi} \quad (4.1)$$

Where,

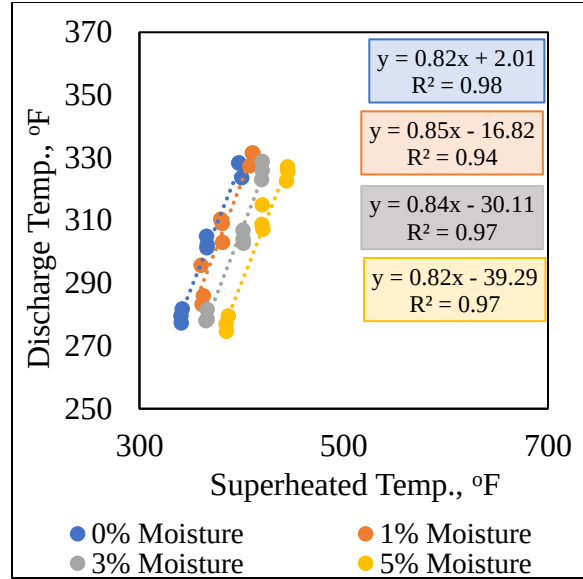
$$\begin{aligned}Temp_{avg}(T_{equi}) &= \text{Average measured temperature of the mixture at } T_{equi}, ^\circ F \\T_{equi} &= \text{Time required for heat transfer completion, sec} \\ \Delta Temp_{avg} &= \text{Average temperature drops from the blending chamber per second, } ^\circ F/sec \\T_{empDischarge} &= \text{True discharge temperature, } ^\circ F\end{aligned}$$

Figure 4.6 and Figure 4.7 show the superheated temperatures versus final discharge temperatures for the dense-graded combinations with fine and coarse RAP, respectively. At a given RAP content, discharge temperature lines shift to the right with a similar slope as the moisture content increases. The developed experimental-based straight-line regression equations were used to interpolate or extrapolate the superheated temperature required for a 300°F discharge temperature. These results were based on laboratory data, not field plant production.

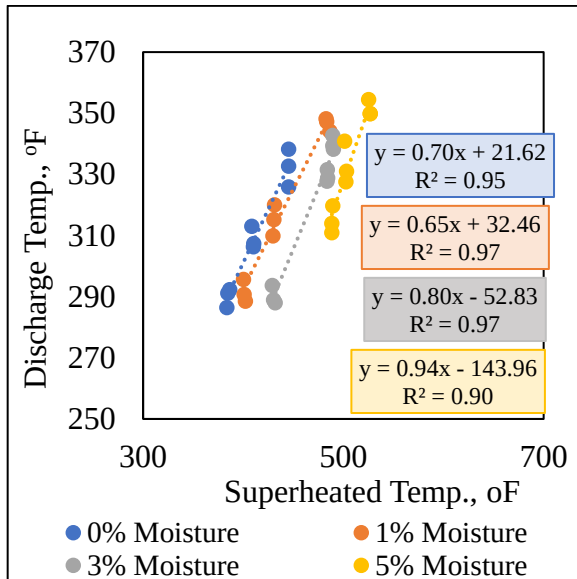
In total, 32 dense-graded material combinations were tested as part of the experimental matrix, resulting in 32 straight line regression equations between superheated temperature and discharge temperature. Two out of 32 had a poor correlation between superheated temperature and discharge temperature ($R^2 < 0.8$). Nevertheless, all the regression equations developed were used for the interpolation of superheated temperatures required for 300°F discharge temperature.



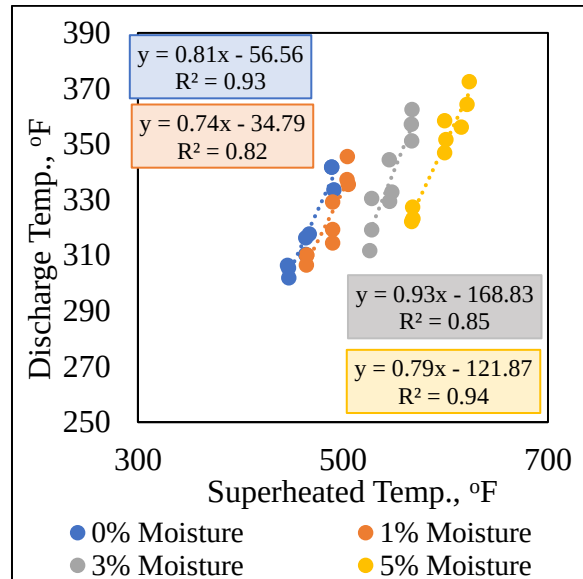
(a)



(b)



(c)



(d)

Figure 4.6: Superheated temperature versus discharge temperature for fine RAP at: (a) 10%, (b) 20%, (c) 30%, and (d) 40% RAP contents using limestone virgin aggregate.

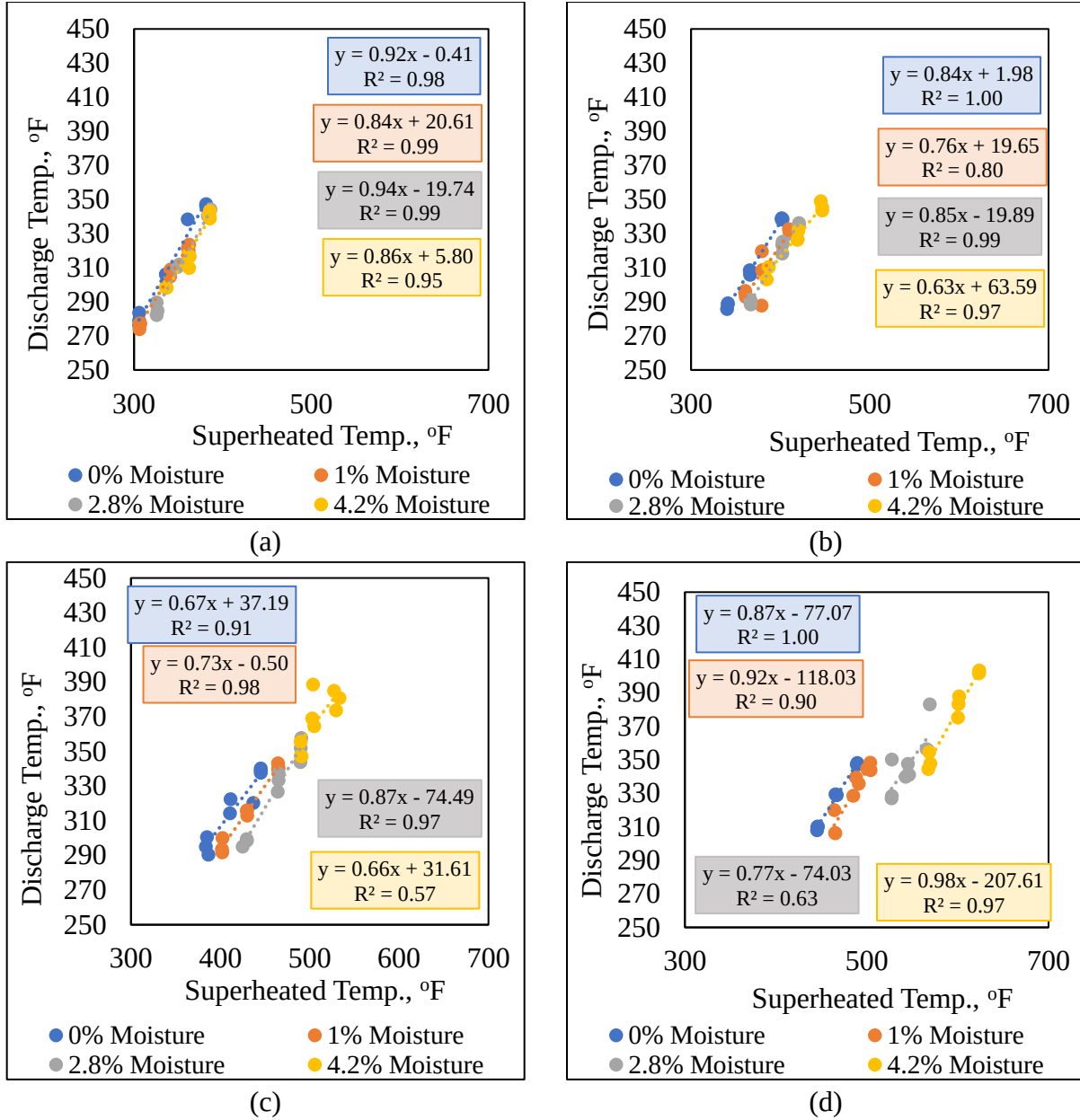


Figure 4.7: Superheated temperature versus discharge temperature for coarse RAP at: (a) 10%, (b) 20%, (c) 30%, and (d) 40% RAP contents using limestone virgin aggregate.

It was discussed earlier in Chapter 1 that ASTEC recommended superheated temperatures were based on Equation 4.2 (ASTEC T-127). A comparison of ASTEC T-127 existing recommendations versus the values obtained from this study is presented in Figure 4.8 ($\pm 2\%$ deviation lines from equality are also plotted). At lower RAP contents and lower moisture contents, values calculated using Equation 4.2 and the results from the laboratory were in good agreement.

However, for mixtures with higher RAP and moisture contents, Equation 4.2 resulted in higher superheated temperatures compared to the experimental results of the study.

$$T_{v.a.} = \frac{T_{RHMA} - S_{RAP} \cdot T_{RAP}}{1 - S_{RAP}} + 4.0 \times \frac{S_{RAP} \cdot W_{RAP}}{1 - S_{RAP}} (100 - T_{RAP} + 537) \quad (4.2)$$

Where,

- $T_{v.a.}$ = Superheating temperature of virgin aggregates, °C
 T_{RHMA} = Required temperature of recycled hot mix asphalt, °C
 S_{RAP} = Percentage of RAP by weight of the dry mixture (without virgin binder), as a decimal
 T_{RAP} = Initial temperature of RAP, °C
 W_{RAP} = Percentage of Moisture by weight of dry RAP, as a decimal

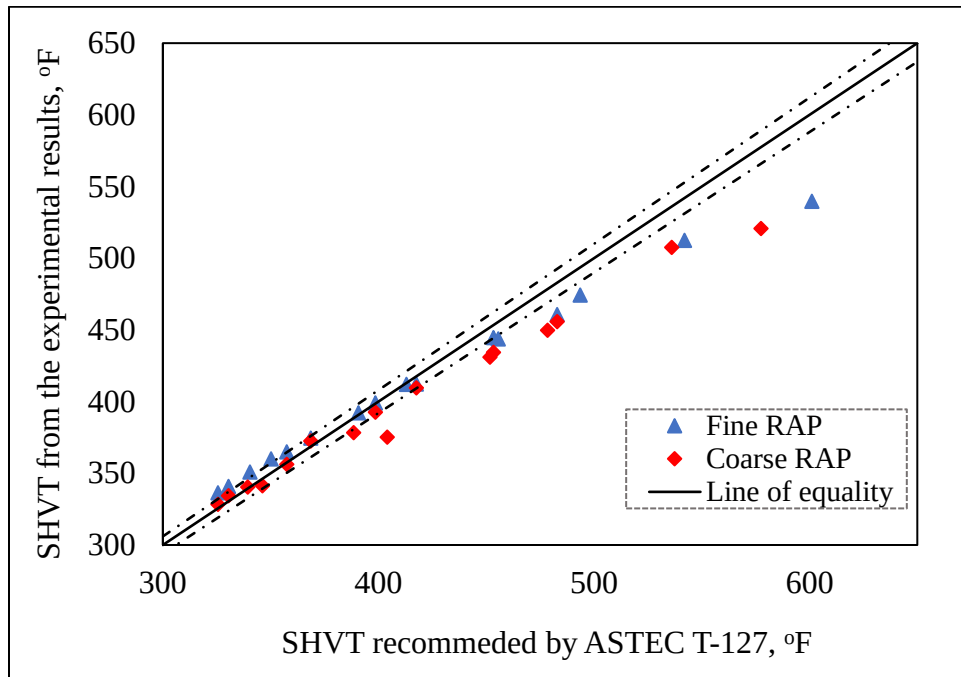


Figure 4.8: Comparison of superheated virgin aggregate temperature (SHVT) obtained from the experimental results and Equation 4.2.

Equation 4.2 was based on the energy balance of excess temperature in virgin aggregate shared to RAP at room temperature, as follows:

- The first part of Equation 4.2 represents the increase in RAP temperature from ambient to discharge temperature, assuming equal specific heat capacities for both RAP and virgin aggregate.

- The second part of the equation represents the temperature required to increase the temperature of moisture in RAP and evaporate it.
 - The term $100 - T_{RAP}$ represents the energy required to increase the temperature of RAP from ambient temperature to 100°C (boiling point of water).
 - The term 537 represents the heat of vaporization of water, the energy required to vaporize water, which is at 100°C.

The possible reason for disagreement between experimental results and energy balance equation at higher moisture contents (Figure 4.8) can be that some of the moisture is trapped within RAP did not evaporate even after reaching 100°C at T_{equi} . Therefore, a reduction factor was added before the heat of vaporization of water part of the equation and was optimized using the solver function in Excel to minimize the overall Root Mean Squared Percentage Error (RMSPE) between experimental results and the modified equation, for both fine and coarse RAP. With the actual heat balance equation in Equation 4.2, the overall RMSPE was 4.4%. However, the addition of an optimized reduction factor of 0.6 to the heat of vaporization of the water part yielded an RMSPE of 2.5%; the modified equation is presented in Equation 4.3. The addition of the reduction factor to the equation was strictly based on the assumption that some of the moisture trapped within RAP did not evaporate during testing.

A comparison of superheated temperatures obtained from this study with the values calculated using modified Equation 4.3 is shown in Figure 4.9. In this case, the modified equation was able to provide similar results as observed from the experimental results of this study. All data points were close to the line of equality, with most falling within $\pm 2\%$ from the line of equality.

$$T_{v.a.} = \frac{T_{RHMA} - S_{RAP} \cdot T_{RAP}}{1 - S_{RAP}} + 4.0 \times \frac{S_{RAP} \cdot W_{RAP}}{1 - S_{RAP}} (100 - T_{RAP} + 0.6 * 537) \quad (4.3)$$

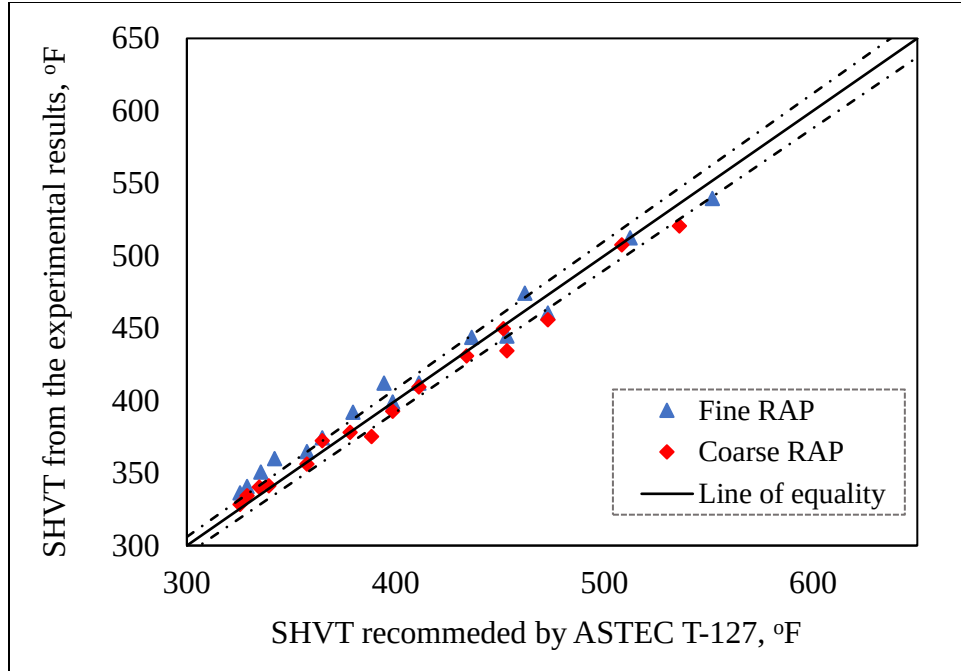


Figure 4.9: Comparison of superheated virgin aggregate temperature (SHVT) obtained from the experimental results and modified equation (Equation 4.3).

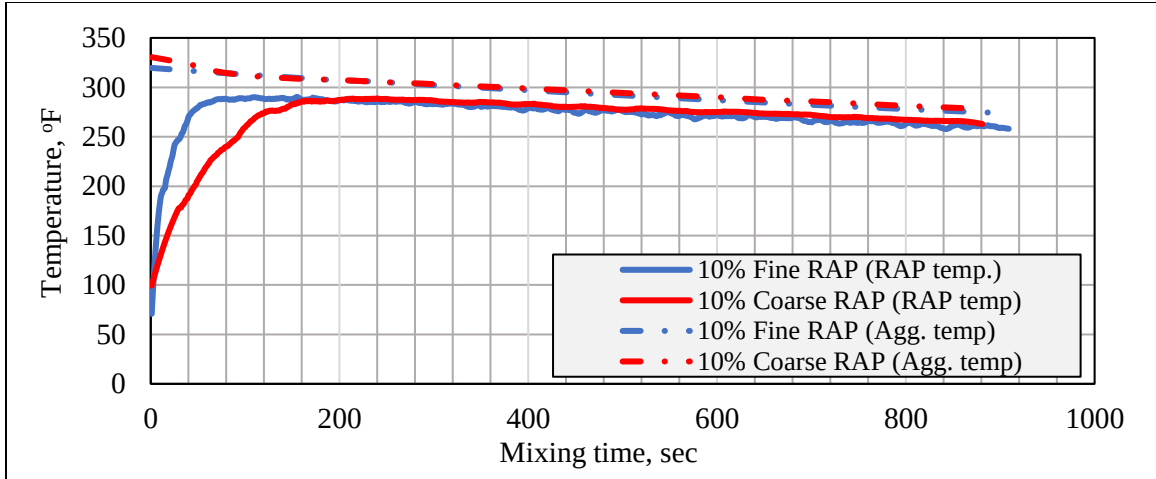
4.3 Investigation of Heat Transfer Process

Each material combination was tested at three different superheated virgin aggregate temperatures for validating the existing superheated temperature recommendations (Table 4.2). For a demonstration of the data in this section, results of heat transfer testing conducted at the existing recommended superheated temperatures (ASTEC T-127) for a given combination of RAP content and RAP moisture intended to attain 300°F discharge temperature were used.

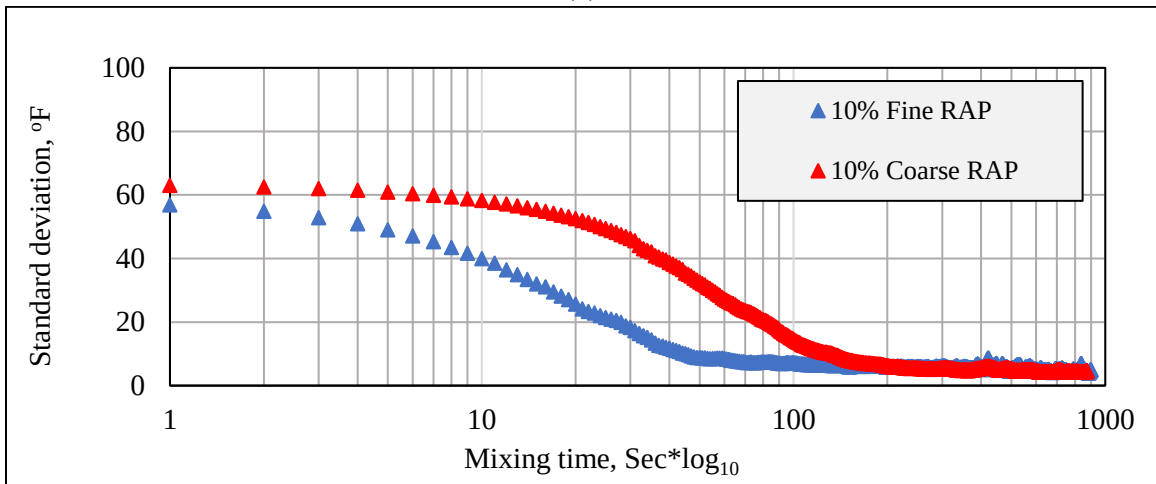
Although the plan was to test dense gradations at 0%, 1%, 3%, and 5% RAP moisture contents, some of the water was not absorbed for coarse RAP at higher RAP moisture contents (3% and 5%). It was observed that an average of 2.8% and 4.2% RAP moisture went into the chamber instead of 3% and 5%, respectively. There was no such problem at 0% and 1% moisture contents or for fine RAP cases. Therefore, RAP moisture contents of 0%, 1%, 3%, and 5% were used for fine RAP scenarios and 0%, 1%, 2.8%, and 4.2% were used for coarse RAP scenarios for further analysis.

Figure 4.10(a) illustrates an example of temperature profiles of RAP and virgin aggregate during heat transfer testing, and it shows the effect of RAP size on the heat transfer process at 10% RAP content. In theory, it was expected for fine RAP to have a rapid heat transfer rate compared to coarse RAP because of higher surface area and potentially greater contact area with superheated virgin aggregate. As expected, RAP and virgin aggregate temperature curves converged earlier in the fine RAP case than in the coarse RAP case due to the higher rate of heat transfer in the former scenario. Figure 4.10(b) shows the variation of the standard deviation of the FOV over mixing time for both fine and coarse RAP scenarios using 10% RAP on a semi-logarithmic scale. The fine RAP reached the asymptotic region along the x-axis time scale rapidly compared to the coarse RAP case. It should be noted that Figure 4.10(a) is presented in the normal time scale, and Figure 4.10(b) is presented in the logarithmic time scale.

Similarly, Figure 4.11 shows the effect of RAP content on heat transfer. Coarse RAP results are shown as an example. Even though higher superheated temperatures were used for higher RAP contents (Table 4.2), RAP and virgin aggregate temperature convergence occurred at a slower rate with the increase in RAP content. The possible reason could be that at higher RAP contents, the volume of virgin aggregate material that shares energy is less compared to a lower RAP content case. At the same time, the volume of RAP material that receives energy is also higher in the higher RAP content cases.

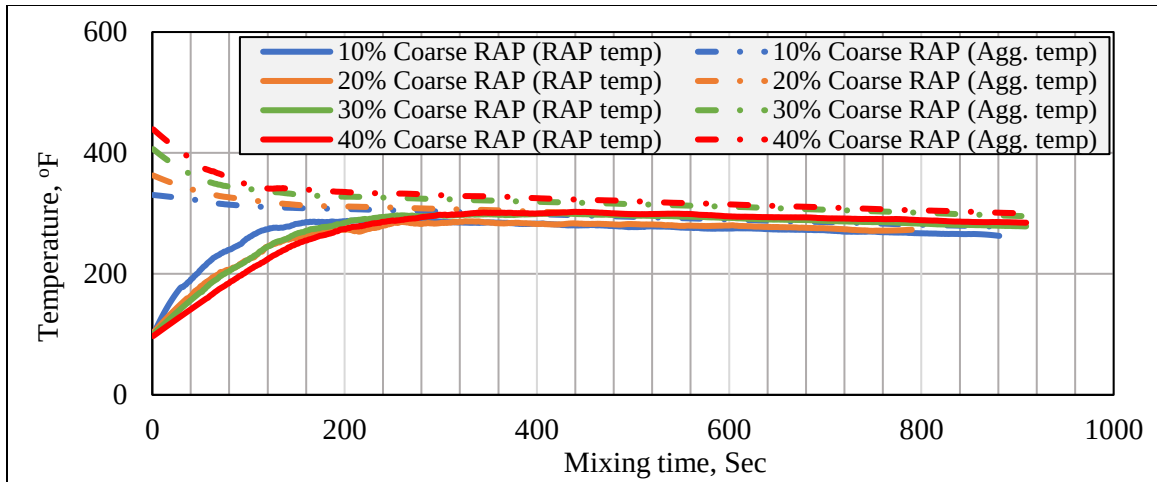


(a)

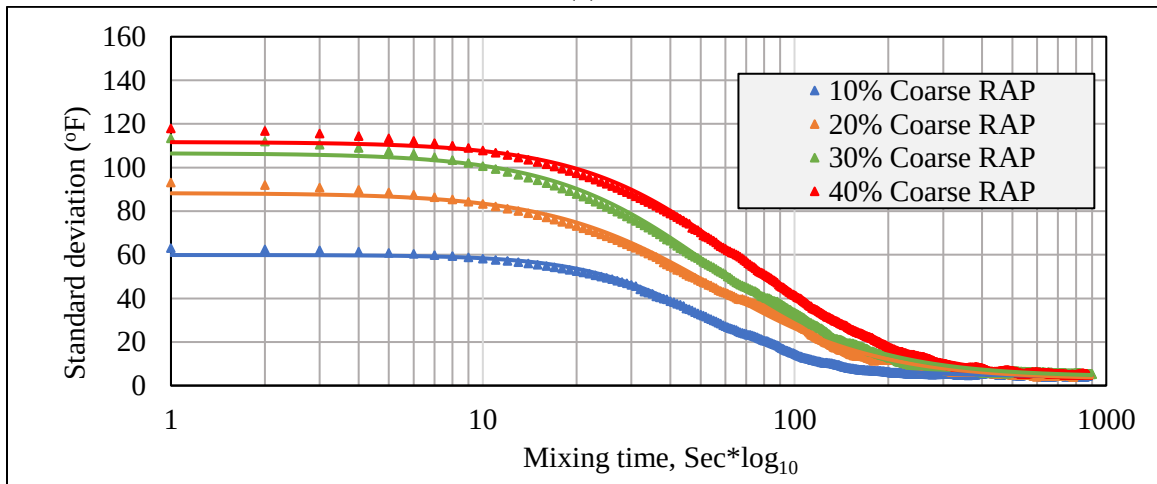


(b)

Figure 4.10: Heat transfer testing results for 10% fine and coarse dry RAP: (a) temperature profiles of virgin aggregate and RAP, and (b) change in the standard deviation of the FOV over mixing time.



(a)

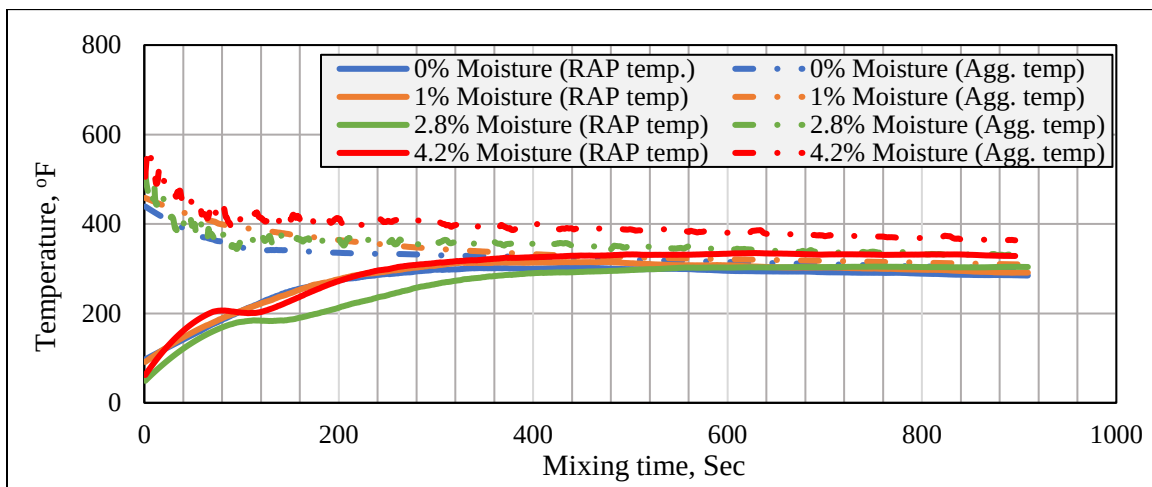


(b)

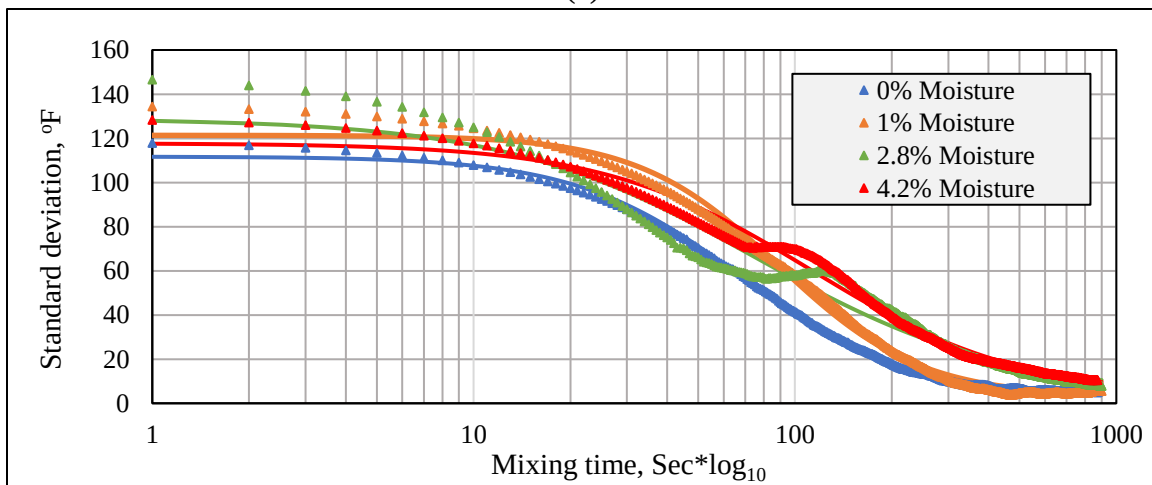
Figure 4.11: Heat transfer testing results for 10%, 20%, 30%, and 40% coarse dry RAP: (a) temperature profiles of virgin aggregate and RAP, and (b) change in the standard deviation of the FOV over mixing time.

Figure 4.12 illustrates the effect of RAP moisture content on the heat transfer process. 40% coarse RAP tested at various moisture contents are shown. RAP and aggregate temperature curves of higher moisture contents converged later compared to the lower moisture cases. However, materials with either low moisture (0% & 1%) or high moisture (2.8% & 4.2%) showed similar trends. From visual observation of the data shown in Figure 4.12, the material with higher RAP moisture required longer mixing times for complete heat transfer.

For mixtures with moisture, the temperature of RAP did not change for a short period of time once it reaches approximately 212°F (plateau region). This plateau region was evident for higher moisture contents. The same phenomena were also observed in the standard deviation curves; at the time RAP reached 212°F, the rate of reduction of standard deviation reduced for some time, forming a plateau region in the sigmoidal curve. It is expected that the plateau region is due to obstruction in the measurement of the IR camera, due to the formation of steam in the mixing drum.



(a)



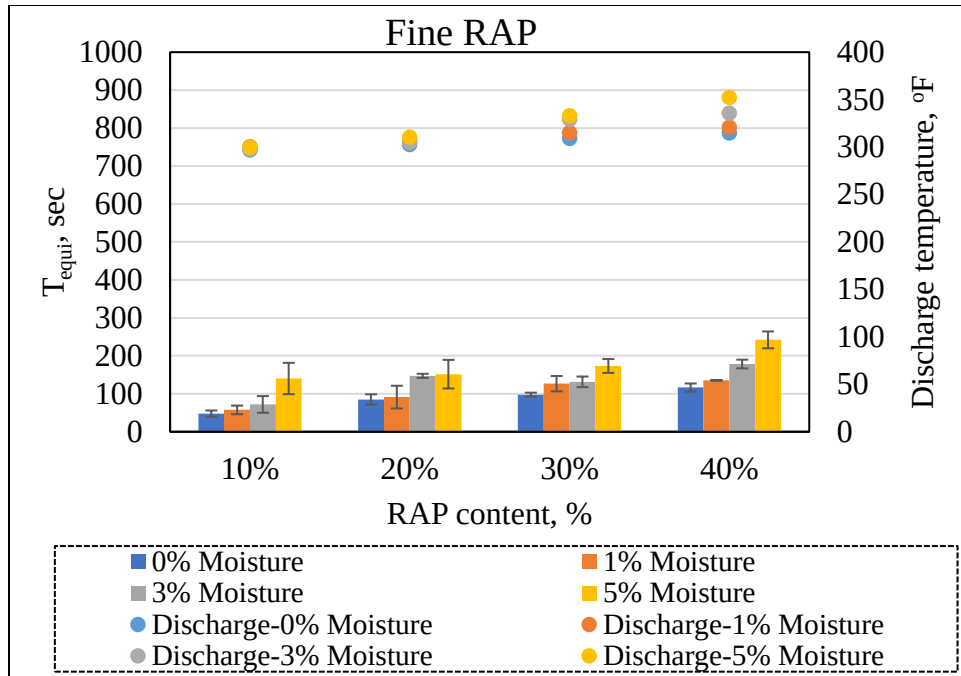
(b)

Figure 4.12: Heat transfer testing results for 40% coarse RAP at 0%, 1%, 2.8%, 4.2% moisture contents: (a) temperature profiles of virgin aggregate and RAP, and (b) change in the standard deviation of the FOV over mixing time.

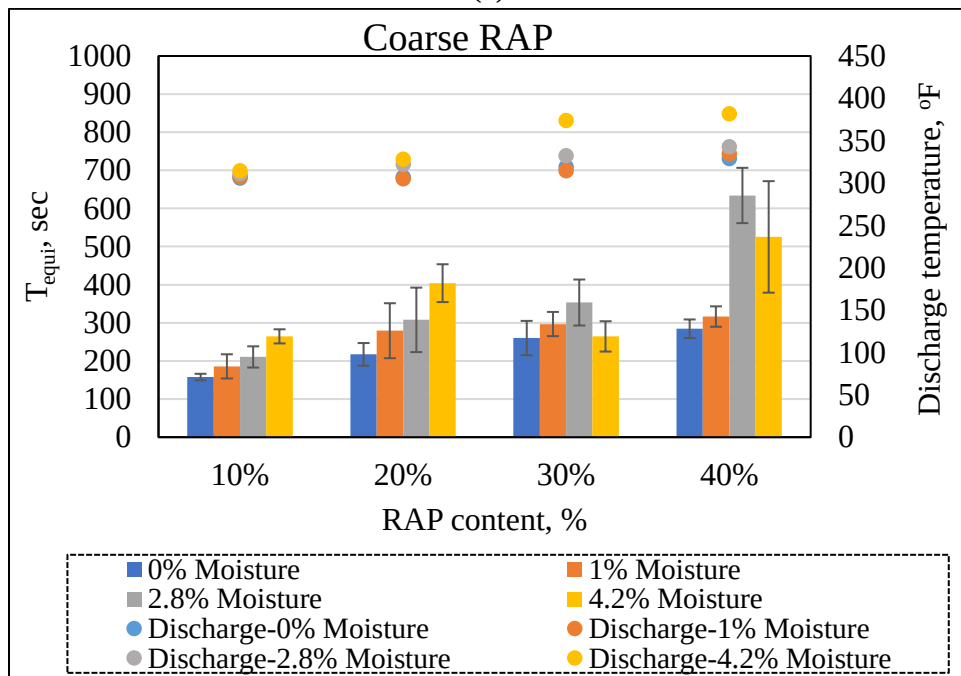
4.3.1 Effect of Mixture Variables on T_{equi}

To investigate the effect of mixture variables on time required for thermal equilibrium between virgin aggregate and RAP, the calculation procedure outlined in section 3.5.1 was used. Figure 4.13 presents the comparison of calculated T_{equi} for fine and coarse RAP (error bars represent $\pm$ one standard deviation from the mean). The amount of RAP significantly affected T_{equi} : higher RAP contents required a longer mixing time to achieve T_{equi} . This was true for both RAP sizes used in the analysis. The only exceptions were for 30% coarse RAP at 4.2% moisture (value appeared to be low) and 40% coarse RAP at 2.8% moisture (value appeared to be high).

Along with the T_{equi} comparison, Figure 4.13 also presents the final mixture discharge temperatures of each mixture presented in the plot. It was intended that all these mixtures will have a final discharge temperature of 300°F. However, due to inconsistency in the existing recommended temperatures (Equation 4.2), mixtures with higher RAP contents and moisture contents yielded very high discharge temperatures. As the mixtures presented in Figure 4.13 were with different final discharge temperatures, a statistical comparison to investigate the effect of mixture variables (RAP content, moisture content, and RAP size) cannot be made directly on this data. In asphalt mixture production, the mixtures are produced with similar final discharge temperatures. Therefore, comparing mixtures with the same final discharge temperature (300°F) to investigate the effect of mixture variables is more logical.



(a)



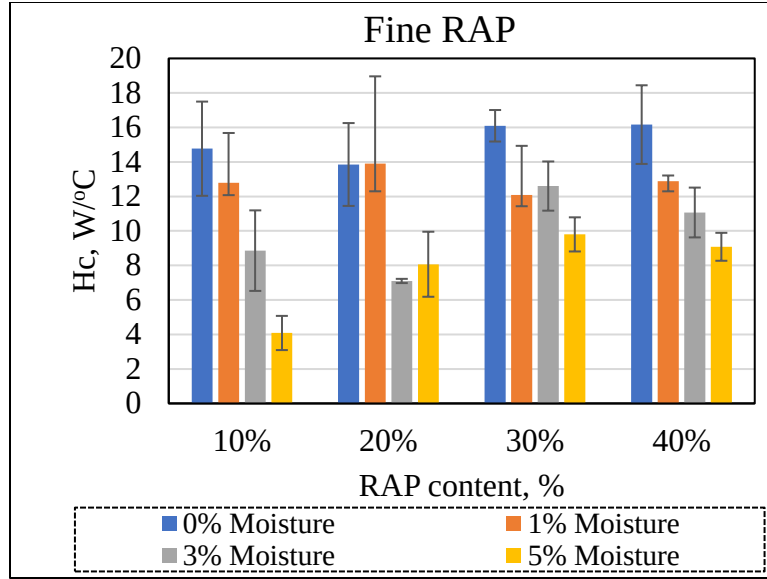
(b)

Figure 4.13: Effect of RAP content and moisture content on T_{equi} along with mix discharge temperatures for (a) Fine RAP, and (b) coarse RAP tested at existing ASTEC recommended superheated temperature.

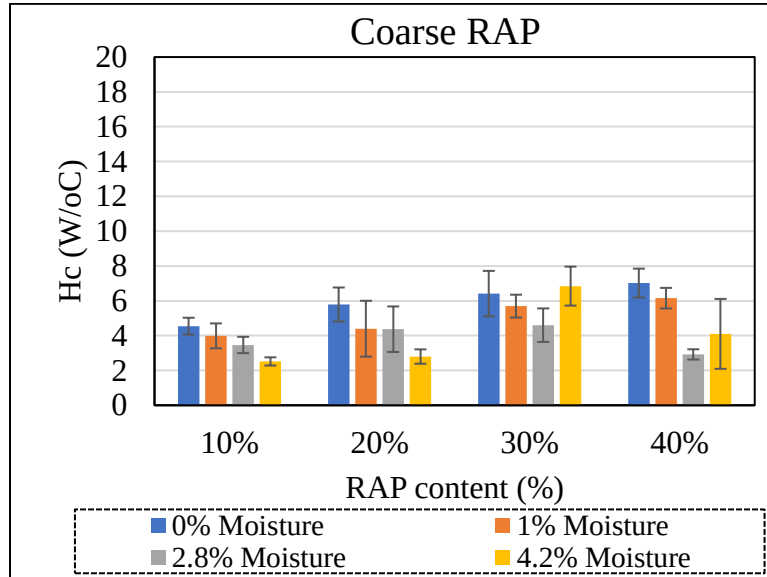
4.4 Development of a New Method of Calculate T_{equi} at Any Superheated Temperature

As mentioned before, for a more logical statistical comparison of time required for thermal equilibrium, T_{equi} must be calculated with the virgin aggregate superheated temperature that can yield 300°F discharge temperature. Based on Equation 4.3, one can calculate the virgin aggregate temperatures required for each mixture to yield a constant 300°F discharge temperature. However, repeating heat transfer testing for the entire experimental matrix at superheated temperature determined using Equation 4.3 is highly impractical. Therefore, a new analytical solution to calculate the time required for thermal equilibrium at any superheated virgin aggregate temperature was developed using the existing test results.

Heat conductance presented in section 3.5.2 represents the rate of heat transfer per unit contact area between RAP and virgin aggregate, per unit temperature difference between RAP and virgin aggregate. Heat conductance is specific to the mixture type that is independent of the superheated temperature of virgin aggregate and the initial temperature of RAP. As shown in Figure 4.14, heat conductance was affected by RAP size, RAP content, and RAP moisture content. By definition, heat conductance for a given material combination tested at different superheated temperatures or different initial RAP temperatures should remain the same.



(a)



(b)

Figure 4.14: Effect of RAP content and moisture content on heat conductance with (a) fine RAP, and (b) coarse RAP tested at existing ASTEC recommended superheated temperature.

Equation 4.4 presents the theoretical basis on which heat conductance was determined for the material combinations tested in this study.

$$\ln \left[\frac{T_{va}^t - T_{rap}^t}{T_{va}^0 - T_{rap}^0} \right] = H_c * \left[\frac{1 + \frac{m_{va}C_{va}}{m_{rap}C_{rap}}}{m_{va}C_{va}} \right] \times t \quad (4.4)$$

Where,

T_{rap}	=	Temperature of RAP, °C
T_{rap}^0	=	Initial temperature of RAP, °C
T_{va}^t	=	Temperature of virgin aggregate at mixing time t, °C
T_{rap}^t	=	Initial superheated virgin aggregate temperature at mixing time t, °C
t	=	Mixing time, sec
H_c	=	Heat conductance between virgin aggregate and RAP, J/sec-°C
m_{rap}	=	Mass of RAP, kg
C_{rap}	=	Specific heat capacity of RAP, J/kg-°C
m_{va}	=	Mass of virgin aggregate, kg
C_{va}	=	Specific heat capacity of virgin aggregate, J/kg-°C

Equation 4.4 can be re-written as follows:

$$A = \left[\frac{1 + \frac{m_{va}C_{va}}{m_{rap}C_{rap}}}{m_{va}C_{va}} \right] \quad (4.5)$$

$$T_{va}^t - T_{rap}^t = [T_{va}^0 - T_{rap}^0] \cdot e^{H_c \times A \times t} \quad (4.6)$$

With Equation 4.6, the difference between virgin aggregate temperature and RAP temperature can be calculated at any mixing time, with any initial temperature of RAP and virgin aggregate, provided all mixture properties (weights and heat conductance values) are known. A virgin aggregate and RAP temperature difference curve can be constructed using Equation 4.6, as shown in Figure 4.15. With a known threshold value for the temperature difference curve at which thermal equilibrium between virgin aggregate and RAP is achieved, one can calculate the mixing time required to reach that threshold temperature difference which is T_{equi} .

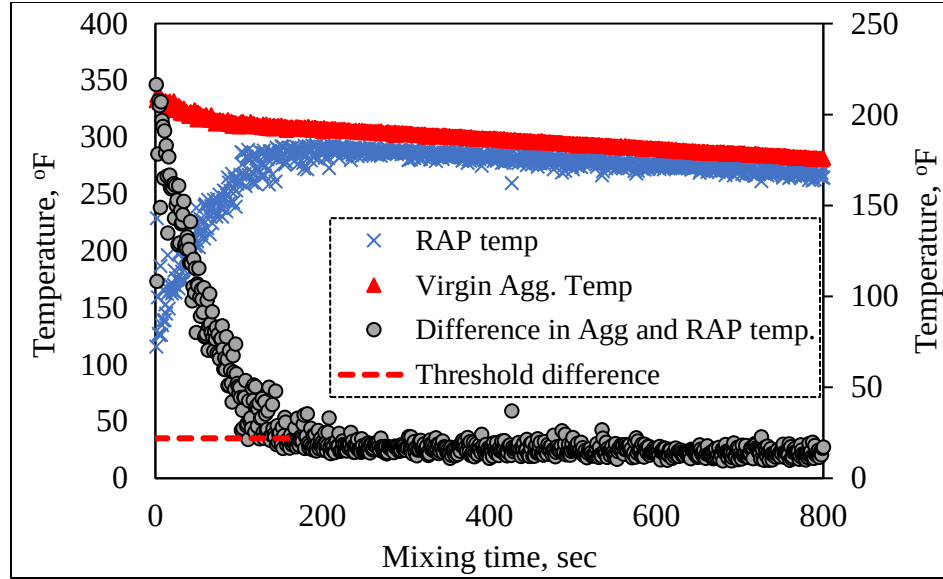


Figure 4.15: Illustration of virgin aggregate and RAP temperature difference curve.

In summary, using Equation 4.6, with known heat conductance results and known threshold value for temperature difference, T_{equi} can be calculated at any superheated aggregate and any initial RAP temperatures.

4.4.1 Establishing Threshold for Aggregate and RAP Temperature Difference for Thermal Equilibrium

A total of 609 heat transfer tests were conducted in this study, and the T_{equi} for all these tests were calculated using the procedure established in section 3.5.1. The temperature difference between virgin aggregate (95th percentile value) and RAP (5th percentile value) was extracted at the T_{equi} of each test. Figure 4.16 presents a histogram of the temperature difference dataset with a mean of 38.2°F and a standard deviation of 9.9°F; the histogram is normal distribution [N(38.2, 9.9)].

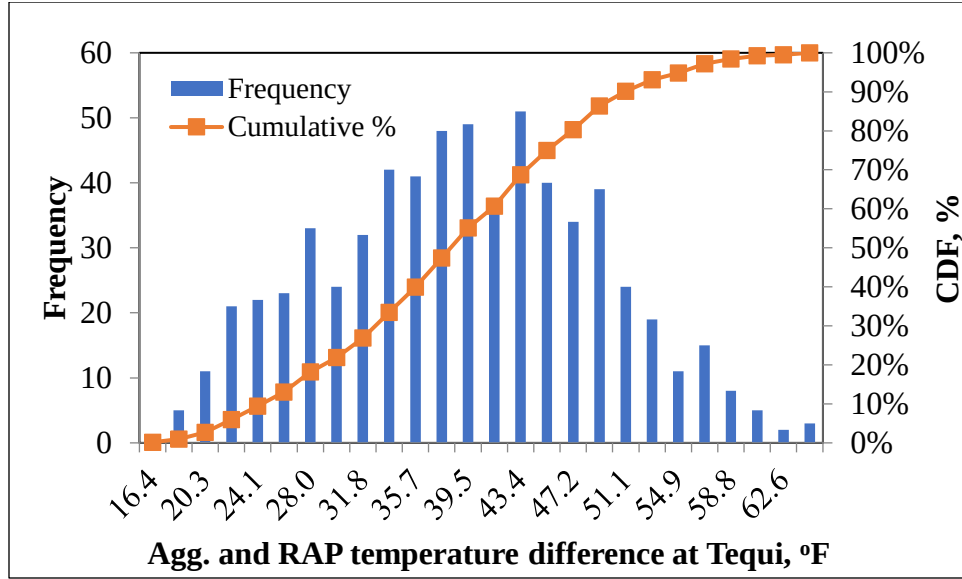


Figure 4.16: Histogram of the temperature difference between virgin aggregate and RAP at T_{equi} (609 tests).

As the threshold value obtained for temperature difference is a distribution instead of a single value, a Monte Carlo simulation was used to calculate T_{equi} from the temperature difference curve.

4.4.2 Monte Carlo Simulation for T_{equi} Calculation

Monte Carlo simulation computes a dependent variable in an equation repetitively using several randomly generated independent variables. The generation of random input values for each Monte Carlo cycle depends on the type of distribution of the input parameter. To calculate T_{equi} using Monte Carlo simulation, it must be computed using randomly generated threshold temperature difference values based on the distribution obtained in the previous section i.e., a normal distribution with a mean of 38.2°F and standard deviation of 9.9°F.

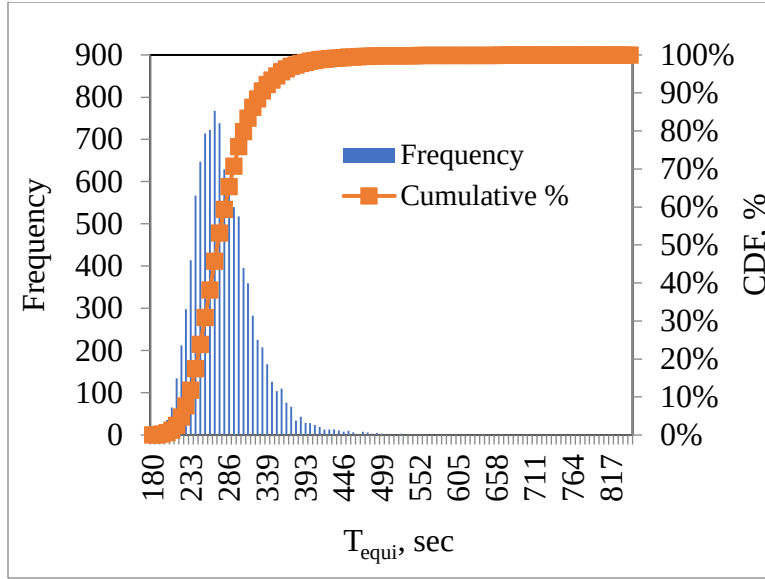
To generate random values for threshold temperature difference, two random numbers between 0 and 1, namely, U_1 and U_2 , were generated. An independent value was calculated from the generated two random numbers using Equation 4.7, as shown below.

$$S1 = \sqrt{-2 * \ln(U_1)} * \cos(2\pi U_2) \quad (4.7)$$

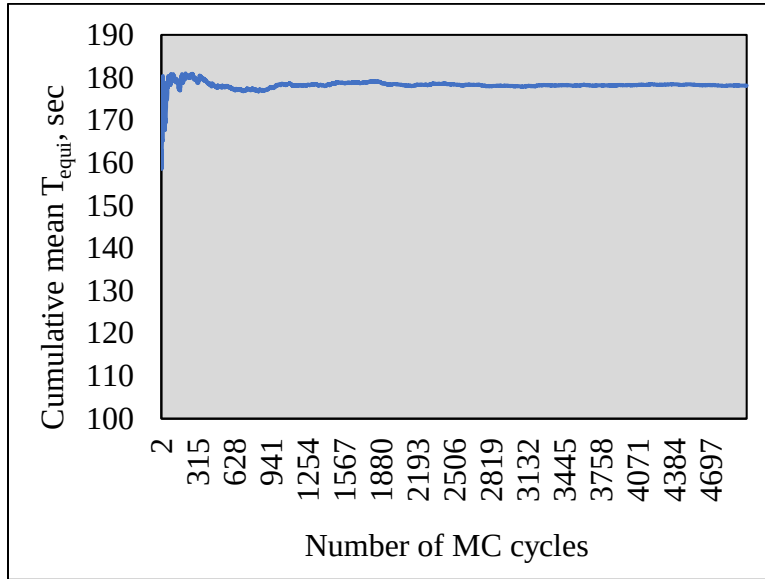
This independent value, along with the average and standard deviation of the threshold temperature difference, was used to generate a random threshold temperature difference value for a single Monte-Carlo Cycle (Equation 4.8). This process was repeated for 5000 cycles.

$$h = 38.2 + S1 \times 9.9 \quad (4.8)$$

Equation 4.6 was used along with randomly generated threshold temperature difference values to calculate a distribution of T_{equi} . As observed in the previous section, the threshold of temperature difference was a normal distribution. Therefore, T_{equi} was calculated multiple times by randomly selecting a threshold. Figure 4.17 shows an example of calculated T_{equi} using Monte Carlo simulation based on temperature difference curve. Figure 4.17(a) presents the distribution of calculated T_{equi} , and Figure 4.17(b) illustrates the Monte Carlo stabilization curve, which showed that 5000 cycles were producing stable results for this method. The average of the calculated T_{equi} distribution (Figure 4.17(a)) developed during MC simulation was considered as the time required for the thermal equilibrium of a material combination.



(a)



(b)

Figure 4.17: Illustration of Monte Carlo simulation to calculate T_{equi} from heat conductance test data.

T_{equi} using measured heat conductance, was determined by applying the proposed Monte Carlo method. In addition, T_{equi} for all these test combinations was also determined using the change in the standard deviation of the FOV method explained in section 3.5.1.

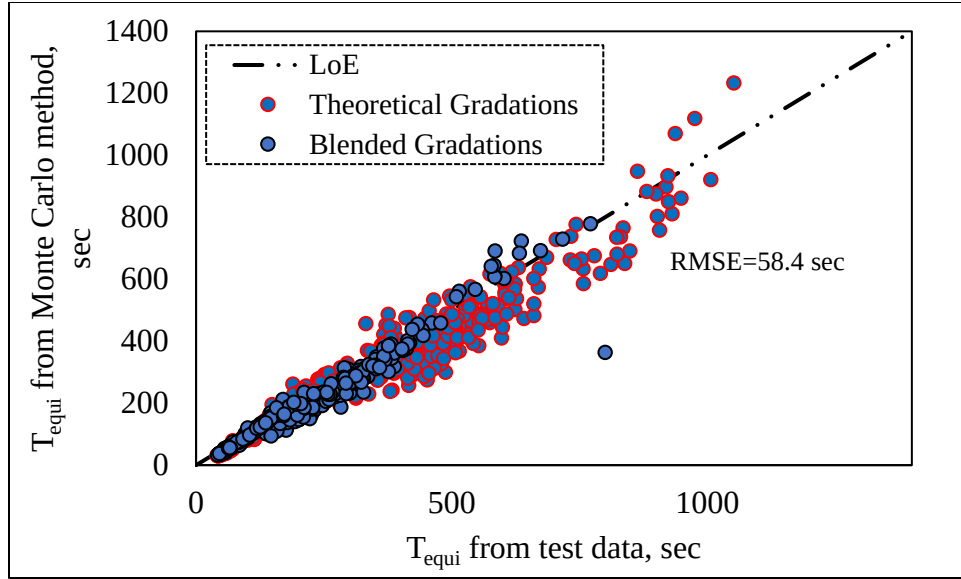


Figure 4.18: Comparison of T_{equi} calculated from Monte Carlo method and the heat transfer test data.

From Figure 4.18, the new analytical T_{equi} calculation procedure using heat conductance data and Monte Carlo simulation was able to reproduce T_{equi} values calculated from the test data closely. Especially for the dense gradations, the data is very close to the line of equality. Even though there is a spread of the data around the line of equality for theoretical gradations, with an overall RMSE of 58.4 sec, it can be concluded that the new analytical method using heat conductance data is a good alternative to calculate T_{equi} . The main advantage of this new analytical method is heat conductance data of any mixture tested at a specific superheated temperature can be used to calculate T_{equi} at any superheated temperature of interest.

4.5 Investigation of Effect of Mixture Variables on T_{equi}

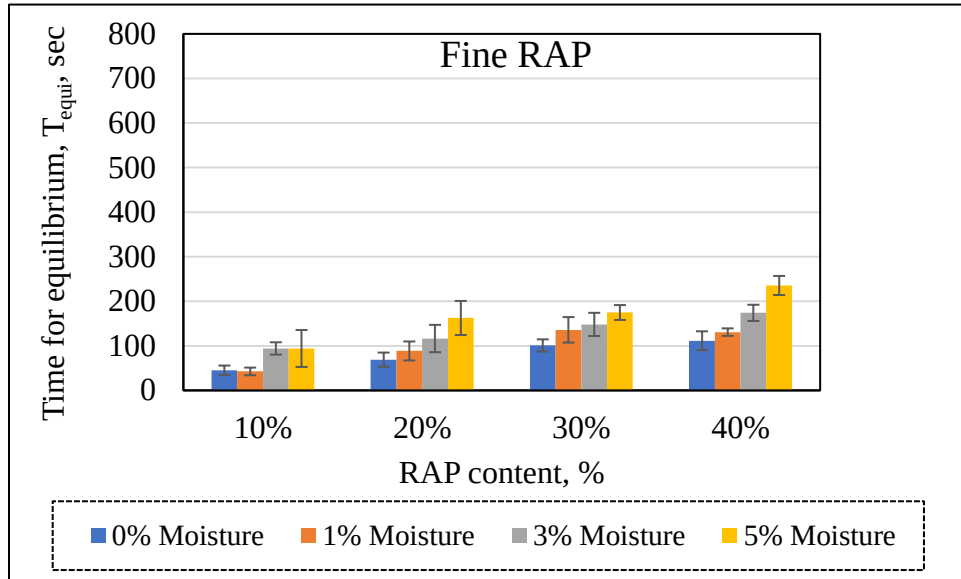
Statistical comparison of mixtures with varying levels of mixture parameters is more logical when all the mixtures produce a constant final discharge temperature. Therefore, the superheated temperature required to yield a final discharge temperature of 300°F was calculated using Equation 4.3 for all dense-graded and theoretical mixtures considered in the study.

For a given mixture, heat transfer testing was conducted at three superheated temperature levels with three replicates at each temperature level. Thus, a total of nine heat transfer tests returned nine heat conductance values for a mixture. These nine heat conductance values along with the calculated superheated temperatures (to yield 300°F), were used to calculate T_{equi} according to the procedure detailed in section 4.4.

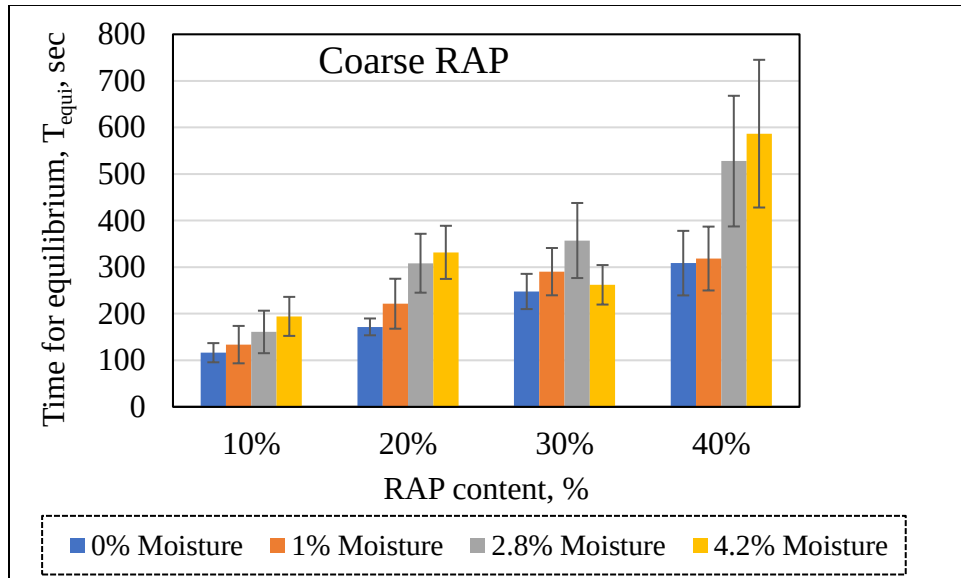
4.5.1 Dense Graded Mixtures

Figure 4.19 presents the time required for thermal equilibrium values of dense-graded mixtures with fine and coarse RAP. It should be noted that all these mixtures yielded a final discharge temperature of 300°F.

To understand the effect of mixture variables on the time required for thermal equilibrium, a three-way Analysis of Variance (ANOVA) analysis on T_{equi} data was conducted. The generalized linear model (GLM) in the Minitab statistical software was used for the ANOVA analysis. RAP content, RAP moisture content, and RAP size were considered as main variables. Since moisture content levels for fine RAP and coarse RAP were not the same, 2.8% and 4.2% moisture content levels were replaced with 3.0% and 5.0% moisture contents, respectively, for coarse RAP mixes. Main effects and two-way interaction effects were analyzed. The null hypothesis for any of these terms was that there was no statistically significant difference between the means of the parameter at selected levels of that term. The alternative hypothesis was that at least one mean is different from the rest. A significance level was set at 5% (p-value = 0.05).



(a)



(b)

Figure 4.19: Calculated T_{equi} with Monte Carlo method to yield a final discharge temperature of 300°F for dense-graded mixtures with (a) fine, and (b) coarse RAP.

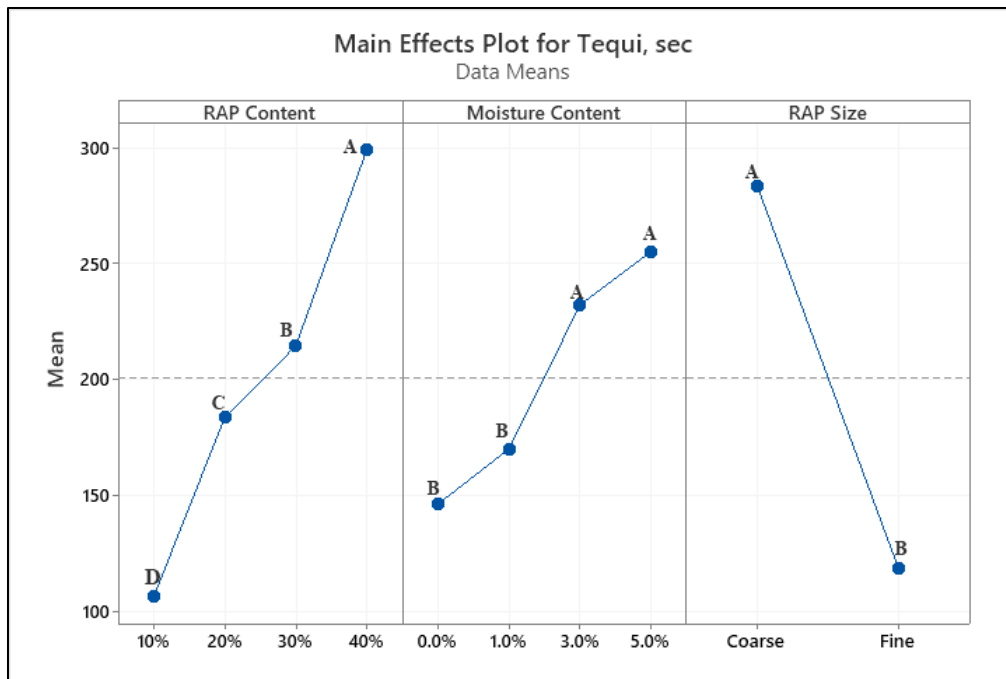
The results of the ANOVA analysis are presented in Table 4.4. The findings show that there is a significant effect of RAP content, moisture content, and RAP size on time required for thermal equilibrium with p-values less than 0.01. Based on the diagnostic plots presented in Figure 4.20(c), the GLM model developed as part of the ANOVA analysis was satisfying all the underlying assumptions of ANOVA analysis.

Tukey's pairwise comparisons were conducted to better understand the effect of main factors on T_{equi} , and Tukey's statistical grouping is presented in Figure 4.20(a). Based on Tukey's comparison, it can be concluded that T_{equi} increases with an increase in RAP content, RAP moisture, and RAP particle size.

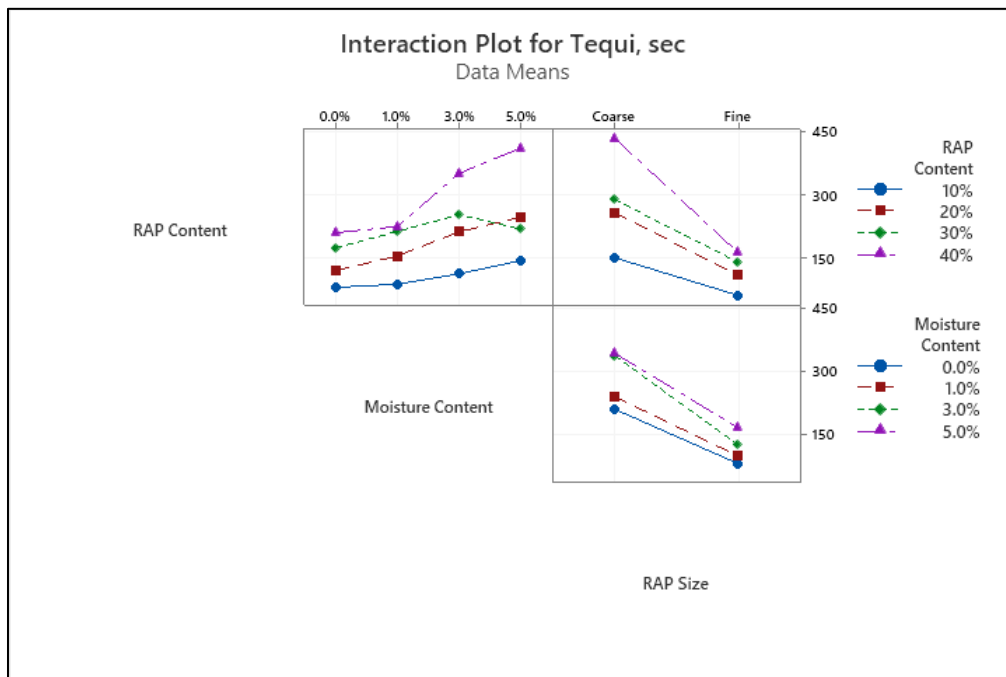
Table 4.4: Three-way ANOVA analysis results of T_{equi} for blended gradations.

Source	DF	Adj SS	Adj MS	F-Value	p-Value
RAP Content	3	1372016	457339	146.4	<0.01
Moisture Content	3	565262	188421	60.3	<0.01
RAP Size	1	1962519	1962519	628.2	<0.01
RAP Content*Moisture Content	9	225759	25084	8.0	<0.01
RAP Content*RAP Size	3	319179	106393	34.1	<0.01
Moisture Content*RAP Size	3	76054	25351	8.1	<0.01
Error	265	827904	3124		
Lack-of-Fit	9	96080	10676	3.7	<0.01
Pure Error	256	731824	2859		
Total	287	5348693			

To summarize, longer mixing times between RAP and virgin aggregate need to be provided to produce mixtures with high RAP contents, high moisture contents, and coarser RAP sizes.

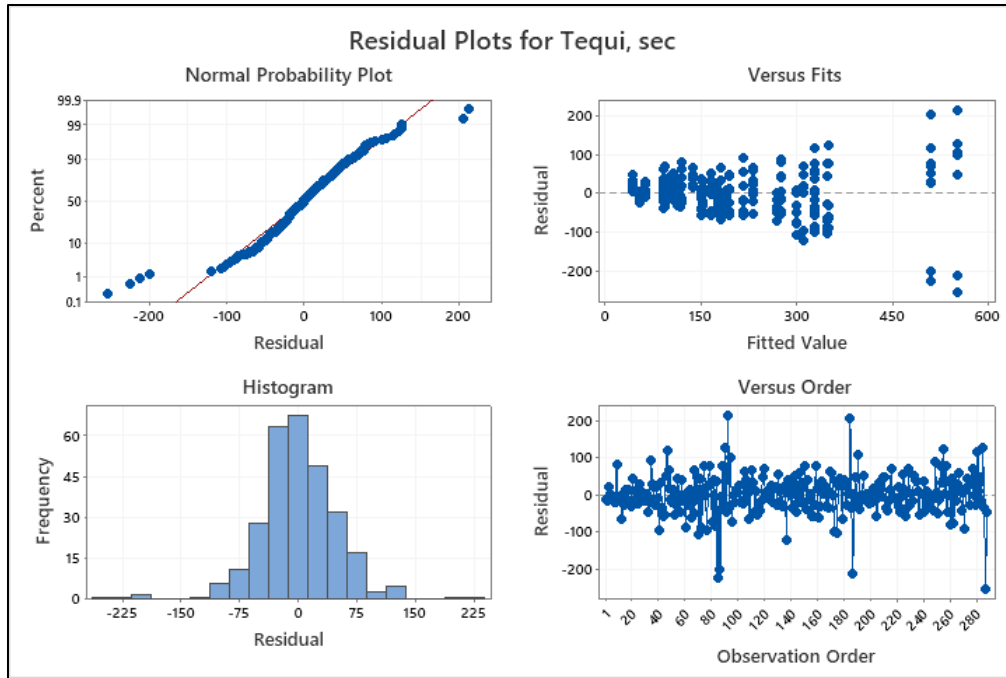


(a)



(b)

Figure 4.20: Three-way ANOVA statistics: (a) main effects plot, (b) interaction effect plot, and (c) model diagnostic plots.



(c)

Figure 4.20: Three-way ANOVA statistics: (a) main effects plot, (b) interaction effect plot, and (c) model diagnostic plots. (continued)

4.5.2 Theoretical gradations

The time required for thermal equilibrium was calculated for mixtures with theoretical gradations using the new analytical approach (Monte Carlo method), and the results are presented in Table 4.5. The main advantage of analyzing the theoretical gradation data is that these mixtures were prepared with different virgin aggregate sources. Hence, the statistical analysis will reveal the importance of aggregate sources on the heat transfer process.

Table 4.5: Calculated T_{equi} with Monte Carlo method to yield a final discharge temperature of 300°F for theoretical gradation mixtures.

Agg. Source	RAP content, %	Agg. Size	RAP Size	T_{equi} , sec	
				Mean	Std. Dev
Limestone	10%	CA*	CA*	291.4	54.7
		CA*	FA*	43.9	4.6
		FA*	CA*	674.0	63.9
		FA*	FA*	279.3	120.0
	40%	CA*	CA*	388.9	37.4
		CA*	FA*	247.5	39.6
		FA*	CA*	442.4	80.2
		FA*	FA*	574.5	259.5
Dolomite	10%	CA*	CA*	321.2	114.8
		CA*	FA*	36.2	6.4
		FA*	CA*	496.6	213.0
		FA*	FA*	156.8	96.4
	40%	CA*	CA*	402.5	39.5
		CA*	FA*	238.5	31.6
		FA*	CA*	521.9	71.1
		FA*	FA*	645.4	257.7
Basalt	10%	CA*	CA*	326.1	96.8
		CA*	FA*	40.8	7.7
		FA*	CA*	435.5	166.6
		FA*	FA*	137.0	89.4
	40%	CA*	CA*	390.1	43.7
		CA*	FA*	220.3	16.4
		FA*	CA*	435.2	32.2
		FA*	FA*	483.1	252.2
Quartzite	10%	CA*	CA*	381.6	123.8
		CA*	FA*	42.8	6.3
		FA*	CA*	440.0	26.3
		FA*	FA*	99.5	20.0
	40%	CA*	CA*	412.7	60.3
		CA*	FA*	215.2	21.7
		FA*	CA*	567.1	71.0
		FA*	FA*	666.9	322.7

The effect of mixture variables on time required for thermal equilibrium was investigated with a four-way Analysis of Variance (ANOVA) analysis using GLM on T_{equi} data presented in

Table 4.5. The generalized linear model (GLM) in the Minitab statistical software was used for the ANOVA analysis. The primary variables were the aggregate source, RAP content, aggregate size, and RAP size. Main effects and two-way interaction effects were observed in the analysis. A significance level of 5% was considered ($p\text{-value} = 0.05$).

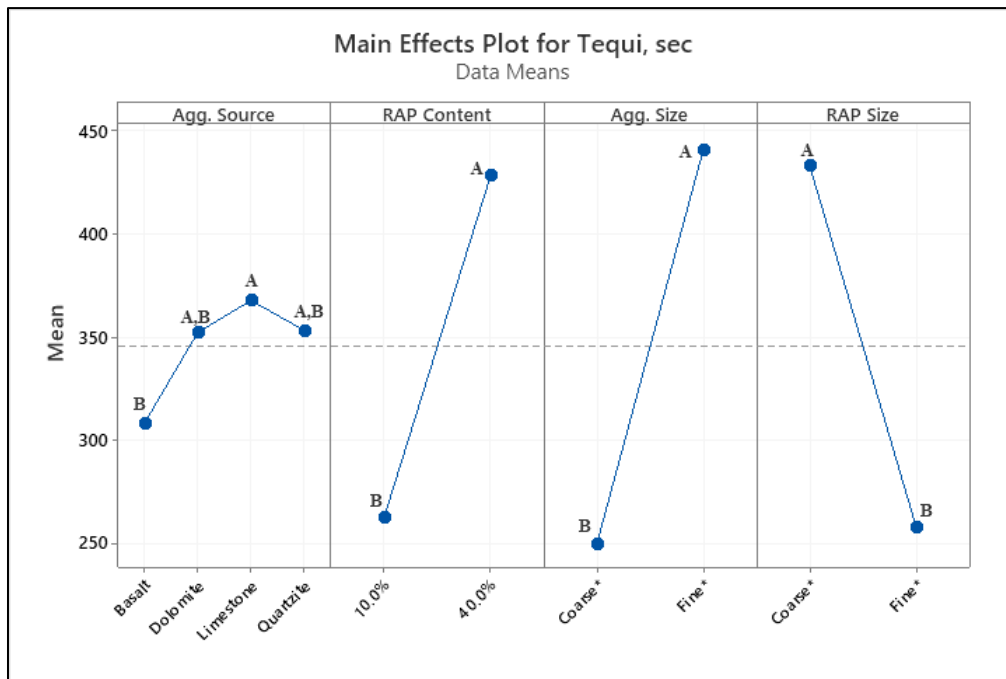
The results of the ANOVA analysis are presented in Table 4.6. From the results, it can be concluded that there is a significant effect of RAP content, aggregate size, and RAP size on time required for thermal equilibrium, with p -values less than 0.01. The aggregate source was also found to be a significant factor; however, the p -value is very close to 0.05. Hence, it can be inferred that the aggregate source affects the heat transfer process, but not as much as other mixture variables. Based on the diagnostic plots presented in Figure 4.21(c), the GLM model developed as part of the ANOVA analysis satisfied all the underlying assumptions of ANOVA analysis.

Tukey's pairwise comparisons were conducted to understand better the effect of main factors on T_{equi} , and Tukey's statistical grouping is presented in Figure 4.21(a). Based on Tukey's comparison, it can be concluded that T_{equi} increases with an increase in RAP content and RAP particle size and decreases with an increase in aggregate particle size. Furthermore, Tukey's grouping of aggregate sources shows that basalt transfers heat quickly. However, the thermal conductivity of basalt was identified as the lowest among all four sources. Therefore, theoretically, basalt should transfer heat slowly and take a longer time for equilibrium.

In summary, longer dry mixing times need to be provided to produce mixtures with high RAP contents and coarser RAP sizes. This conclusion is validated based on the dense-graded mixtures.

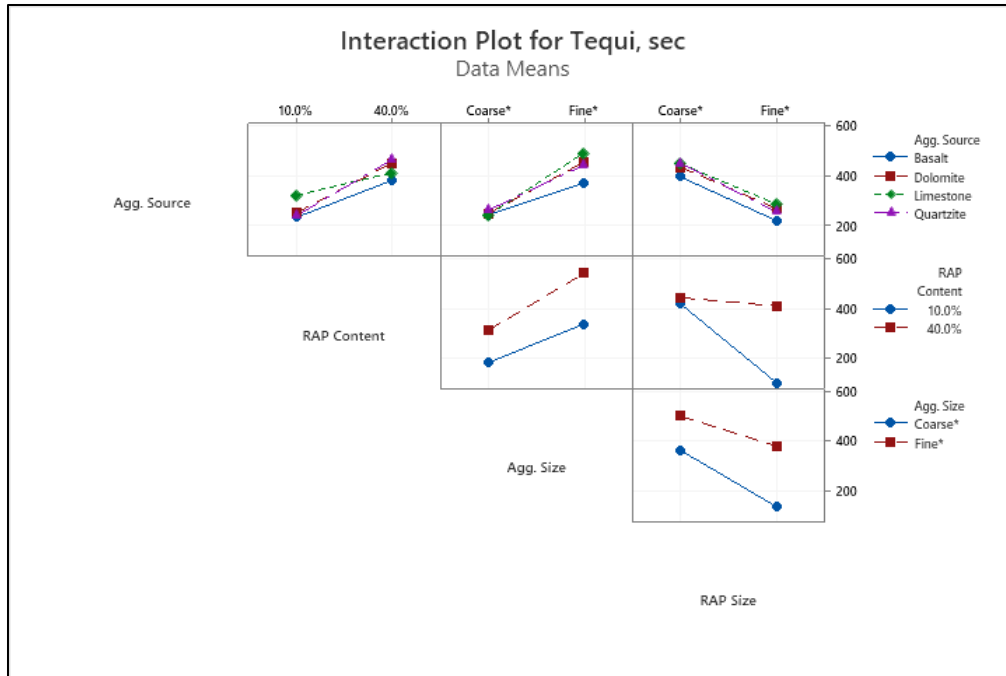
Table 4.6: Four-way ANOVA analysis results of Tequi for theoretical gradations.

Source	DF	Adj SS	Adj MS	F-Value	p-Value
Agg. Source	3	141723	47241	2.7	0.046
RAP Content	1	1974364	1974364	113.3	<0.01
Agg. Size	1	2625559	2625559	150.6	<0.01
RAP Size	1	2204151	2204151	126.4	<0.01
Agg. Source*RAP Content	3	188742	62914	3.6	0.01
Agg. Source*Agg. Size	3	138431	46144	2.7	0.05
Agg. Source*RAP Size	3	10695	3565	0.2	0.89
RAP Content*Agg. Size	1	96578	96578	5.5	0.02
RAP Content*RAP Size	1	1437488	1437488	82.5	<0.01
Agg. Size*RAP Size	1	207653	207653	11.9	<0.01
Error	269	4689847	17434		
Lack-of-Fit	13	835387	64261	4.3	<0.01
Pure Error	256	3854460	15056		
Total	287	13715232			

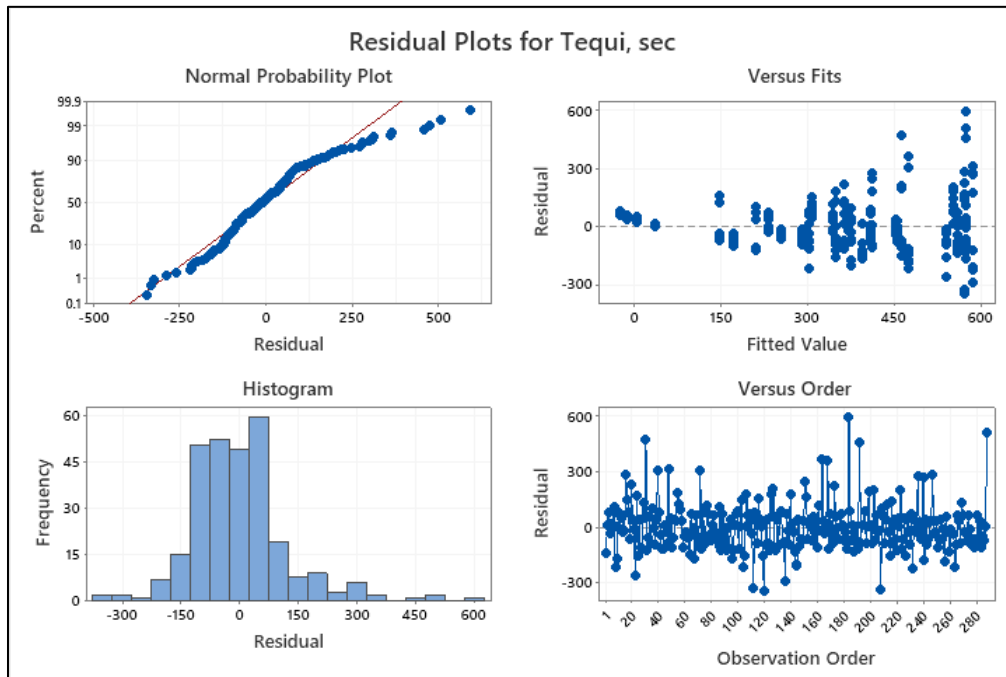


(a)

Figure 4.21: Four-way ANOVA statistics (a) main effects plot, (b) interaction effect plot, and (c) model diagnostic plots.



(b)



(c)

Figure 4.21: Four-way ANOVA statistics (a) main effects plot, (b) interaction effect plot, and (c) model diagnostic plots. (continued)

4.6 Development of Regression Equation for Heat Conductance

Developing a regression equation for the heat conductance between virgin aggregate and RAP helps the pavement research community and asphalt producers to relatively compare the heat transfer process among different mixtures. In addition, the predicted heat conductance can be used in conjunction with the analytical method discussed in section 4.4.2 to calculate the time required for thermal equilibrium.

A Multiple Linear Regression (MLR) analysis was performed in Minitab 19 software to establish a regression model between heat conductance and variables selected in the experimental matrix, namely RAP content, RAP moisture content, RAP gradation, virgin aggregate gradation, virgin aggregate source, and superheated temperature level. For the MLR analysis, each parameter must be presented in numeric form. Virgin aggregate and RAP gradations were characterized by a parameter called average particle size (d_p), which is the weighted average particle size of the gradation calculated using Equation 4.8. Measured thermal conductivity of the virgin aggregate material is used to represent the virgin aggregate source in the MLR analysis.

Table 4.7 lists the average particle sizes of the virgin aggregate and RAP gradations used in the study. For RAP and virgin aggregate combinations with fine and coarse RAP, a blending exercise was conducted to establish the virgin aggregate gradations to maintain a consistent final mixture gradation.

$$d_p = \frac{100}{\sum_{i=1}^n \frac{P_i}{D_i}} \quad (4.8)$$

Where,

- d_p = Average particle size of the gradation, mm
- P_i = Percentage retained on sieve i
- D_i = Average particle size of material between sieve i and $i-1$, mm

Table 4.7: Average particle size of the RAP and virgin aggregate gradations used in the study.

RAP (%)	Average particle size, d_p (mm)							
	Dense Gradations				Theoretical Gradations			
	Fine RAP		Coarse RAP		FA*		CA*	
	VA	RAP	VA	RAP	VA	RAP	VA	RAP
10%	2.82	0.68	2.41	9.83	2.66	2.66	18.88	18.88
20%	3.27	0.68	2.27	9.83	2.66	2.66	18.88	18.88
30%	3.98	0.68	2.07	9.83	2.66	2.66	18.88	18.88
40%	5.93	0.68	1.89	9.83	2.66	2.66	18.88	18.88

VA-virgin aggregate

An MLR analysis for heat conductance was conducted to develop a model for heat conductance prediction. Main variable effects and two-way interaction between selected independent variables were used for the analysis. A stepwise MLR analysis was used to eliminate independent variables and interactions that are not statistically significant in affecting heat conductance. Table 4.8 presents the results of the MLR analysis for heat conductance. A total of 203 datasets were used, with 70% of the data selected randomly and used for developing the MLR model and the remaining 30% of data for testing the MLR model.

Table 4.8: Multiple linear regression analysis results for heat conductance.

Term	Coef	SE Coef	T-Value	P-Value
Constant	12.19	0.76	16.1	<0.05
Virgin agg. gradation	0.29	0.05	5.9	<0.05
RAP gradation	-0.90	0.09	-10.2	<0.05
Moisture Content	-1.48	0.19	-7.9	<0.05
RAP Content*Virgin agg. gradation	-0.01	0.00	-3.7	<0.05
RAP Content*RAP gradation	0.01	0.00	3.8	<0.05
RAP gradation*Moisture Content	0.12	0.03	4.4	<0.05

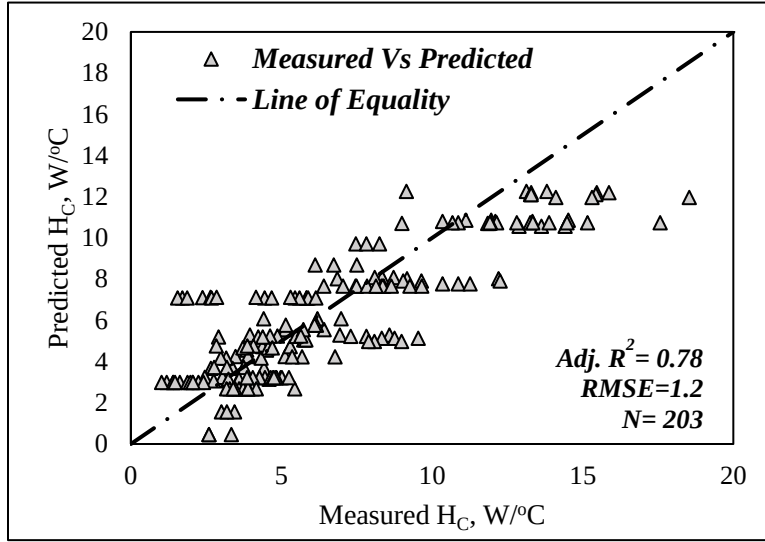


Figure 4.22: Comparison of measured and predicted heat conductance.

Figure 4.22 presents the predictive capability of the developed regression equation for heat conductance prediction. With an adjusted R^2 of 0.78 and RMSE of 1.2 W/°C, the developed regression equation shown in Equation 4.8 was able to predict heat conductance between virgin aggregate and RAP reasonably.

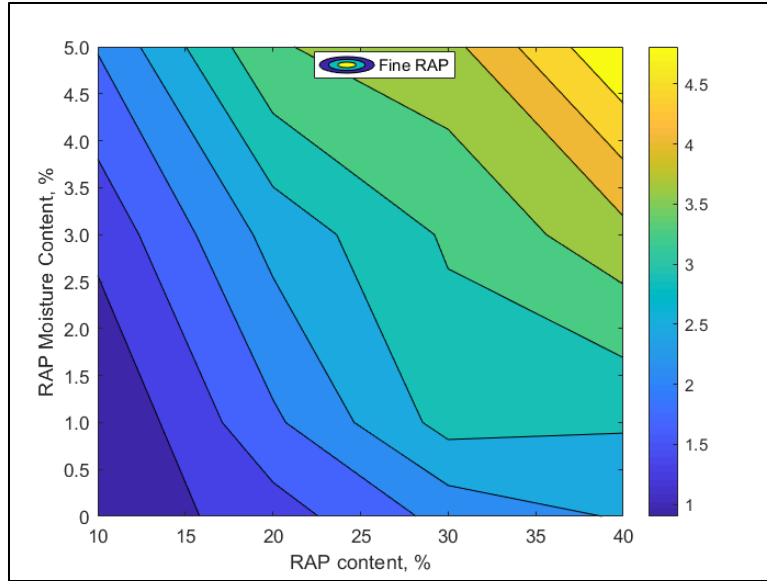
$$\begin{aligned}
 H_C = & 12.19 + 0.29 \times d_{pAgg.} - 0.90 \times d_{pRAP} - 1.48 \times MC \\
 & - 0.01 \times S \times d_{pAgg.} + 0.01 \times S \times d_{pRAP} \\
 & + 0.12 \times d_{pRAP} \times MC
 \end{aligned} \tag{4.8}$$

4.7 Summary

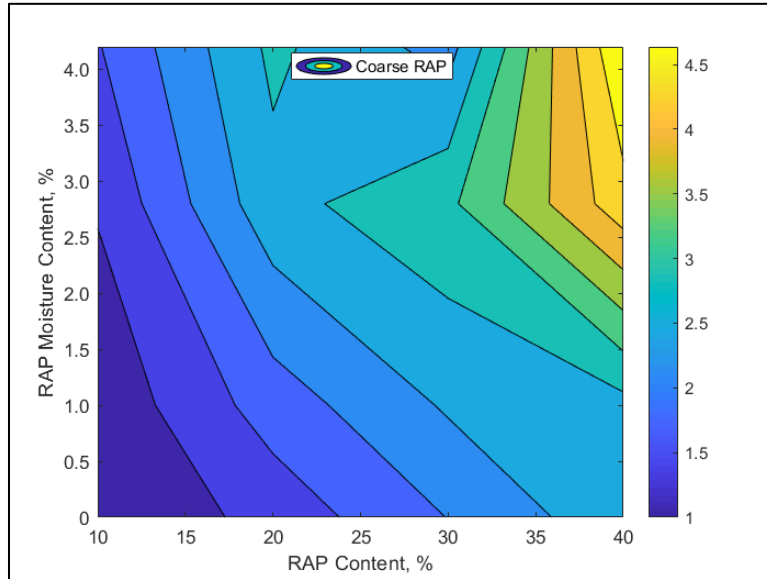
The following observations and conclusions are extracted from the efforts of this chapter:

- Based on the experimental results of the study, the existing equation for estimating superheated temperature required based on target discharge temperature, and mixture information was overestimating the temperatures.

- It was hypothesized that this over-prediction could be due to incomplete evaporation of moisture trapped within RAP particles. A new modified equation was recommended for estimating superheated temperatures required.
- An analytical method was developed to calculate the time required for thermal equilibrium with any initial RAP and virgin aggregate temperatures using heat conductance data of the mixture tested at a specific superheated temperature.
- A regression equation to predict heat conductance was developed. The established regression equation along with the analytical method can be used to calculate the time required for thermal equilibrium.
- Based on the ANOVA analysis results, longer mixing times between RAP and virgin aggregate needs to be provided to produce mixtures with high RAP contents, high moisture contents, and coarser RAP sizes.
- Mixing times needed for heat transfer completion in a mixture with varying RAP content and RAP moisture contents are expressed as a ratio to the mixing time required for a 10% RAP and a 0% moisture mixture (low-dry RAP mixture) in Figure 4.23.



(a)



(b)

Figure 4.23: Relative comparison of mixing times required for heat transfer completion/thermal equilibrium for (a) fine, and (b) coarse RAP mixtures.

CHAPTER 5 CONCEPT OF PREHEATING RECLAIMED ASPHALT PAVEMENT DURING HMA PRODUCTION

During the production of HMA mixtures with RAP, it is expected that sufficient heat transfer between superheated virgin aggregate and RAP happens in the dry mixing zone before the addition of a virgin binder to the mixture. Adequate heating of RAP before virgin binder entry helps RAP binder to activate, break agglomerated fine particles, and blend with virgin binder thoroughly. Based on the results of the previous chapter, for thermal equilibrium, it was discovered that the cold feed recycling method necessitates longer dry mixing times for mixtures with higher RAP contents, RAP moisture, and coarse RAP gradations. In the cold feed recycling method, where RAP is added at ambient temperature to virgin aggregate, possible solutions to allow longer dry mixing times are: (a) increase the length of the drum to allow a longer dry mixing zone or (b) reduce the production rate. However, both these solutions are practically difficult. Therefore, a hypothesis was explored analytically to check whether preheating RAP (warm feed recycling) for high-moisture RAP mixtures would lead to the same mixing times for thermal equilibrium compared to low-dry RAP mixtures (cold feed recycling).

As explained in section 4.4.2, the developed analytical method of calculating the time for thermal equilibrium can be used to calculate the T_{equi} of a mixture with any initial temperatures of RAP and virgin aggregate. As heat conductance values were determined as part of the study for the dense-graded mixtures used in the study, the analytical method was used to calculate T_{equi} of the dense-graded asphalt mixtures with varying preheated (initial) RAP temperatures.

When initial RAP temperatures are varied, the initial virgin aggregate temperature should also be changed to achieve a constant final discharge temperature of 300°F. Equation 5.1 was used to calculate initial virgin aggregate temperatures needed for different RAP initial temperatures and

presented in Table 5.1. For RAP preheated to temperatures of over 212°F, it was assumed that all the moisture in RAP was evaporated during preheat process.

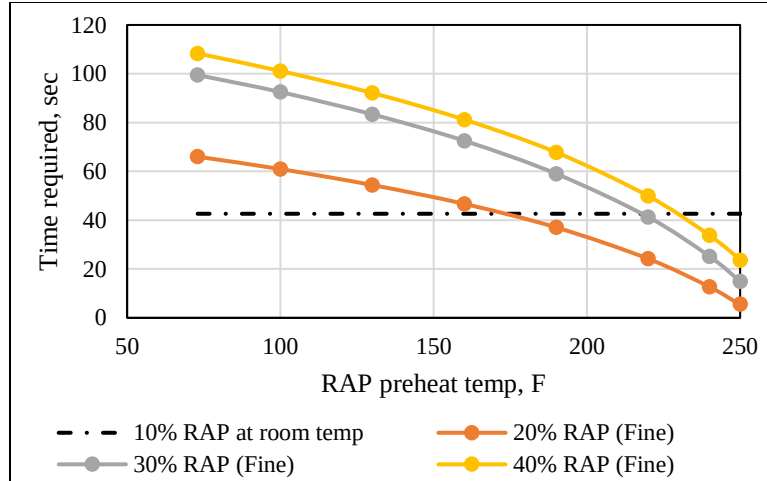
$$T_{v.a.} = \frac{T_{RHMA} - S_{RAP} \cdot T_{RAP}}{1 - S_{RAP}} + 4.0 \times \frac{S_{RAP} \cdot W_{RAP}}{1 - S_{RAP}} (100 - T_{RAP} + \underline{0.6 * 537}) \quad (5.1)$$

$$T_{va}^t - T_{rap}^t = [T_{va}^0 - T_{rap}^0] \cdot e^{H_C \times A \times t} \quad (5.2)$$

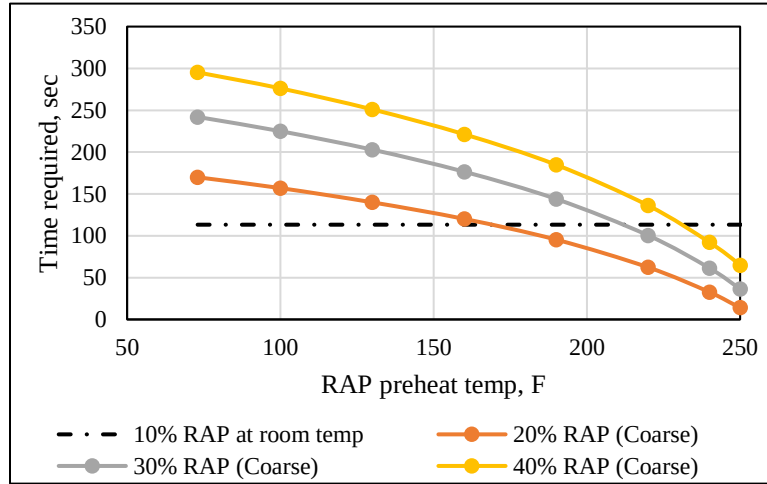
Table 5.1: Virgin aggregate temperatures needed for varying initial RAP temperature to yield 300°F discharge temperature.

RAP preheat temp, °F		73	100	130	160	190	220	240
RAP, %	MC, %							
10%	0%	325.2	322.2	318.9	315.6	312.2	308.9	306.7
10%	1%	328.4	325.3	321.8	318.4	314.9	311.4	309.1
10%	3%	325.2	322.2	318.9	315.6	312.2	308.9	306.7
10%	5%	325.2	322.2	318.9	315.6	312.2	308.9	306.7
20%	0%	356.8	350.0	342.5	335.0	327.5	320.0	315.0
20%	1%	356.8	350.0	342.5	335.0	327.5	320.0	315.0
20%	3%	356.8	350.0	342.5	335.0	327.5	320.0	315.0
20%	5%	356.8	350.0	342.5	335.0	327.5	320.0	315.0
30%	0%	397.3	385.7	372.9	360.0	347.1	334.3	325.7
30%	1%	397.3	385.7	372.9	360.0	347.1	334.3	325.7
30%	3%	397.3	385.7	372.9	360.0	347.1	334.3	325.7
30%	5%	397.3	385.7	372.9	360.0	347.1	334.3	325.7
40%	0%	451.3	433.3	413.3	393.3	373.3	353.3	340.0
40%	1%	451.3	433.3	413.3	393.3	373.3	353.3	340.0
40%	3%	451.3	433.3	413.3	393.3	373.3	353.3	340.0
40%	5%	451.3	433.3	413.3	393.3	373.3	353.3	340.0

T_{equi} for various preheat RAP temperatures were calculated using the analytical method developed in section 4.4.2 for dense-graded mixtures with fine and coarse RAP and plotted in Figure 5.1.



(a)



(b)

Figure 5.1: Change in calculated T_{equi} with preheating RAP before adding to virgin aggregate using: (a) fine, and (b) coarse dry RAP.

From Figure 5.1, it can be observed that with an increase in preheat temperature of RAP, the amount of time required for thermal equilibrium reduces. Therefore, preheating RAP before adding to virgin aggregate shortens the mixing time needed for complete heat transfer. It can be concluded that for mixtures with high RAP and moisture contents, RAP can be processed by preheating in a separate plant add-on to produce mixtures with complete heat transfer without changing the plant configuration and production rate. Therefore, a warm feed recycling technique can be an alternative for higher and moist RAP mixtures to allow sufficient heat transfer between RAP and virgin aggregate, ultimately enhancing the quality of produced asphalt mixtures.

Based on Figure 5.1, RAP preheat temperatures required for higher RAP and moisture mixtures can be determined to reach thermal equilibrium within the same time as low-dry RAP mixture (10% RAP and 0% moisture mixture). An automated script was written in MATLAB to calculate the required RAP preheat temperatures. Figure 5.2 shows the algorithm used to calculate preheat temperature needed for any asphalt mixture to attain thermal equilibrium at the same mixing time as a 10% dry RAP mixture.

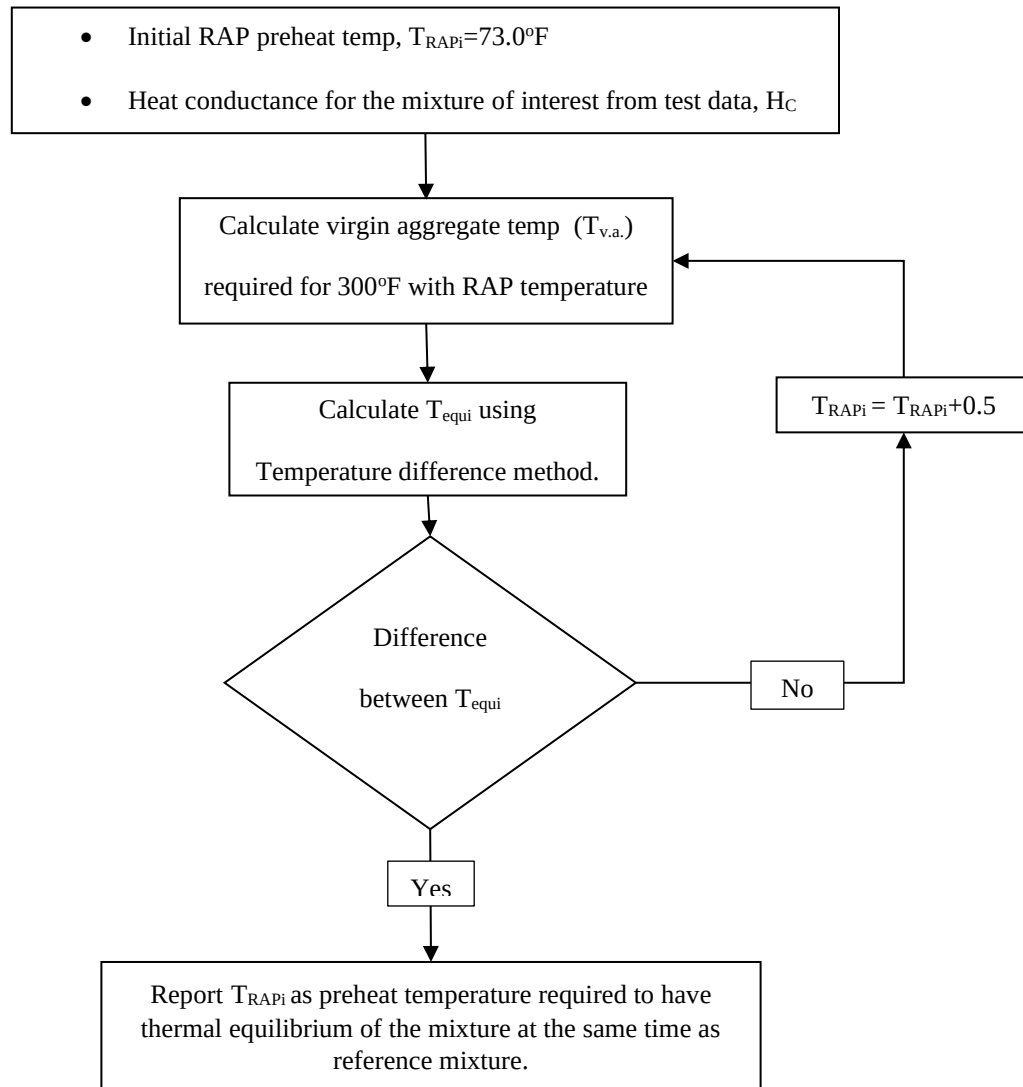
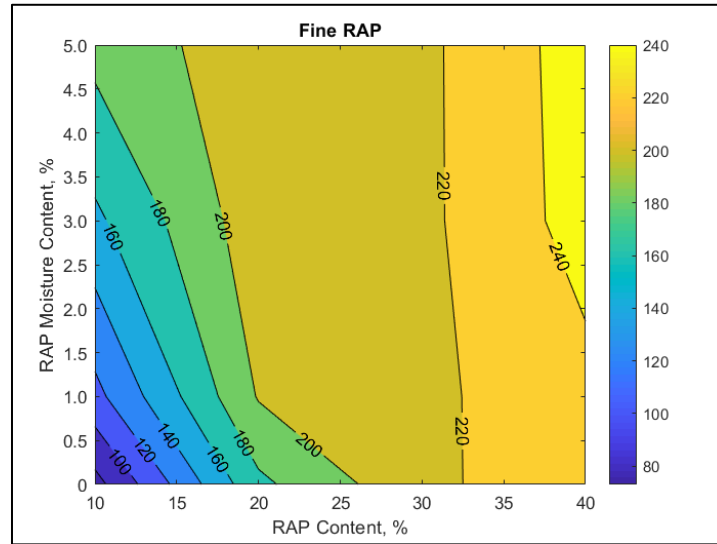
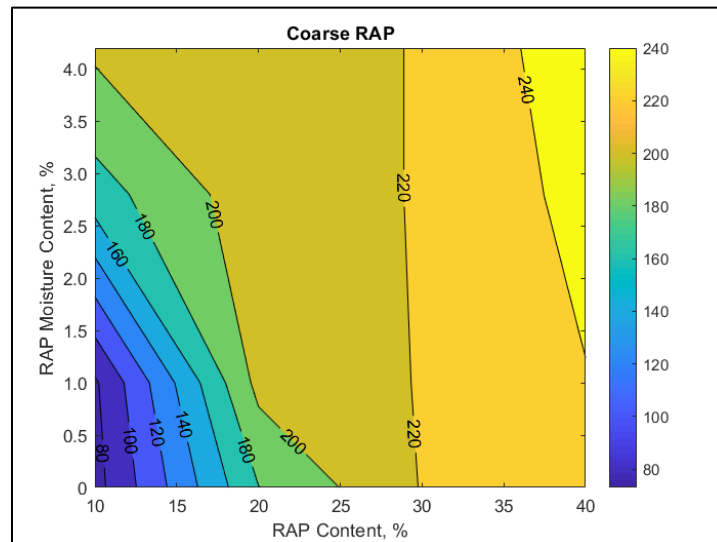


Figure 5.2: Flowchart of the algorithm used for MATLAB code to calculate required RAP temperature.

Figure 5.3 shows the recommended preheat temperatures of RAP so that an asphalt mixture with either 10% RAP or 40% RAP can reach thermal equilibrium at the same mixing time. These recommendations are based on the laboratory test results from this study.



(a)



(b)

Figure 5.3: RAP preheat temperatures required for mixtures with varying RAP and moisture contents to achieve T_{equi} as of 10%, and 0% RAP moisture mix for: (a) Fine, and (b) Coarse RAP.

5.1 Energy Consumption Analysis

For high RAP mixtures and mixtures with high RAP moisture, the warm feed recycling method can produce high-quality mixtures compared to cold feed recycling technology. As in the warm

feed recycling method, the RAP binder will be heated to sufficient temperatures in the dry mixing stage before the addition of the virgin binder. This will help better activating the RAP binder and form homogeneous mixtures by breaking fine RAP agglomerates. However, recommending warm feed recycling for HMA production has to be based on energy consumption analysis besides the benefits in terms of the heat transfer process.

In an HMA plant, heat energy required to superheat virgin aggregate is the primary source of heat energy consumption, apart from that needed for heating virgin binder and maintaining a storage silo at mixing temperature. However, the heat energy required for heating virgin binder and maintaining storage silo remains the same for both processing methods. Hence, in this section, only the heat energy required to produce one metric ton of HMA before the wet mixing stage was analyzed for both conventional cold feed recycling and warm feed recycling methods.

5.1.1 Energy Consumption in Cold Feed Recycling Method

In a conventional cold feed recycling method, virgin aggregates are superheated to required temperatures to attain the target discharge temperature. Equation 5.1 was used to calculate superheated temperatures required for various RAP contents and RAP moisture contents. As virgin aggregate has to be heated from room temperature to superheated temperatures, Equation 5.3 was used to calculate the energy required to heat the virgin aggregate in a cold feed recycling method.

$$E_{va} = m_{va} \times C_{va} \times (T_{va} - T_{ambient}) \quad (5.3)$$

Where,

E_{va}	=	Heat energy required to superheat virgin aggregate, J
m_{va}	=	Mass of virgin aggregate, kg
C_{va}	=	Specific heat capacity of virgin aggregate, J/kg-°C
T_{va}	=	Temperature of virgin aggregate, °C
$T_{ambient}$	=	Ambient temperature, °C

5.1.2 Energy Consumption in Warm Feed Recycling Method

In warm feed recycling, there are two sources of energy consumption to: (a) Preheat RAP and (b) Heat virgin aggregate. For heating RAP material, RAP has to be heated from ambient temperature to the required preheat temperature, as shown in Equation 5.4.

$$E_{rap} = m_{rap} \times C_{rap} \times (T_{rap} - T_{ambient}) \quad (5.4)$$

Where,

$$\begin{aligned} E_{rap} &= \text{Heat energy required to preheat RAP, J} \\ m_{rap} &= \text{Mass of RAP, kg} \\ C_{rap} &= \text{Specific heat capacity of RAP, J/kg-}^{\circ}\text{C} \\ T_{rap} &= \text{Preheat temperature of RAP required, }^{\circ}\text{C} \\ T_{ambient} &= \text{Ambient temperature, }^{\circ}\text{C} \end{aligned}$$

For RAP with moisture, RAP moisture should be evaporated in the RAP preheating system. It was assumed that for preheating temperatures above 212°F, RAP moisture would be evaporated in the preheating system. Based on the validation analysis results, energy required for the evaporation part of the RAP moisture is reduced to 60%. Therefore, the energy required to evaporate RAP moisture was calculated using Equation 5.5, where latent heat of vaporization of water was taken as 2,260 kJ/kg.

$$E_{rapmoisture} = 0.6 \times m_{rap} \times S \times 2260 \times 10^3 \quad (5.5)$$

Where,

$$\begin{aligned} E_{rapmoisture} &= \text{Heat energy required to evaporate RAP moisture, J} \\ m_{rap} &= \text{Mass of RAP, kg} \\ S &= \text{Percentage of moisture by weight of dry RAP, as decimal} \end{aligned}$$

SSSS

Heating temperatures required for virgin aggregate were calculated using Equation 5.1. To yield a final discharge temperature of 300°F, the heat energy needed to heat virgin aggregate to required temperatures was calculated using Equation 5.3.

Heat energies required for both cold feed recycling and warm feed recycling were calculated for the following mixtures and presented in Table 5.2 and Table 5.3

- RAP contents: 10, 20, 30, and 40%
- RAP size: fine and coarse RAP
- Moisture contents: 0, 1, 3, 5% for fine RAP and 0, 1, 2.8, 4.2% for coarse RAP

Based on the energy results, it can be concluded that both cold feed recycling and warm feed recycling methods of processing RAP need the same heat energies. The total energies required for virgin aggregate and RAP heating remained same as the energy required to preheat RAP is balanced by the reduction in required superheated temperatures in warm feed recycling method.ssss

Table 5.2: Heat energies required to heat virgin aggregate and RAP using both cold and warm feed recycling for fine RAP.

RAP Content, %	RAP Moisture Content, %	Cold Feed Recycling	Warm Feed Recycling			Extra Heat Energy Needed for Warm Feed Recycling, %
		Total Heat Energy Required, MJ	Energy Required to heat Virgin aggregate, MJ	Energy Required to preheat RAP, MJ	Total Energy Required, MJ	
10%	0.0%	117.4	117.4	0	117.4	0%
	1.0%	118.9	118.7	0.2	118.9	0%
	3.0%	121.9	116.2	5.7	121.9	0%
	5.0%	124.8	116.7	8.1	124.8	0%
20%	0.0%	117.4	106.4	11	117.4	0%
	1.0%	120.4	106.1	14.3	120.4	0%
	3.0%	126.3	103	23.3	126.3	0%
	5.0%	132.3	103	29.3	132.3	0%
30%	0.0%	117.4	93.2	24.2	117.4	0%
	1.0%	121.9	93.3	28.6	121.9	0%
	3.0%	130.8	93.3	37.5	130.8	0%
	5.0%	139.7	93.3	46.4	139.7	0%
40%	0.0%	117.4	82.1	35.3	117.4	0%
	1.0%	123.4	82.1	41.3	123.4	0%
	3.0%	135.3	82.1	53.2	135.3	0%
	5.0%	147.2	82.1	65.1	147.2	0%

Table 5.3: Heat energies required to heat virgin aggregate and RAP using both cold and warm feed recycling for coarse RAP.

RAP Content, %	RAP Moisture Content, %	Cold Feed Recycling	Warm Feed Recycling			Extra Heat Energy Needed for Warm Feed Recycling, %
		Total Heat Energy Required, MJ	Energy Required to heat Virgin aggregate, MJ	Energy Required to preheat RAP, MJ	Total Energy Required, MJ	
10%	0.0%	117.4	117.4	0	117.4	0%
	1.0%	118.9	118.7	0.2	118.9	0%
	2.8%	121.6	116.2	5.4	121.6	0%
	4.2%	123.7	116.7	7	123.7	0%
20%	0.0%	117.4	106.4	11	117.4	0%
	1.0%	120.4	106.1	14.3	120.4	0%
	3.0%	125.7	103	22.7	125.7	0%
	5.0%	129.9	103	26.9	129.9	0%
30%	0.0%	117.4	93.2	24.2	117.4	0%
	1.0%	121.9	93.3	28.6	121.9	0%
	3.0%	129.9	93.3	36.6	129.9	0%
	5.0%	136.2	93.3	42.9	136.2	0%
40%	0.0%	117.4	82.1	35.3	117.4	0%
	1.0%	123.4	82.1	41.3	123.4	0%
	3.0%	134.1	82.1	52	134.1	0%
	5.0%	142.4	82.1	60.3	142.4	0%

5.2 Summary

The following observations and conclusions are extracted from the efforts of this chapter:

- Preheating RAP before adding it to virgin aggregate would reduce the time required for thermal equilibrium.
- Preheating RAP temperatures required for asphalt mixtures with various RAP and RAP moisture content to attain thermal equilibrium at the same mixing time as 10% dry RAP mixture are recommended.
- Based on the energy consumption analysis, the warm feed recycling method requires the same amount of energy to process RAP as cold feed recycling.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study was to characterize the heat transfer between superheated virgin aggregate and RAP material. However, there was no standard test method available to achieve the objective of the study. Therefore, a new laboratory test method was developed to characterize the heat transfer between these two materials that included the fabrication of a blending chamber with reduced heat losses and having uniform and continuous mixing of particles in the chamber. Two analysis frameworks were developed to calculate: (a) the time required for thermal equilibrium (T_{equi}) and (b) heat conductance (H_C) using raw data from the heat transfer testing. An experimental matrix was designed to evaluate the effect of asphalt mixture variables on the heat transfer process. The following conclusions were made based on the results of the study:

6.1 Conclusions

- DEM simulation results were used to validate the assumption made for the heat transfer test method. Segregation index analysis conducted on DEM images and Infrared images concluded that the blending chamber used in the study achieved uniform dispersion of RAP particles into the mixture in 8-12 sec. DEM results also concluded that temperature characteristics of the particles on the surface of the mix were representative of the entire mix, and the 5th and 95th percentile of the FOV temperature data were reasonable estimates of RAP and virgin aggregate particle temperatures.
- Based on the variability analysis results, the heat transfer test method used in the study was able to produce repeatable results with three replicates, with an average COV of 12% and 14% for T_{equi} and H_C , respectively.

- Based on the discharge temperature results of this study, the existing energy balance-based equation for superheated temperature determination was overestimating the superheated virgin aggregate temperature required, especially for mixtures with higher RAP contents and higher moisture contents. A modification was recommended to the existing equation to calculate the necessary superheated temperature based on the data of this study (Equation 4.3).
- The time required for thermal equilibrium is affected by the size of the RAP material. For example, T_{equi} was determined to be 45 seconds for 10% dry, fine RAP compared to 116 seconds for 10% dry, coarse RAP.
- Based on the ANOVA analysis: RAP content, RAP moisture content, RAP gradation, virgin aggregate gradation, and source were identified as statistically significant mixture variables that can explain the time required for thermal equilibrium variability.
- Tukey's statistical comparison shows the following general trends for the time required for thermal equilibrium with mixture variables:
 - T_{equi} increased with an increase in RAP content,
 - T_{equi} increased with an increase in RAP moisture content,
 - T_{equi} increased with an increase in RAP particle size,
 - T_{equi} decreased with an increase in virgin aggregate particle size,
 - Virgin aggregate source limestone took longer time for thermal equilibrium, followed by quartzite, dolomite, and basalt.
- The new analytical method developed in the study to calculate T_{equi} using heat conductance from testing and Monte Carlo simulation was proved to be a reliable method based on the comparison of T_{equi} obtained from testing and the new analytical approach.

- A regression equation was constructed to estimate the heat conductance using mixture variables. The regression equation, coupled with the analytical approach, can compute the time required for thermal equilibrium.
- The preheating RAP hypothesis was tested, it was concluded that preheating RAP resulted in reduced time required for thermal equilibrium.
- Preheating RAP temperatures required for asphalt mixtures with various RAP and RAP moisture content to attain thermal equilibrium at the same mixing time as 10% dry RAP mixture were recommended.
- Energy consumption analysis was conducted to compare cold and warm feed recycling methods of handling RAP. It was concluded that the warm feed recycling method needs the same amount of energy to process RAP as cold feed recycling.

6.2 Recommendations

- The modified equation for superheated temperature estimation is based on the experimental results; this needs to be verified using asphalt plant production data. It is difficult to measure aggregate and RAP particle temperatures inside the drum, but it is possible to measure the mixture temperature as it is discharged from the drum. This measure of particle temperatures (not just average mixture temperature) combined with the estimated contact time within the drum could be compared to the study results.
- The present study characterized heat transfer between virgin aggregate and RAP without the use of hot gases and a continuously heated chamber. The scope of the study can be extended to add these two heat sources to the blending chamber to better replicate the heat transfer mechanisms in an asphalt plant. This study was a fundamental examination of the interaction between the virgin aggregate and RAP. While there are numerous variations in

the configuration of asphalt plants, all plants have other sources of heat that influence the change in aggregate and RAP particle temperatures.

- The present study characterized the heat transfer and mixture variables affecting the heat transfer process. The scope of the work can be extended to evaluate the effect of heat transfer on the performance of an asphalt mixture; in particular, how the superheated aggregate surface temperature in contact with the RAP influences the aged asphalt binder coating the RAP.
- Further literature review on thermal properties of rocks revealed that specific heat capacity of rocks depends on temperature of the material (Robertson, 1988; Landolt-Börnstein, 2002; Silva & Schmidt, 2010). The scope of the work can be extended to validate the existing superheated temperature recommendations by taking the temperature dependency of aggregate specific heat into account.

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APPENDIX: A

Test method for the laboratory evaluation of heat exchange between superheated virgin aggregate and reclaimed asphalt pavement (RAP) material

1. Scope:

The scope of this test protocol is to have a detailed test procedure to study the fundamental heat transfer between superheated virgin aggregate and the cold RAP material using infrared camera measurements.

2. Test Sample Preparation:

The sample preparation should be completed one day prior to testing.

- The dry weight of the test sample, including virgin aggregate and RAP, should be 4000 ± 40 g. Prepare a blending sheet for blending the aggregate and RAP materials for 4000 g tests along with the weight of water to be added to the dry RAP material based on the percent RAP moisture content required.
- Obtain dry virgin aggregate material from the required processed aggregate bins. The amount of material taken from the bin should be 2 to 4 times the amount required for the sample weight. Then, split the virgin aggregate material to the required sample size using a quartering splitting technique.
- Similarly, obtain dry RAP material from the processed RAP bins. The amount of material taken from the bin should be 2 to 4 times the amount required for the sample weight. Then, split the dry RAP material to the required sample size using a quartering splitting technique.
- Adjust the weight of the dry virgin aggregate material obtained from the split bin sample to form the aggregate portion of the total test sample weight of 4000 ± 40 g, based on the blending sheet.

- Adjust the weight of dry RAP material obtained from the split bin sample to form the RAP portion of the total test sample weight of 4000 ± 40 g, based on the blending sheet. Place the dry RAP sample in a gallon zip-lock bag and add the amount of water required to the RAP material. Gently shake the dry RAP material with added water to uniformly disperse the water. Sampled wet RAP material should be prepared the day ahead of testing and allowed to cure overnight (minimum of 12 hours).
- Place the container with the virgin aggregate sample in an oven at the required temperature for testing for a minimum duration of 6 hr., an oven with a timer can be used to exactly start the oven 6 hr. before the testing.
- Obtain a sample of single-sized virgin aggregate (4.75 mm) to preheat the blending chamber before the start of each test. The weight of the preheating sample should be 4000 ± 40 g. Place the preheat sample into the same oven with the test sample at least 6 hr. prior to testing.

3. Apparatus:

- *Weighing balances*
- *Aggregate/RAP Blending Chamber:* A steel drum with 9 in. diameter and 10.75 in. height inserted into a laboratory asphalt bucket mixture with 11 in. diameter and 13.5 in. height, the gap between these two steel drums is filled with a glass fiber insulating material to reduce heat losses from the blending chamber. The schematic of the blending chamber is shown in Figure A.1. Internal flight assembly (Figure A.2), the rotational speed of the blending chamber, and the inclination of the blending chamber were designed by ASTEC Industries, Inc. using the Discrete Element Modelling (DEM) simulation method. To have a uniform and continuous blending of virgin aggregate and RAP material inside the

blending chamber. A rotational speed of 8 rpm and an angle of inclination of 21.5° are used for testing.

A segregation index analysis was conducted using mixture temperature information obtained during testing. The brief analysis showed that virgin aggregate and RAP in the chamber are uniformly blended in 5 sec. A wooden sheet is used as a lid to the front end of the chamber; circular insulation was attached to the lid of the mixer to control heat losses from the front end of the mixer. A 3x3 in. opening is provided through the lid to record the material temperature during testing and add RAP to the blending chamber. Continuous airflow is provided across the opening on the front lid to provide an air curtain to control heat losses from the opening on the lid and protect the lens of the camera, as shown in Figure A.3.

- *Infrared camera with telephoto lens:* Set up the Infrared camera at 0.4 m from the surface of the aggregate as perpendicular to the plane of the aggregate material as possible. Adjust the infrared camera using the desktop software to obtain the necessary focus and the required Field of View. Set the infrared camera controlling software to record infrared measurements every 1 sec.
- *Computer*
- *Tripod*
- *Funnels to charge the material.*
- *Pans for sampling and cooling the material.*

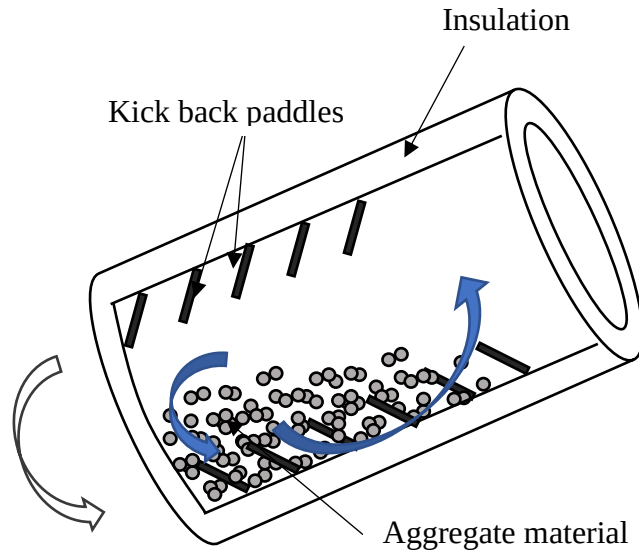


Figure A.1:Schematic of the blending chamber.

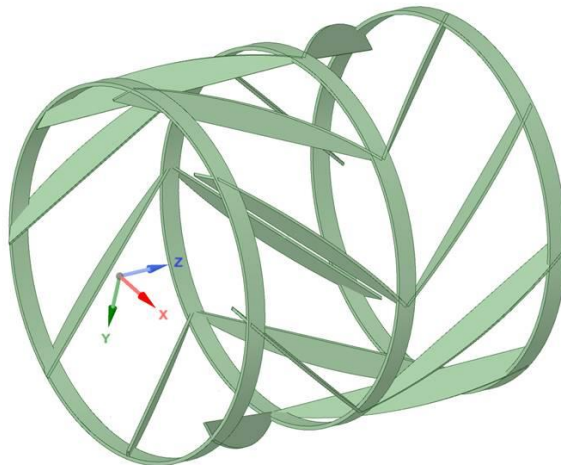
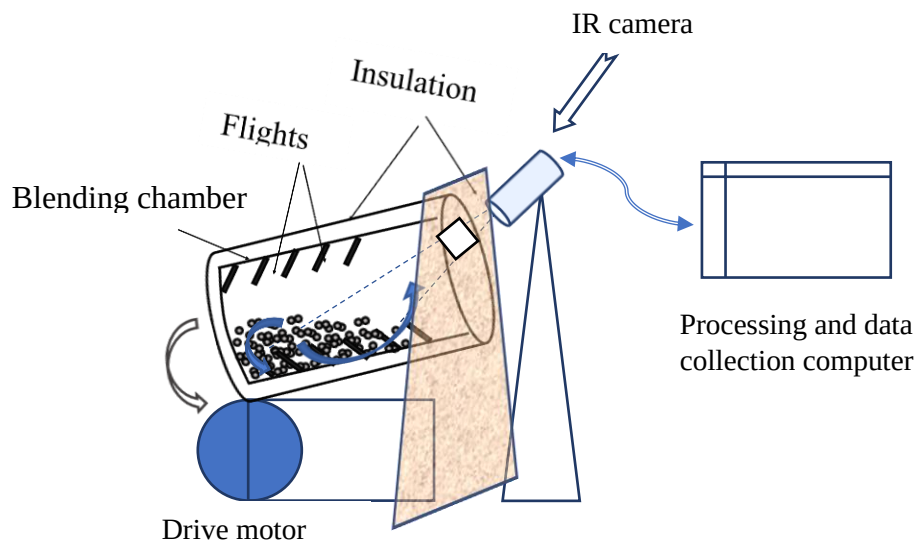
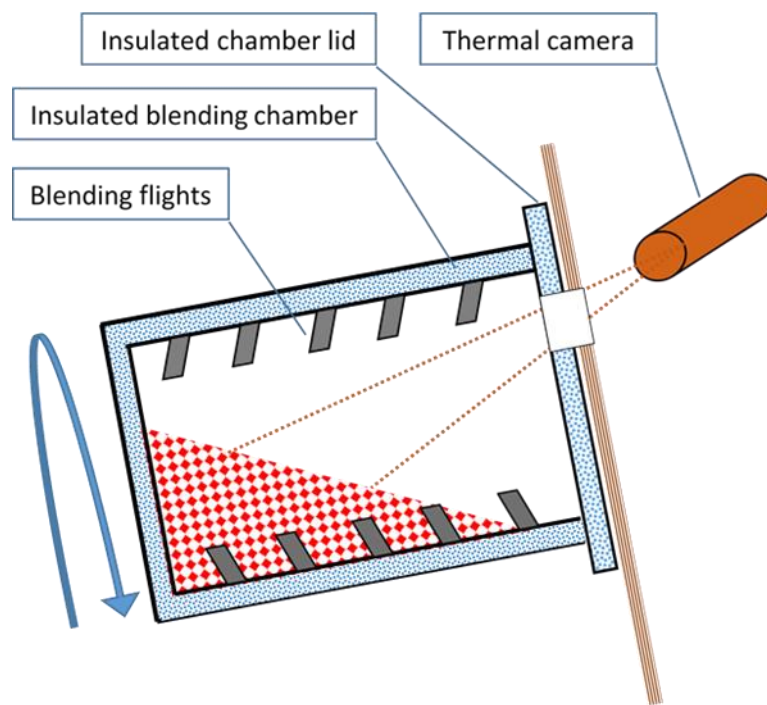


Figure A.2:Schematic of the Flight Design inside the blending chamber.



(a)



(b)

Figure A.3: Schematic of the heat transfer test setup: (a) entire assembly (b) blending chamber.

4. Testing Procedure:

A preheat time of 5 minutes is required for the preheat material to heat the chamber.

1. Set the blending chamber inserted into the rotating frame in the vertical position. Remove the preheat material from the oven and transfer that to the blending chamber. Lower the blending chamber and frame to the required inclination and place the lid on the chamber. Turn on the chamber blending motor to begin the preheat rotation cycle.
2. After 5 minutes, stop the rotation motor, removed the lid, and bring back the rotating frame assembly to the vertical position. Next, remove the blending chamber from the frame to place the preheat aggregate into a cool pan for reuse, set the blending chamber back into the rotating frame assembly.
3. Load the heated aggregate sample into the blending chamber, lower the rotating frame assembly to the required inclination and place the lid on the chamber. Removing the preheat material and loading and aggregate sample into the preheated chamber needs to be accomplished quickly.
4. Start the motor of the blending chamber and start recording the infrared camera, re-confirm the focus and field of view of the infrared camera and adjust accordingly.
5. Introduce the RAP sample through the lid opening when the superheated aggregate reached the required test superheat temperature. Place the RAP inside a 2 in. pipe, extend it 3 in. into the chamber, and discharge the RAP to the right of the superheated aggregate.
6. Continue the test for 15 minutes after the introduction of RAP into the chamber.

7. Stop the motor, remove the lid, and bring back the frame assembly to the vertical position.

Next, remove the blending chamber from the frame to place the testing material into a cool pan and store it for other testing purposes.

8. Set blending chamber back into the frame, repeat steps same procedure for the remaining replicates of the test.

5. Analysis Procedure:

The following steps present the standard method for calculating heat transfer parameters from the above-mentioned standard test method.

Time Required for Thermal Equilibrium:

- Calculate the standard deviation of the FOV from excel files collected from the IR camera, calculate the standard deviation for every second.
- Smoothen the standard deviation versus mixing time with the Savitzky-Golay filter method.
- Fit a negative growth sigmoidal curve between standard deviation and mixing time as shown in Equation A.1

$$SD(t) = f(t) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log_{10}(t)}} \quad (A.1)$$

t = Mixing time, sec

$SD(t)$ = Standard deviation of FOV at mixing time t , °F

$\alpha, \beta, \gamma, \delta$ = Curve fitting coefficients

- Calculate the second inflection point of the second derivative of the fitted function by equating fourth-order derivative of $f(t)$ to zero, which is T_{equi} .

Heat Conductance Determination:

- Determine the time required for thermal equilibrium from the above section.
- Determine virgin aggregate and RAP temperatures from the collected IR camera data at every second of the mixing. The 5th and 95th percentile temperatures of the FOV are RAP and virgin aggregate temperatures.
- Calculate $\ln \left[\frac{T_{va}-T_{rap}}{T_{va}^0-T_{rap}^0} \right]$ at each second of mixing time. Plot $\ln \left[\frac{T_{va}-T_{rap}}{T_{va}^0-T_{rap}^0} \right]$ against mixing time until T_{equi}
- Fit a straight-line regression equation to the plot. Calculate heat conductance using the slope of the fitted straight line, as follows:

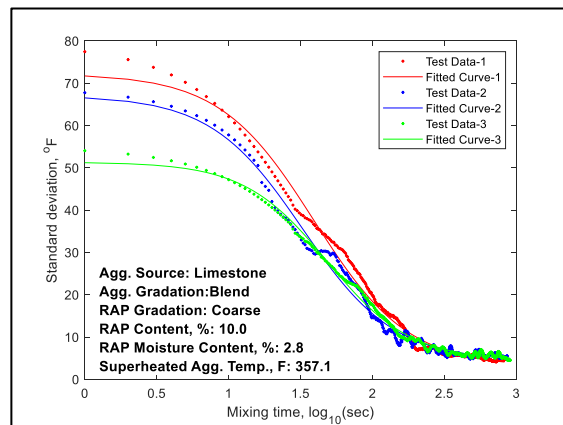
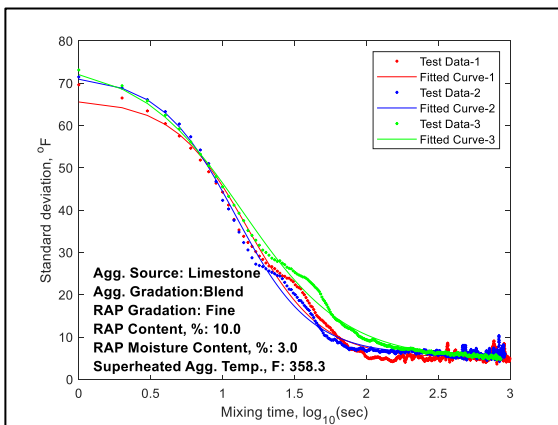
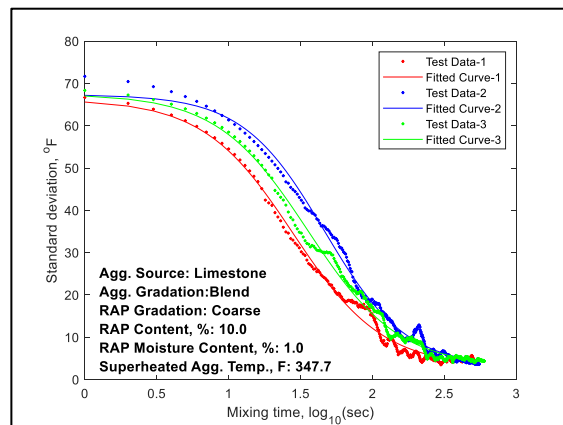
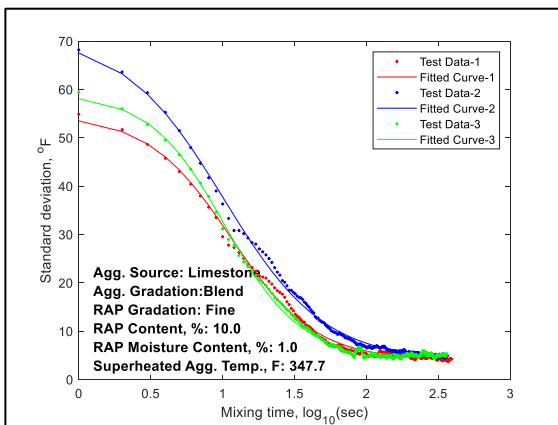
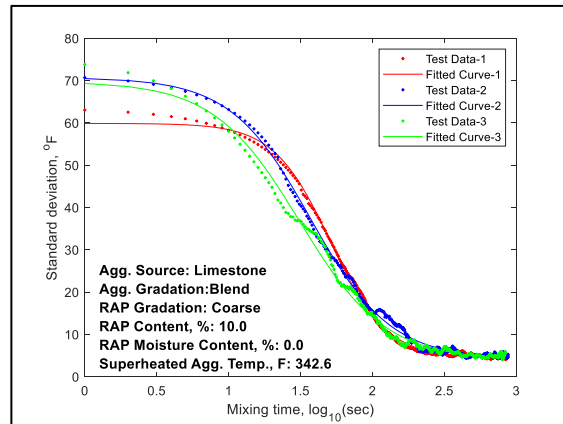
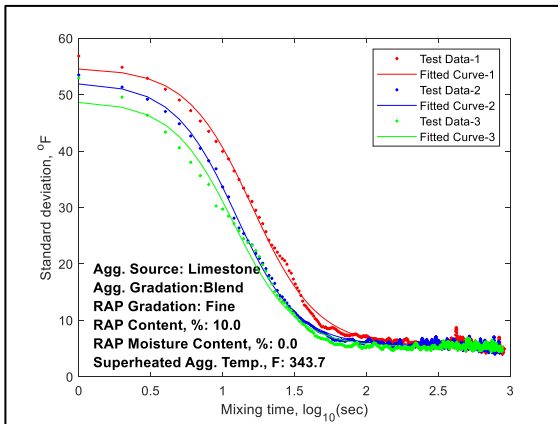
$$H_C = \frac{\text{Slope}}{\left[1 + \frac{m_{va}C_{va}}{m_{rap}C_{rap}} \right] \frac{m_{va}C_{va}}{m_{va}C_{va}}} \quad (A.2)$$

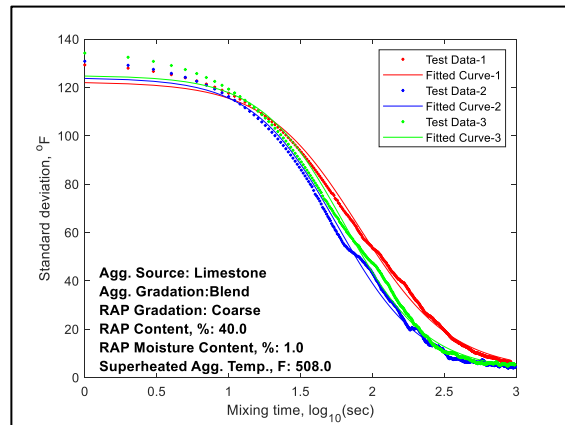
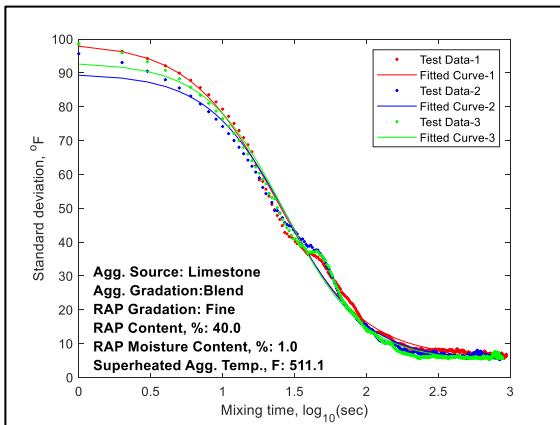
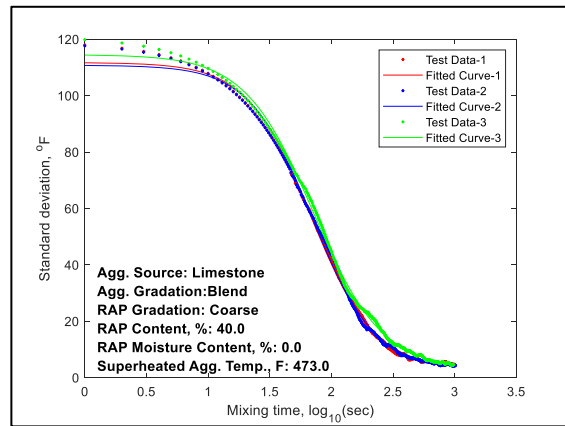
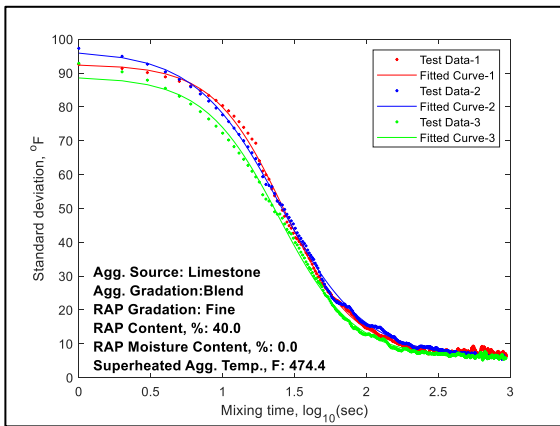
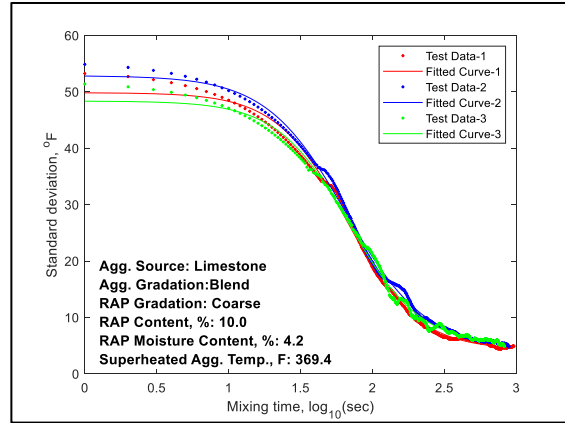
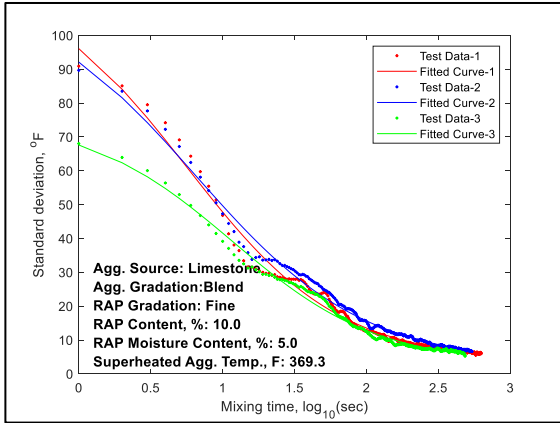
Where,

- T_{rap} = Temperature of RAP, °C
- T_{rap}^0 = Initial temperature of RAP, °C
- T_{va} = Temperature of virgin aggregate, °C
- T_{va}^0 = Initial superheated virgin aggregate temperature, °C
- t = Mixing time, sec
- H_C = Heat conductance between virgin aggregate and RAP, J/sec-°C
- m_{rap} = Mass of RAP, kg
- C_{rap} = Specific heat capacity of RAP, J/kg-°C
- m_{va} = Mass of virgin aggregate, kg
- C_{va} = Specific heat capacity of virgin aggregate, J/kg-°C

APPENDIX: B

Example plots used to determine T_{equi} and heat conductance.





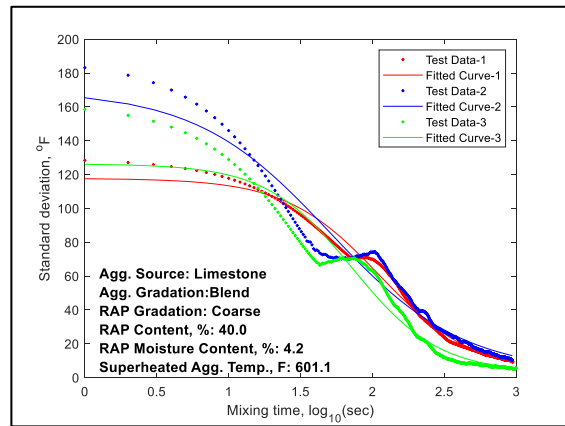
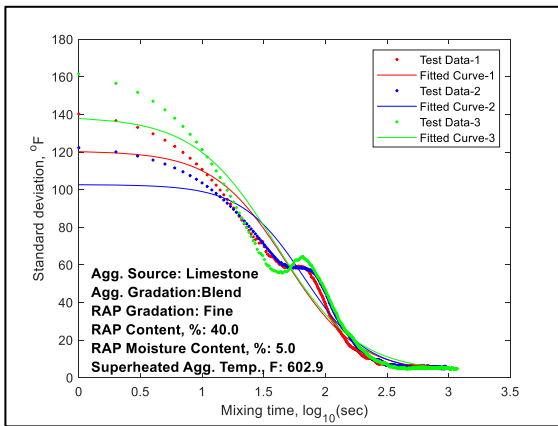
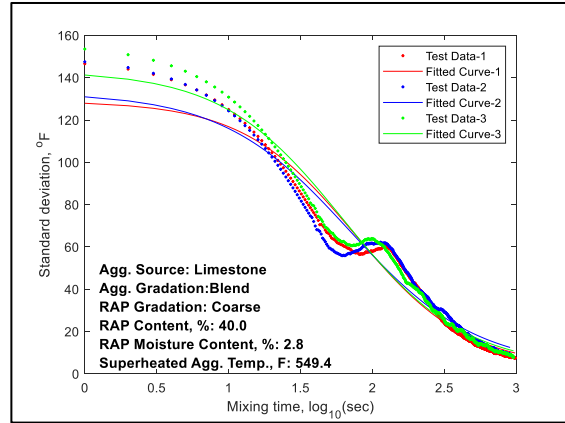
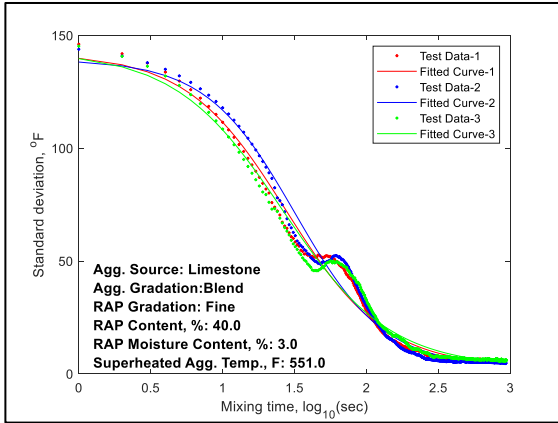
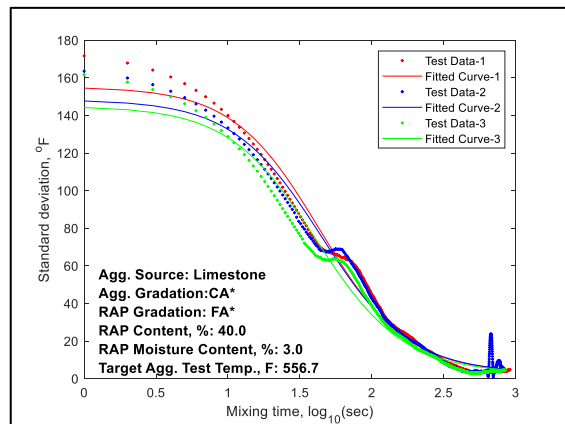
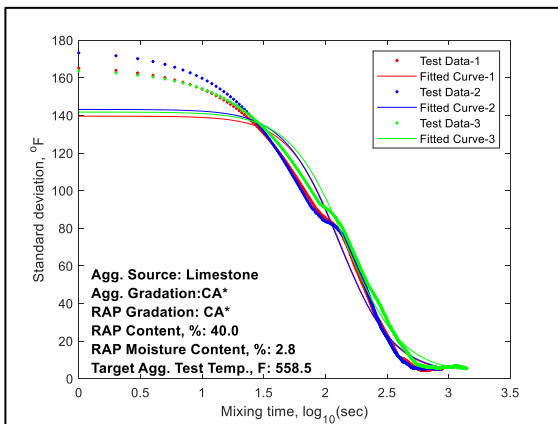
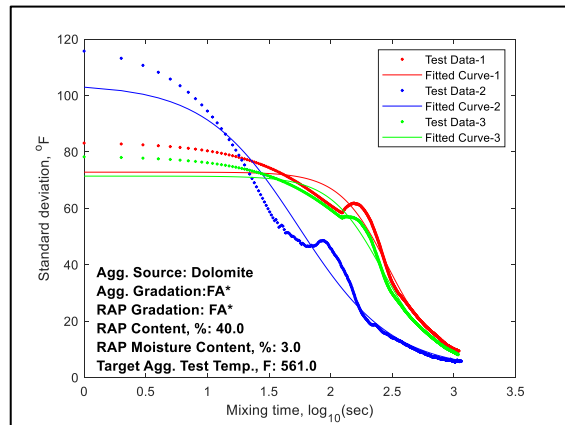
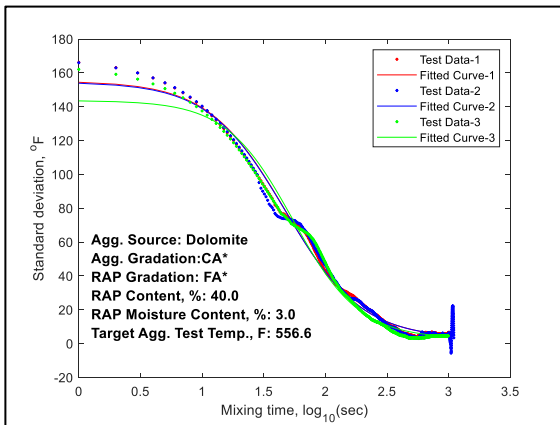
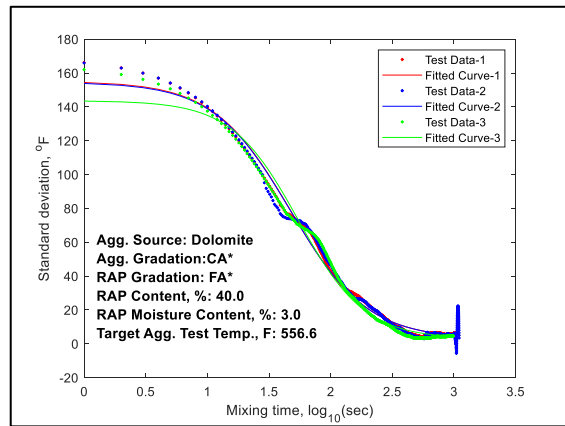
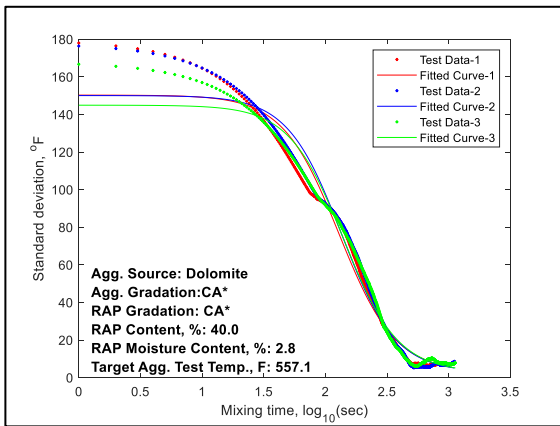
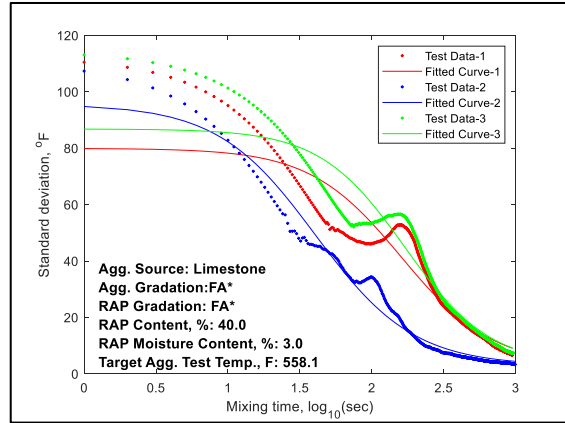
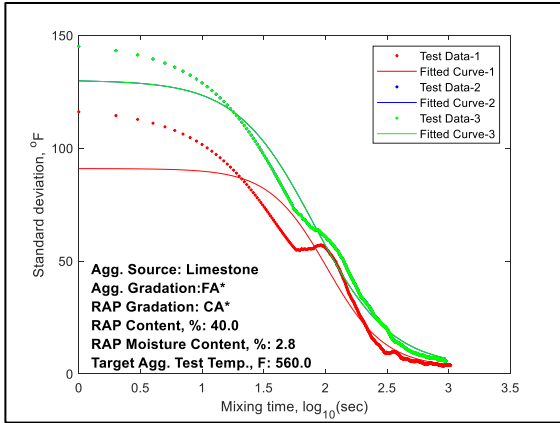
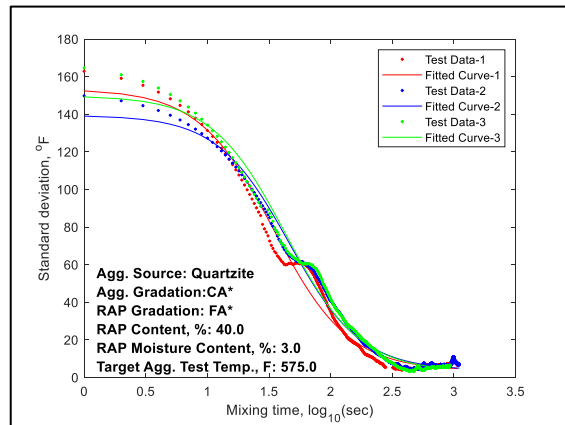
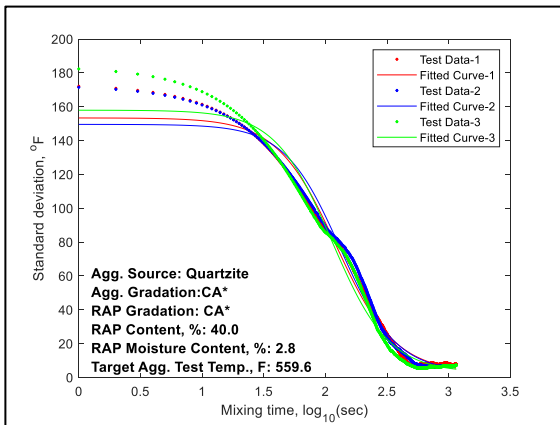
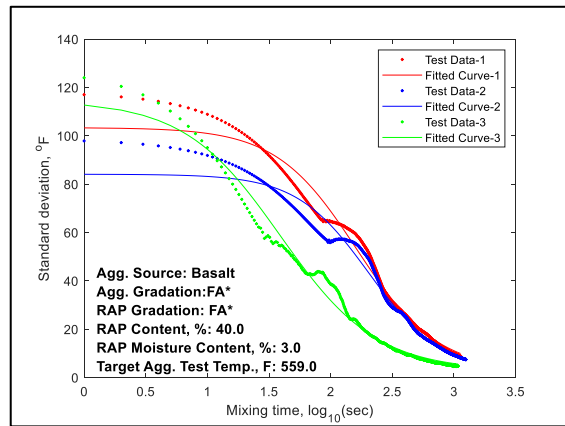
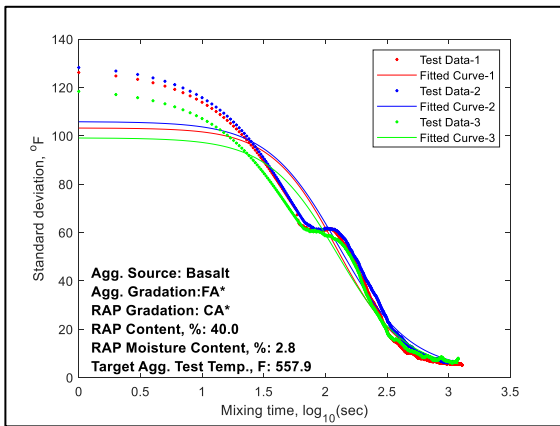
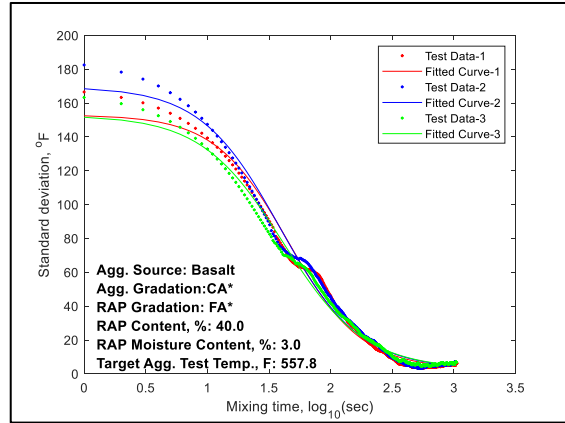
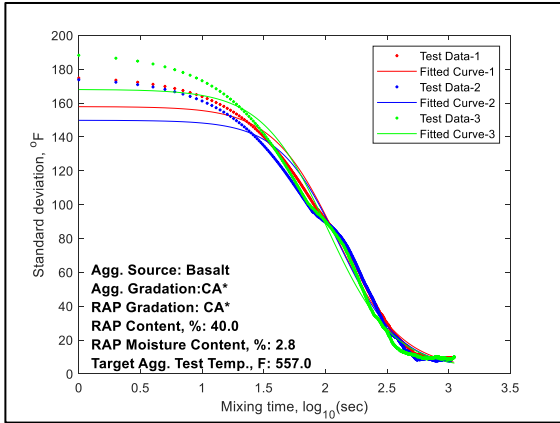


Figure B.1: Example change in FOV standard deviation with mixing time curves of dense graded mixtures used for T_{equi} determination.







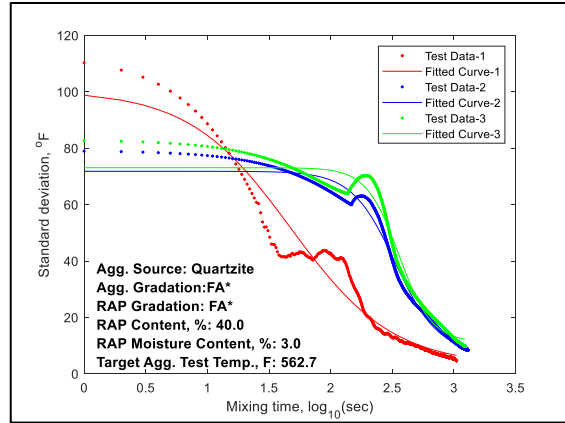
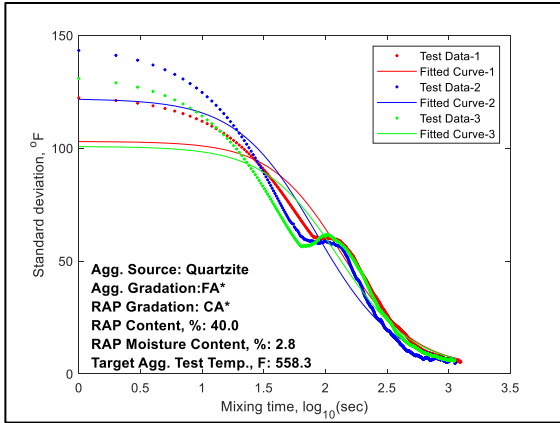
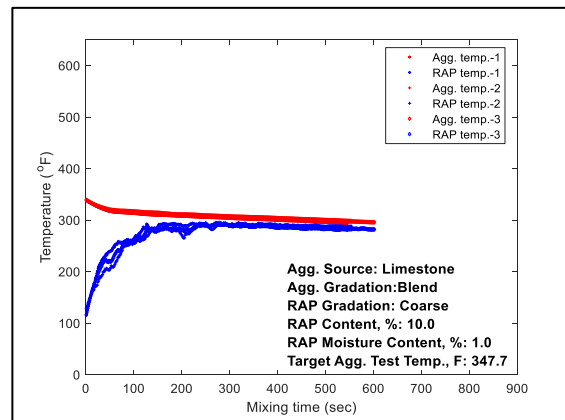
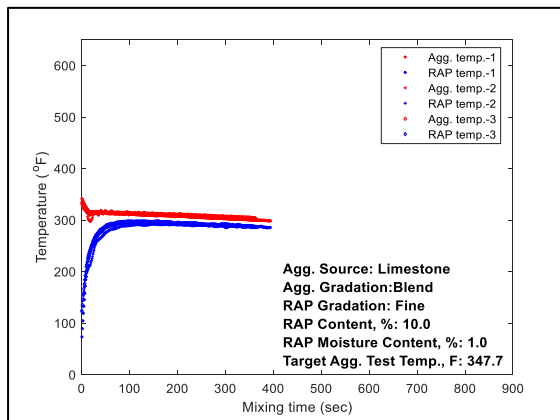
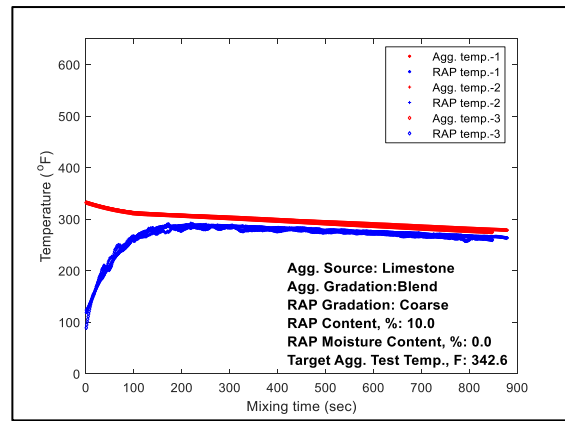
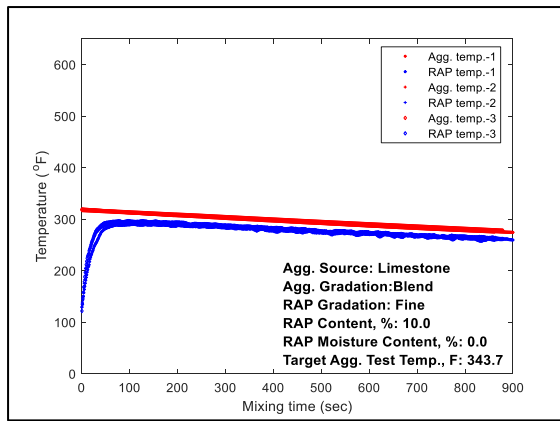
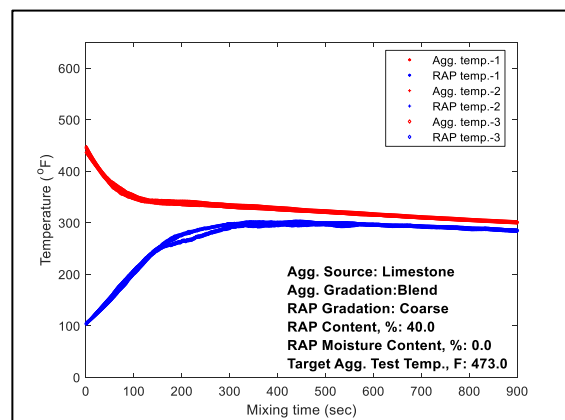
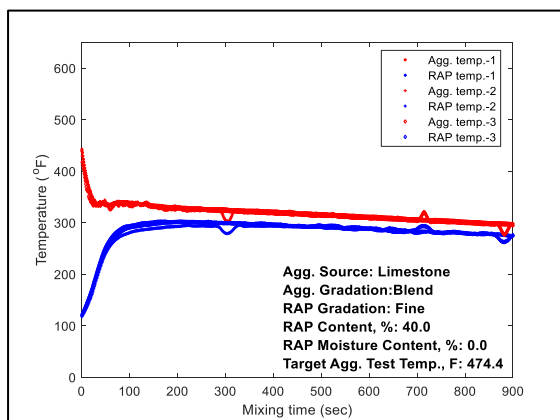
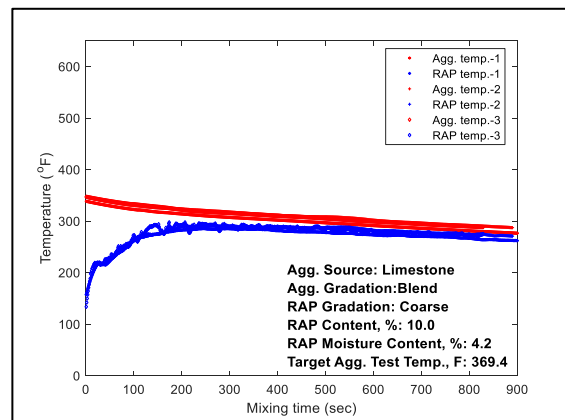
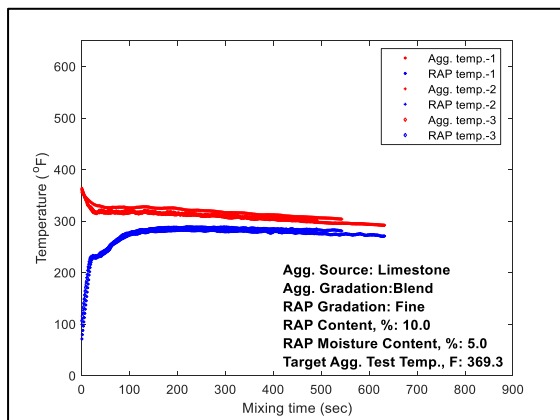
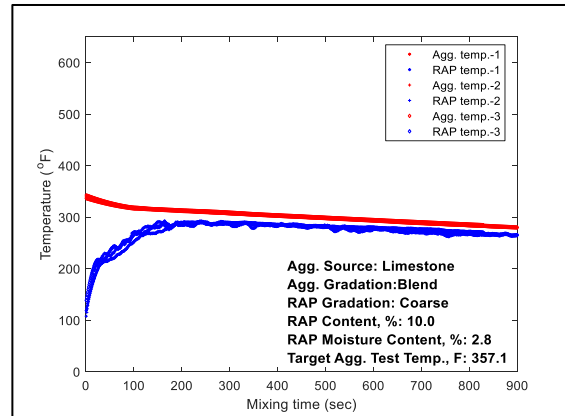
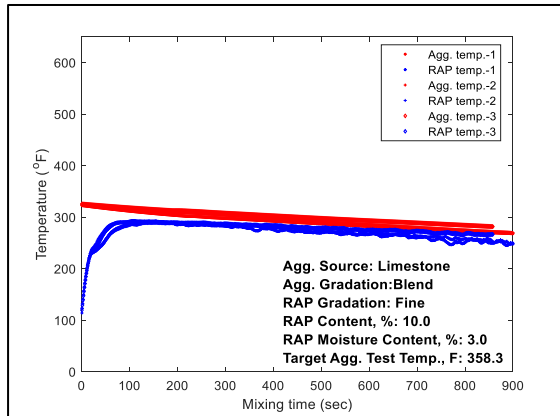


Figure B.2: Example change in FOV standard deviation with mixing time curves of theoretical graded mixtures used for T_{equi} determination.





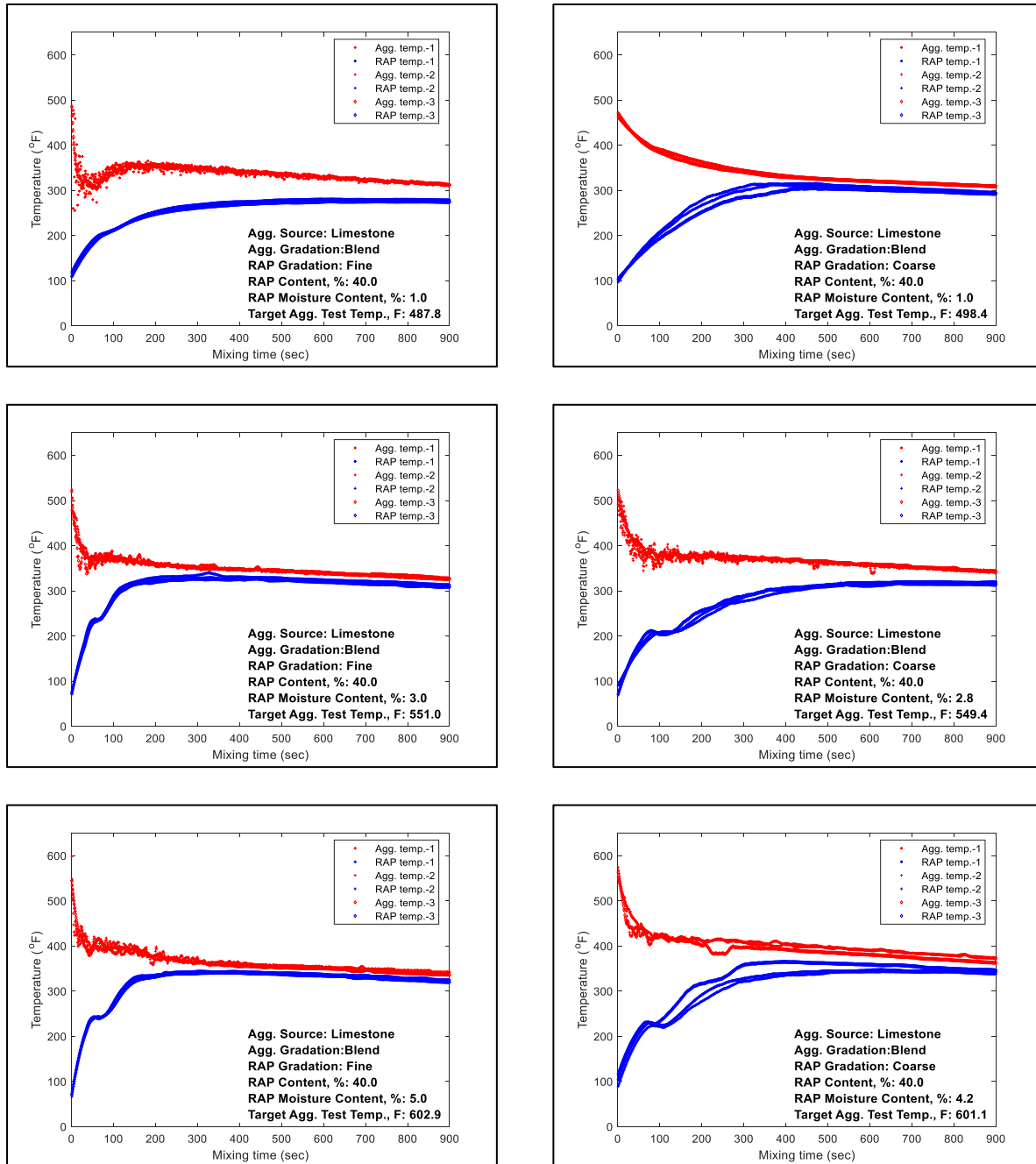
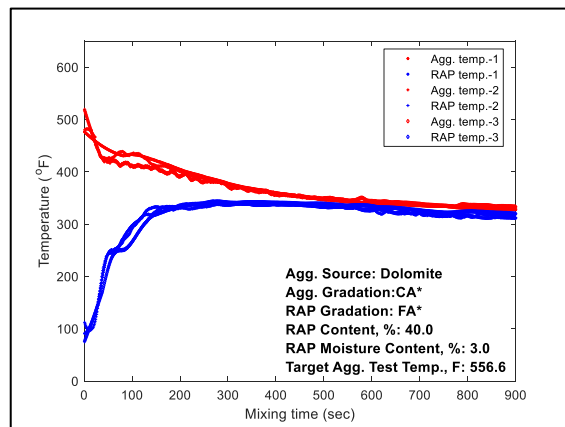
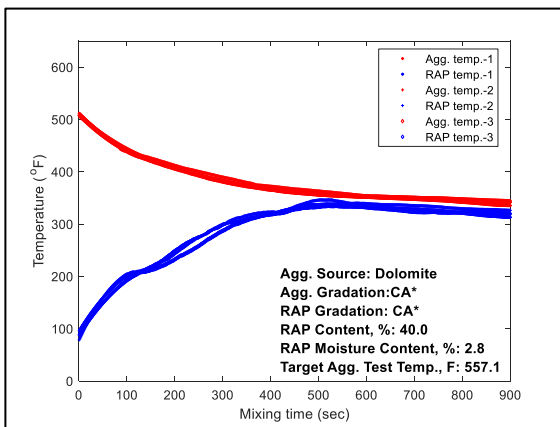
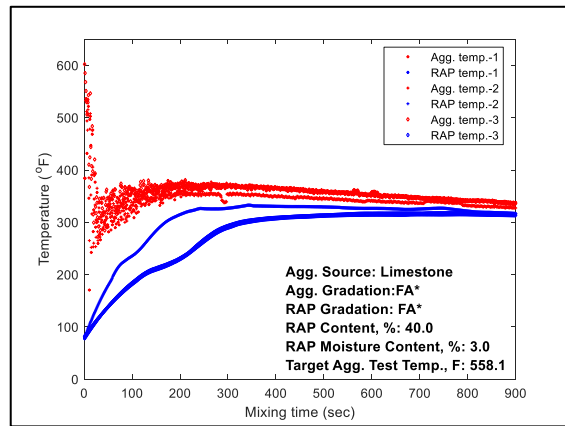
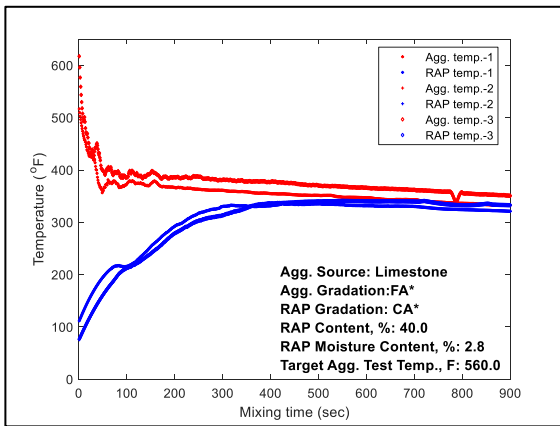
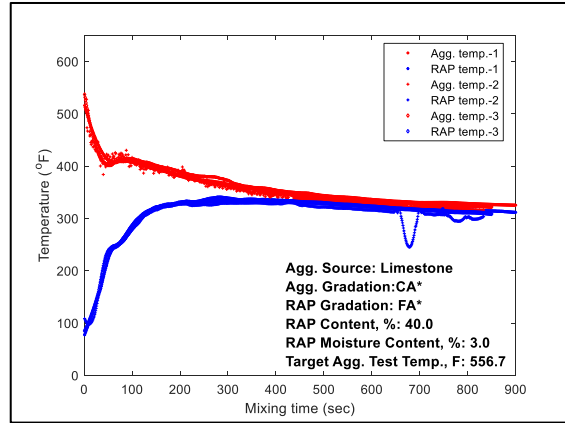
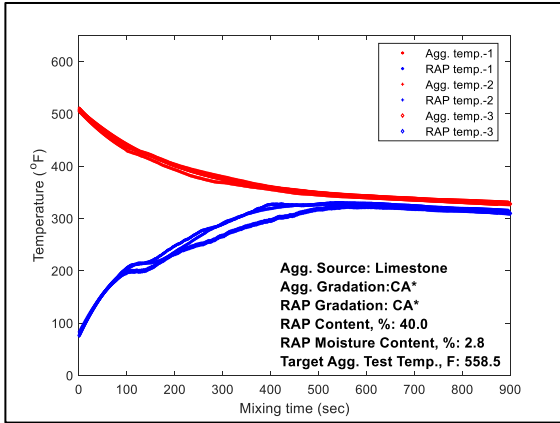
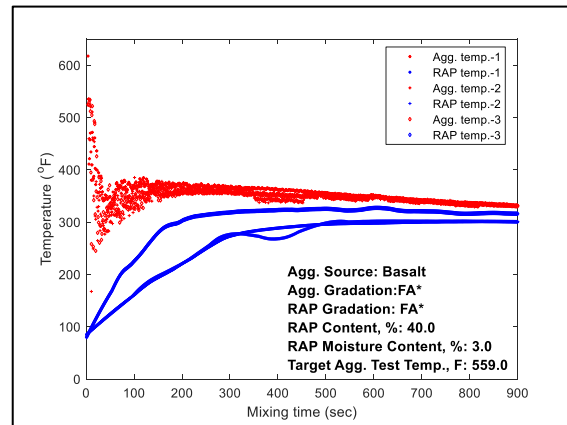
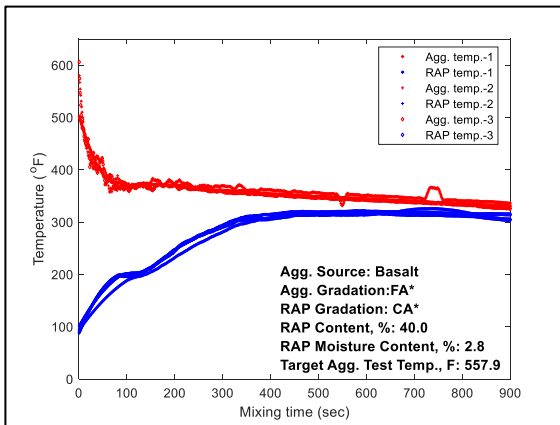
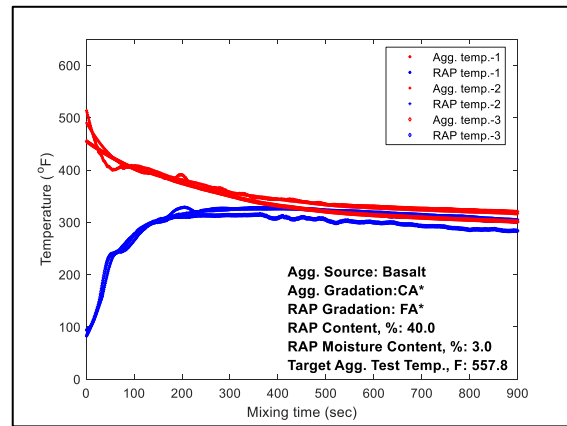
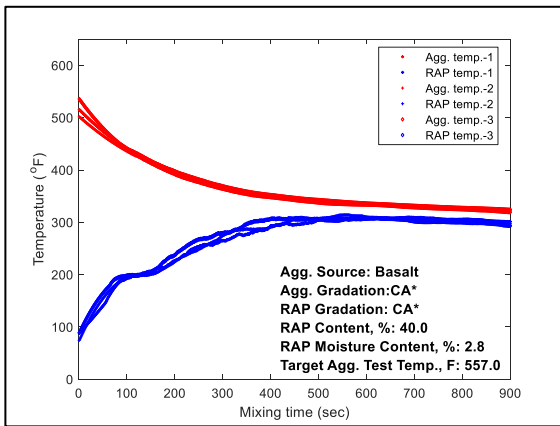
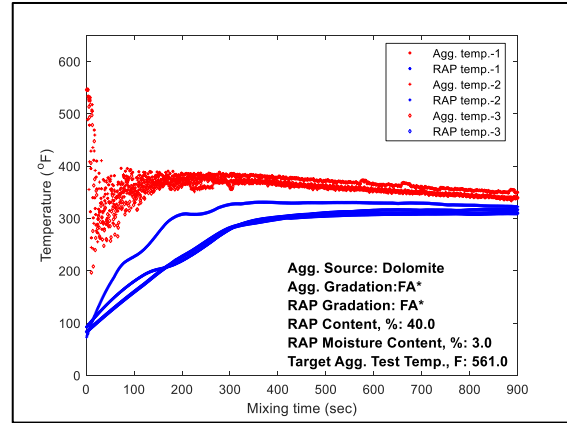
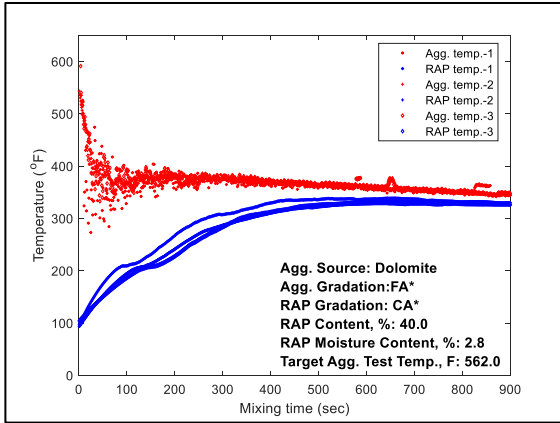


Figure B.3: Example virgin aggregate and RAP temperature profiles with mixing time of dense graded mixtures used in the study.





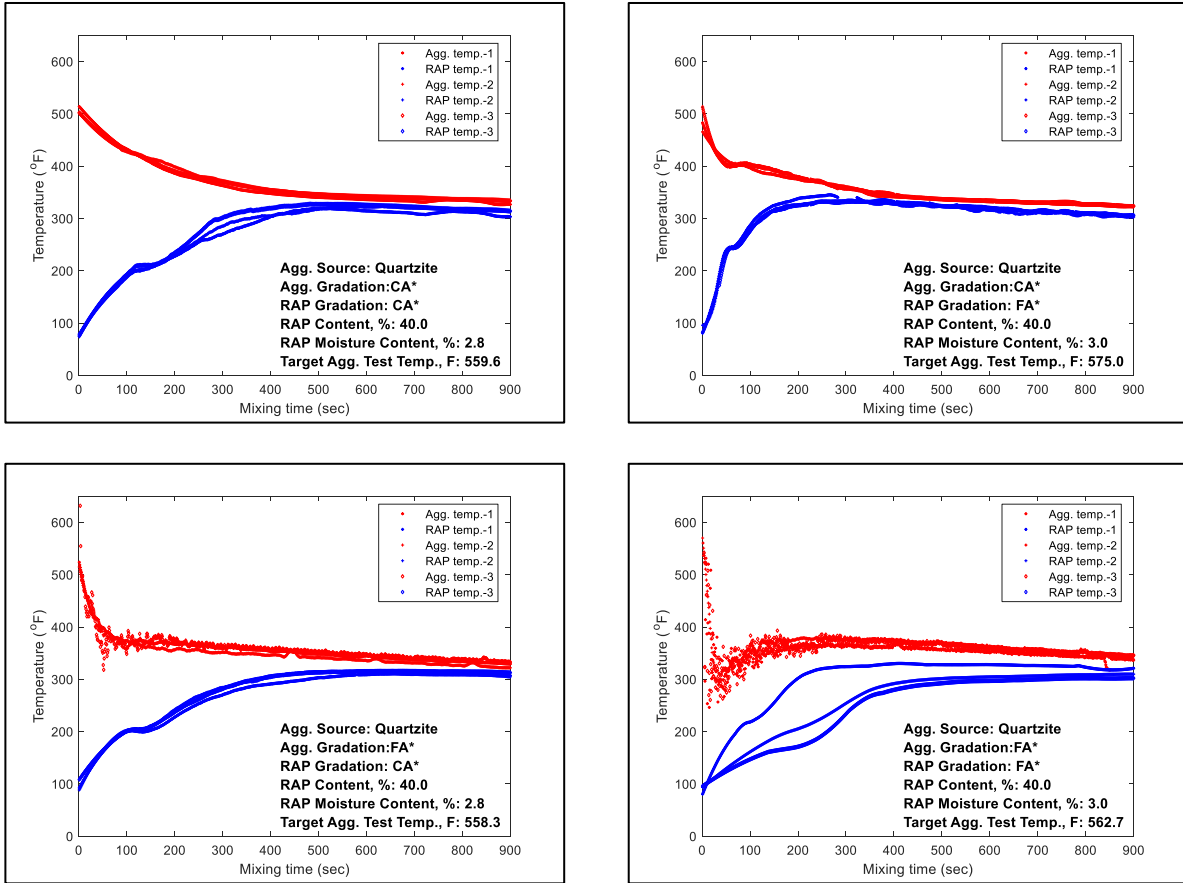
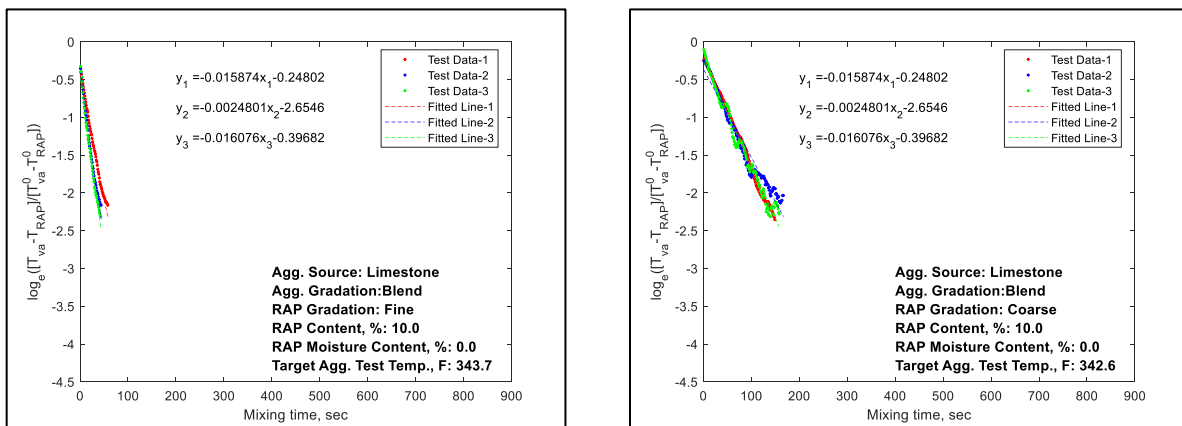
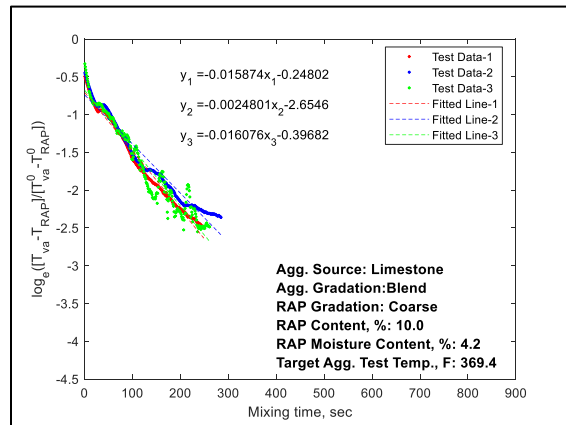
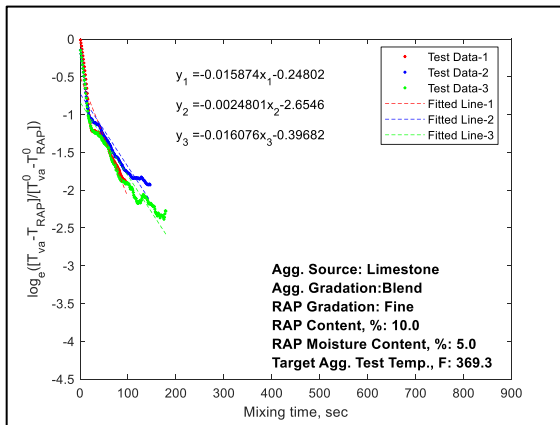
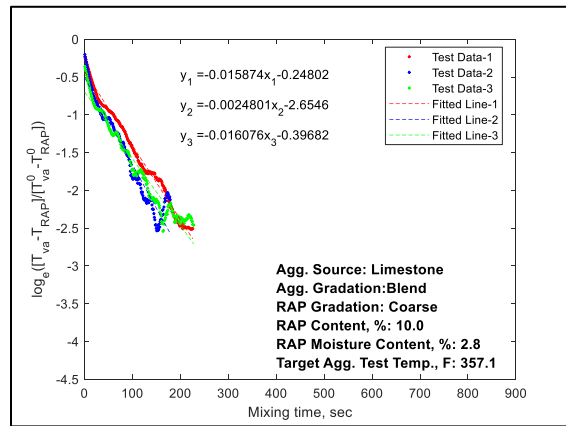
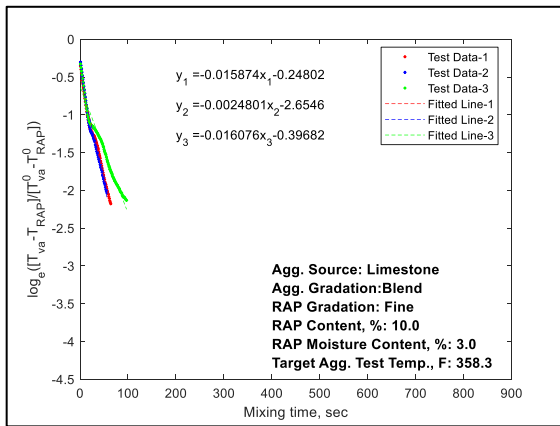
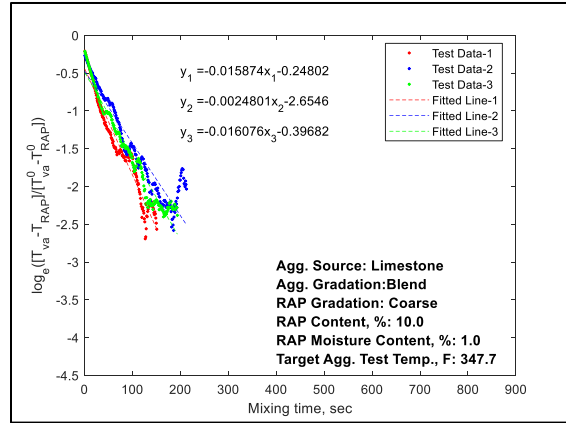
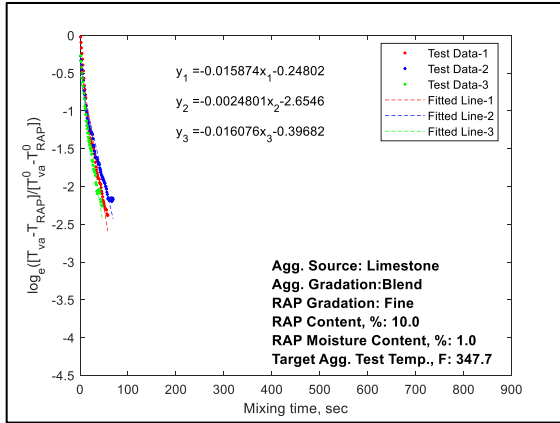
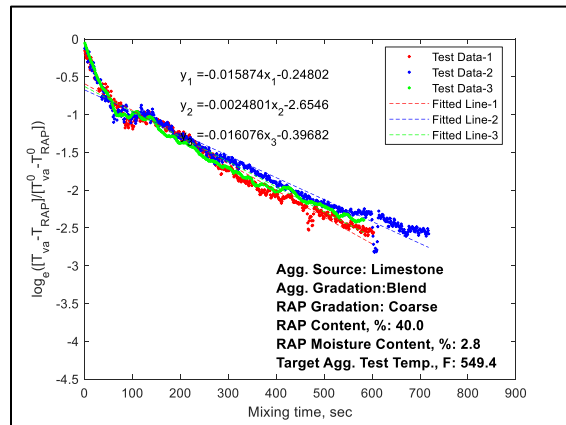
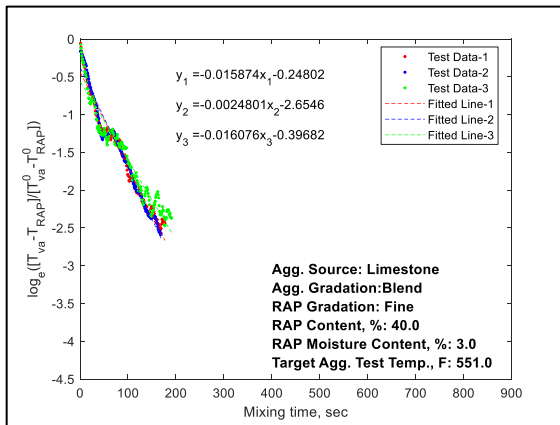
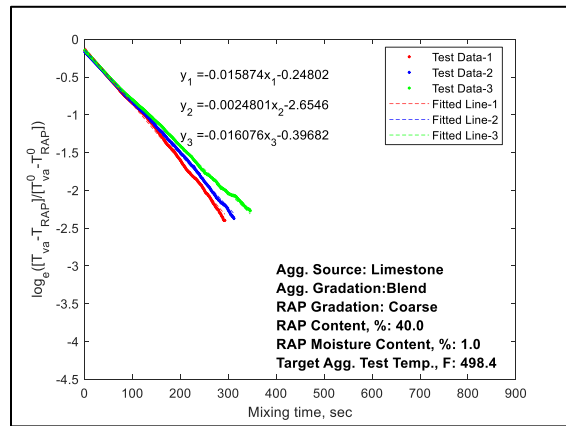
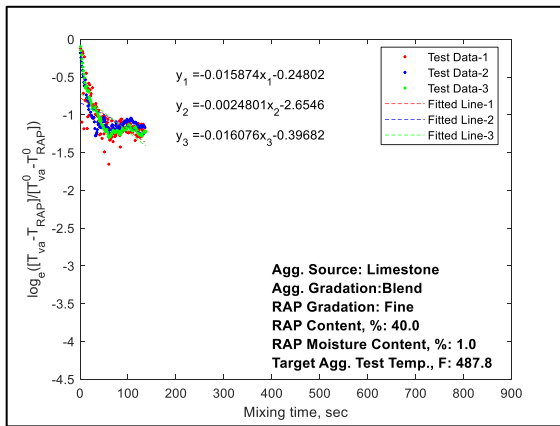
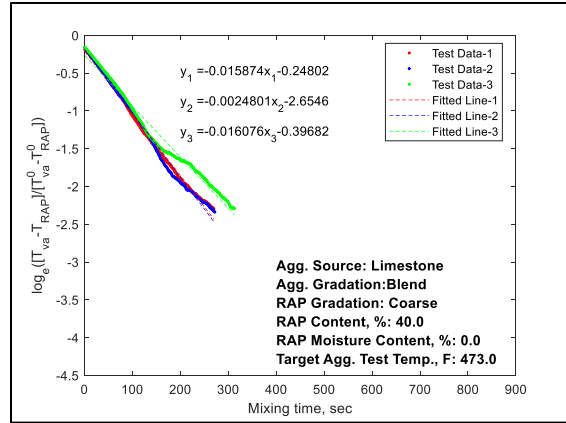
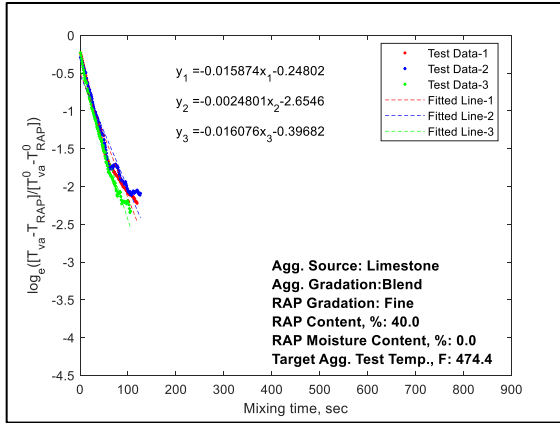


Figure B.4: Example virgin aggregate and RAP temperature profiles with mixing time of Theoretical graded mixtures used in the study.







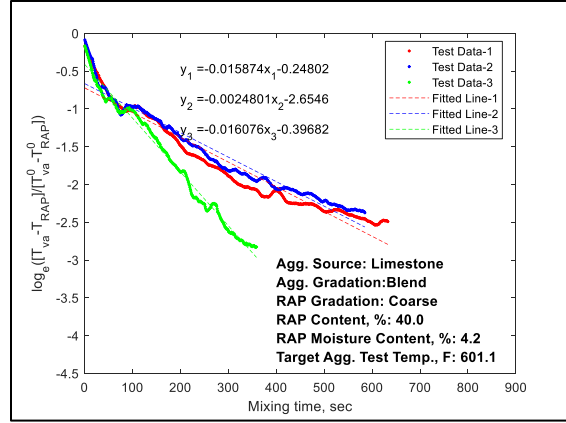
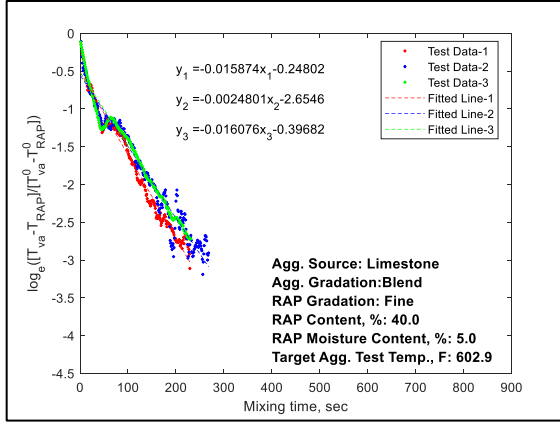
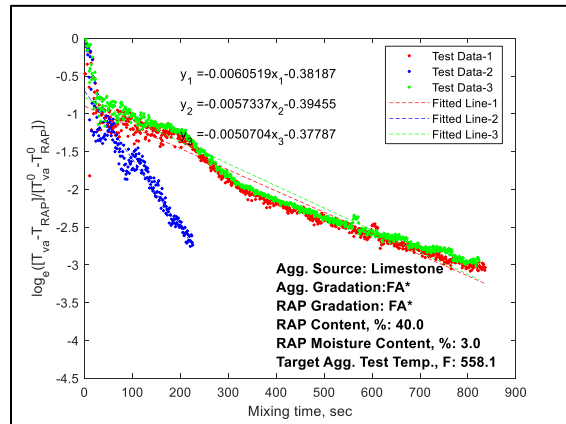
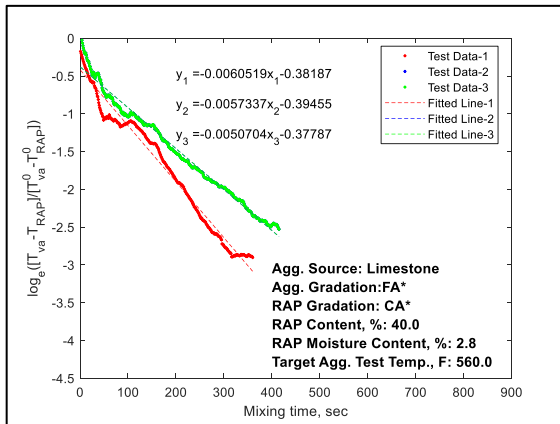
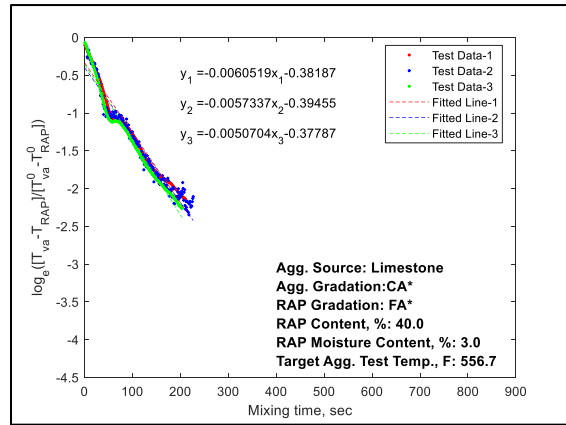
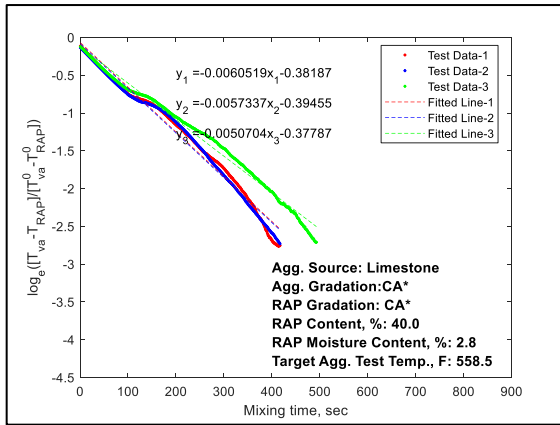
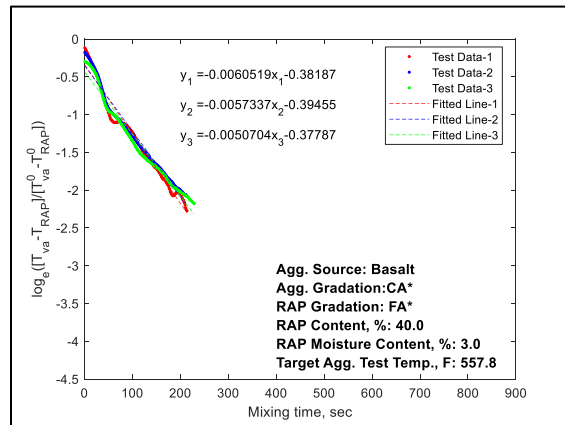
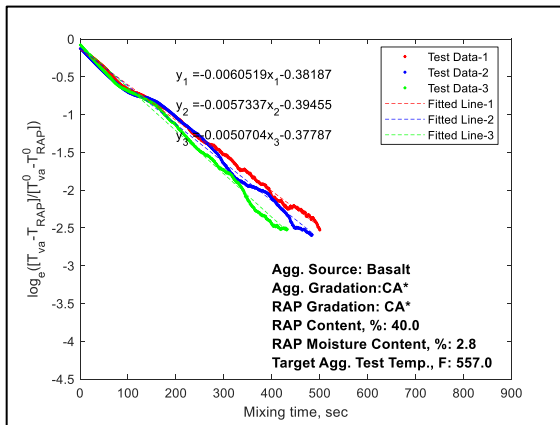
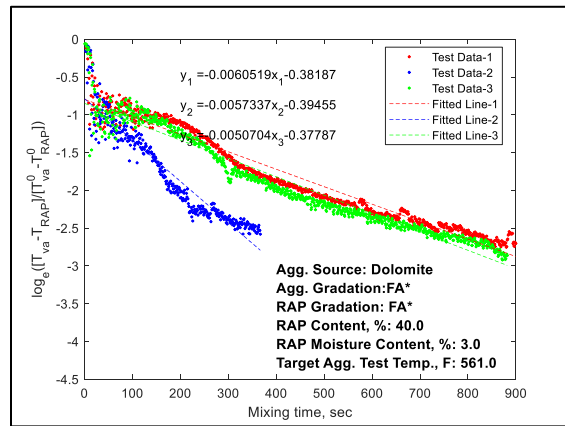
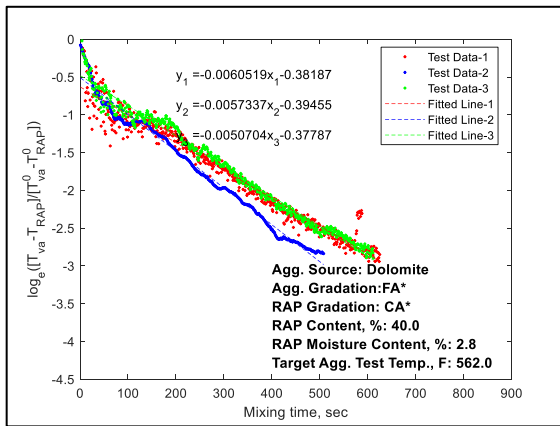
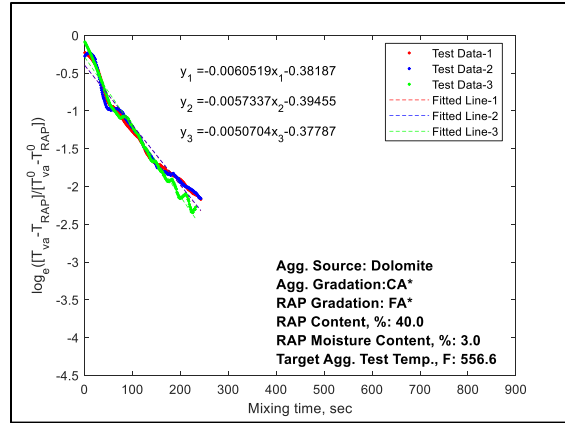
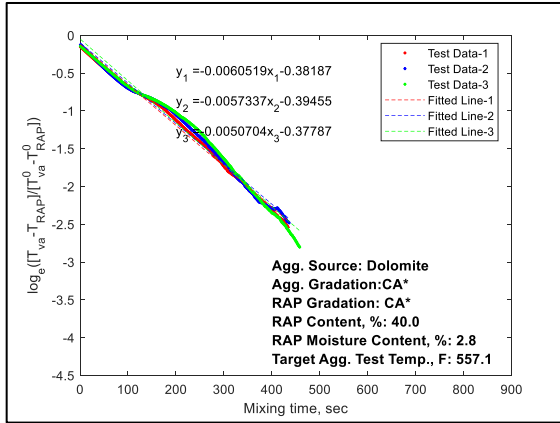


Figure B.5: Example plots used for heat conductance determination between virgin aggregate and RAP for dense graded mixtures used in the study.





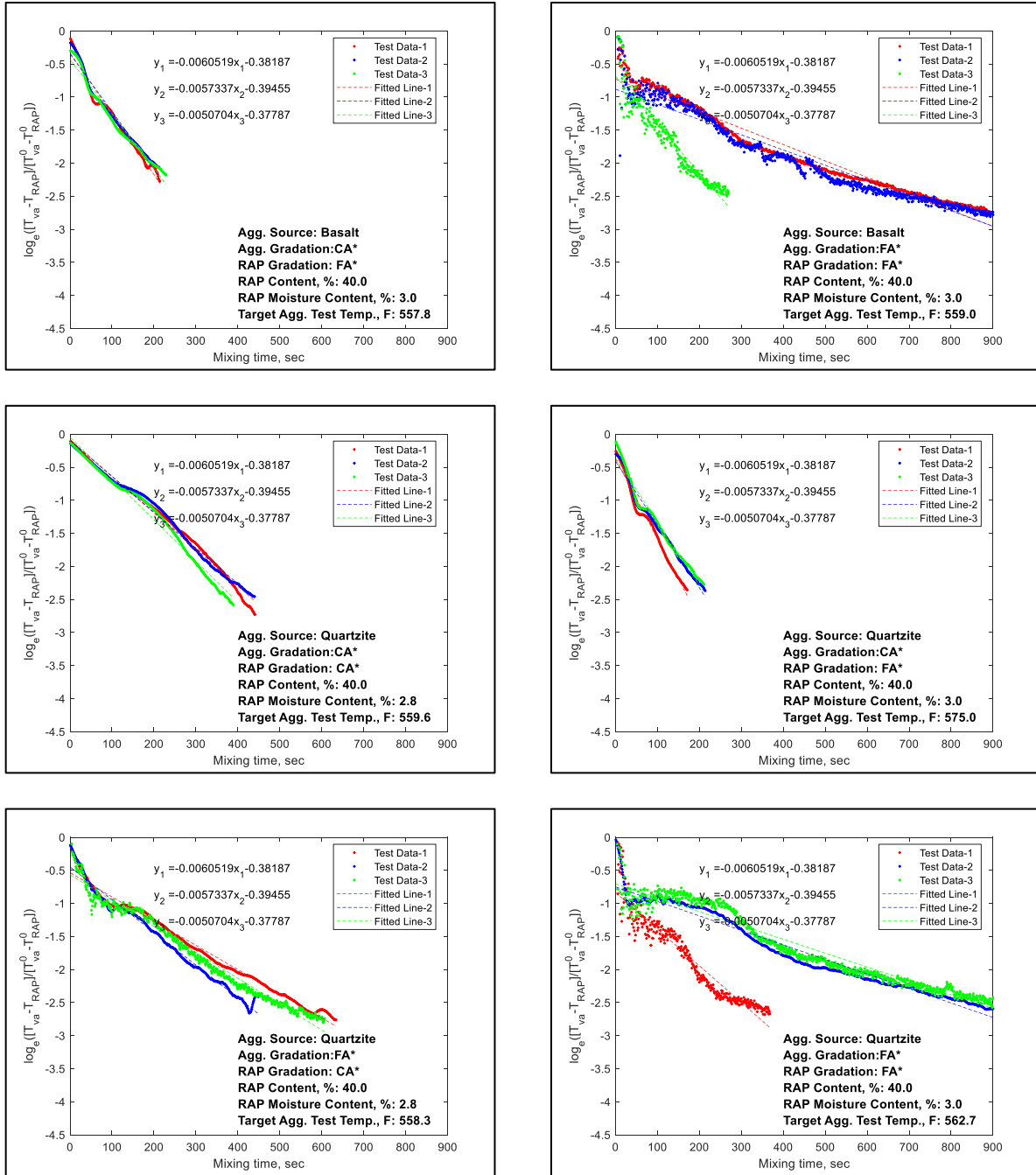


Figure B.6: Example plots used for heat conductance determination between virgin aggregate and RAP for theoretical graded mixtures used in the study.

APPENDIX: C

Time for thermal equilibrium (T_{equi}) and heat conductance (H_C) results for the experimental matrix

Table C.1: Heat transfer testing complete dataset obtained in the study: Shaded values were determined to be outliers.

RAP Content, %	Virgin agg. Source	Virgin agg. gradation	RAP gradation	Moisture, %	Superheated temp, F	H_C , W/°C				T_{equi} , sec				Status
						1	2	3	CoV (%)	1	2	3	CoV (%)	
10%	Limestone	Blend	Fine RAP	0%	305	9.2	8.7	9.5	5%	66.2	64.9	63.4	2%	
10%	Limestone	Blend	Coarse RAP	0%	305	4.0	4.3	3.2	14%	177.7	175.9	222.6	14%	
10%	Limestone	Blend	Fine RAP	0%	335	11.6	16.0	16.7	18%	57.2	43.2	42.4	17%	
10%	Limestone	Blend	Coarse RAP	0%	335	5.0	4.0	4.7	11%	149.0	166.2	157.9	5%	
10%	Limestone	Blend	Fine RAP	0%	360	15.3	16.6	9.6	27%	47.7	45.0	69.1	24%	
10%	Limestone	Blend	Coarse RAP	0%	360	5.3	4.8	5.6	7%	153.3	154.4	139.3	6%	
10%	Limestone	Blend	Fine RAP	1%	305	11.4	13.8	10.2	16%	55.3	45.6	58.2	12%	
10%	Limestone	Blend	Coarse RAP	1%	305	2.5	2.8	5.1	41%	283.0	225.6	146.9	31%	
10%	Limestone	Blend	Fine RAP	1%	340	13.0	9.8	15.6	23%	57.9	68.7	46.0	20%	
10%	Limestone	Blend	Coarse RAP	1%	340	4.8	3.4	3.8	18%	150.8	212.6	193.9	17%	
10%	Limestone	Blend	Fine RAP	1%	360	15.5	15.6	14.5	4%	47.5	47.6	51.9	5%	
10%	Limestone	Blend	Coarse RAP	1%	360	5.0	5.2	5.4	4%	144.9	136.1	136.8	4%	
10%	Limestone	Blend	Fine RAP	3%	325	9.4	7.3	10.4	18%	70.4	88.9	63.2	18%	
10%	Limestone	Blend	Coarse RAP	3%	325	3.5	2.2	2.5	24%	185.8	327.8	254.1	28%	
10%	Limestone	Blend	Fine RAP	3%	350	9.5	10.8	6.3	26%	63.3	55.8	97.0	30%	
10%	Limestone	Blend	Coarse RAP	3%	350	3.3	4.0	3.1	14%	225.7	178.3	227.4	13%	
10%	Limestone	Blend	Fine RAP	3%	385	11.1	7.8	8.4	19%	55.4	87.2	80.0	22%	
10%	Limestone	Blend	Coarse RAP	3%	385	4.6	4.7	4.5	2%	162.1	154.5	164.3	3%	
10%	Limestone	Blend	Fine RAP	5%	335	7.5	7.6	7.2	3%	77.2	72.7	79.1	4%	
10%	Limestone	Blend	Coarse RAP	4%	335	2.2	3.7	3.7	26%	300.7	201.4	201.4	24%	
10%	Limestone	Blend	Fine RAP	5%	360	5.2	3.5	3.5	24%	96.6	145.5	178.7	29%	

RAP Content, %	Virgin agg. Source	Virgin agg. gradation	RAP gradation	Moisture, %	Superheated temp, F	<i>H_c. W/C</i>				<i>T_{equi}, sec</i>				Status
						1	2	3	CoV (%)	1	2	3	CoV (%)	
10%	Limestone	Blend	Coarse RAP	4%	360	2.7	2.2	2.6	9%	248.6	284.8	260.2	7%	
10%	Limestone	Blend	Fine RAP	5%	385	9.8	8.5	10.2	9%	68.2	81.0	67.3	11%	
10%	Limestone	Blend	Coarse RAP	4%	385	3.2	3.9	2.3	26%	207.0	188.6	300.2	26%	
20%	Limestone	Blend	Fine RAP	0%	340	14.1	16.1	18.7	14%	83.3	70.4	66.8	12%	
20%	Limestone	Blend	Coarse RAP	0%	340	6.1	5.3	6.0	8%	205.3	231.9	209.8	7%	
20%	Limestone	Blend	Fine RAP	0%	365	16.6	12.6	12.3	17%	69.8	91.0	94.8	16%	
20%	Limestone	Blend	Coarse RAP	0%	365	5.7	4.9	6.8	17%	227.4	240.4	183.6	14%	
20%	Limestone	Blend	Fine RAP	0%	400	11.0	18.8	18.8	28%	95.5	66.6	66.6	22%	
20%	Limestone	Blend	Coarse RAP	0%	400	6.5	5.4	5.7	9%	188.0	232.1	228.0	11%	
20%	Limestone	Blend	Fine RAP	1%	360	12.6	14.9	9.8	21%	88.5	84.7	113.4	16%	
20%	Limestone	Blend	Coarse RAP	1%	360	5.9	4.2	3.7	25%	225.6	274.2	300.9	14%	
20%	Limestone	Blend	Fine RAP	1%	380	8.6	14.5	18.6	36%	124.2	83.9	65.6	33%	
20%	Limestone	Blend	Coarse RAP	1%	380	3.3	3.7	6.2	36%	334.3	305.9	197.8	26%	
20%	Limestone	Blend	Fine RAP	1%	410	11.1	9.4	12.3	13%	106.9	122.9	101.4	10%	
20%	Limestone	Blend	Coarse RAP	1%	410	5.0	5.1	5.9	8%	241.0	243.6	210.4	8%	
20%	Limestone	Blend	Fine RAP	3%	365	10.1	7.5	10.7	18%	106.1	149.9	102.9	22%	
20%	Limestone	Blend	Coarse RAP	3%	365	3.1	3.2	3.3	3%	387.7	352.0	376.3	5%	
20%	Limestone	Blend	Fine RAP	3%	400	7.2	7.0	7.1	2%	153.5	143.4	145.0	4%	
20%	Limestone	Blend	Coarse RAP	3%	400	4.8	5.4	2.9	30%	272.5	246.6	404.3	27%	
20%	Limestone	Blend	Fine RAP	3%	420	12.6	12.4	12.6	1%	101.5	100.3	96.8	2%	
20%	Limestone	Blend	Coarse RAP	3%	420	3.1	3.2	2.7	8%	352.3	382.7	413.7	8%	
20%	Limestone	Blend	Fine RAP	5%	385	5.0	5.5	6.8	17%	170.1	196.6	159.6	11%	
20%	Limestone	Blend	Coarse RAP	4%	385	3.9	3.6	3.9	4%	303.3	335.8	323.1	5%	
20%	Limestone	Blend	Fine RAP	5%	420	5.9	9.0	9.3	23%	191.5	146.8	116.7	25%	
20%	Limestone	Blend	Coarse RAP	4%	420	2.4	2.8	3.2	15%	460.9	381.5	369.8	12%	
20%	Limestone	Blend	Fine RAP	5%	445	9.9	6.5	6.2	27%	122.3	186.2	181.9	22%	
20%	Limestone	Blend	Coarse RAP	4%	445	3.6	3.1	2.9	11%	328.7	387.7	413.7	12%	

RAP Content, %	Virgin agg. Source	Virgin agg. gradation	RAP gradation	Moisture, %	Superheated temp, F	<i>H_c. W/C</i>				<i>T_{equi}, sec</i>				Status
						1	2	3	CoV (%)	1	2	3	CoV (%)	
30%	Limestone	Blend	Fine RAP	0%	385	11.2	15.2	15.2	17%	124.5	102.9	99.5	12%	
30%	Limestone	Blend	Coarse RAP	0%	385	6.6	4.8	5.8	16%	247.7	327.8	293.7	14%	
30%	Limestone	Blend	Fine RAP	0%	410	15.8	15.4	17.1	6%	100.1	101.4	91.8	5%	
30%	Limestone	Blend	Coarse RAP	0%	410	7.8	5.3	6.1	20%	215.2	305.3	259.5	17%	
30%	Limestone	Blend	Fine RAP	0%	445	13.0	14.3	12.5	7%	105.1	101.2	100.9	2%	
30%	Limestone	Blend	Coarse RAP	0%	445	4.7	5.5	5.2	8%	322.5	291.9	306.3	5%	
30%	Limestone	Blend	Fine RAP	1%	400	7.9	10.6	9.5	15%	181.6	140.0	146.8	14%	
30%	Limestone	Blend	Coarse RAP	1%	400	6.2	4.5	4.0	24%	281.1	318.3	366.7	13%	
30%	Limestone	Blend	Fine RAP	1%	430	10.7	15.4	10.2	24%	137.0	103.3	139.5	16%	
30%	Limestone	Blend	Coarse RAP	1%	430	5.6	5.1	6.4	12%	302.0	325.6	262.8	11%	
30%	Limestone	Blend	Fine RAP	1%	465	9.8	13.2	13.8	17%	149.4	118.6	117.5	14%	
30%	Limestone	Blend	Coarse RAP	1%	465	4.5	4.0	5.4	15%	350.7	367.0	291.4	12%	
30%	Limestone	Blend	Fine RAP	3%	430	8.9	9.0	9.8	5%	175.6	167.2	146.9	9%	
30%	Limestone	Blend	Coarse RAP	3%	430	4.6	3.5	3.2	21%	331.0	444.2	478.6	18%	
30%	Limestone	Blend	Fine RAP	3%	465	11.3	12.4	14.1	11%	142.7	136.0	115.8	11%	
30%	Limestone	Blend	Coarse RAP	3%	465	5.2	5.1	3.5	21%	317.1	319.9	422.9	17%	
30%	Limestone	Blend	Fine RAP	3%	490	9.4	12.0	8.1	20%	176.6	138.2	197.0	18%	
30%	Limestone	Blend	Coarse RAP	3%	490	5.7	5.1	3.5	24%	321.8	330.7	433.4	17%	
30%	Limestone	Blend	Fine RAP	5%	490	8.4	9.7	8.8	8%	180.2	154.1	157.5	9%	
30%	Limestone	Blend	Coarse RAP	4%	490	5.2	5.1	6.9	18%	298.0	352.3	258.2	16%	
30%	Limestone	Blend	Fine RAP	5%	505	8.7	10.4	10.3	10%	192.8	156.3	170.9	11%	
30%	Limestone	Blend	Coarse RAP	4%	505	7.9	5.7	6.9	16%	234.5	309.5	249.2	15%	
30%	Limestone	Blend	Fine RAP	5%	530	7.5	8.9	8.9	10%	238.6	211.2	211.2	7%	
30%	Limestone	Blend	Coarse RAP	4%	530	6.1	5.0	5.1	11%	314.5	365.9	337.5	8%	
40%	Limestone	Blend	Fine RAP	0%	445	19.7	19.9	17.3	8%	98.8	96.2	106.3	5%	
40%	Limestone	Blend	Coarse RAP	0%	445	4.3	4.5	4.5	3%	417.8	411.7	402.7	2%	
40%	Limestone	Blend	Fine RAP	0%	465	15.5	14.3	18.7	14%	118.7	125.9	104.7	9%	

RAP Content, %	Virgin agg. Source	Virgin agg. gradation	RAP gradation	Moisture, %	Superheated temp, F	<i>H_c. W/C</i>				<i>T_{equi}, sec</i>				Status
						1	2	3	CoV (%)	1	2	3	CoV (%)	
40%	Limestone	Blend	Coarse RAP	0%	465	7.4	7.6	6.1	12%	269.1	271.8	312.6	9%	
40%	Limestone	Blend	Fine RAP	0%	490	16.6	11.1	14.6	20%	112.9	151.7	126.4	15%	
40%	Limestone	Blend	Coarse RAP	0%	490	7.1	5.9	5.5	14%	286.2	326.5	350.9	10%	
40%	Limestone	Blend	Fine RAP	1%	465	13.2	14.6	14.6	6%	142.4	125.5	125.5	7%	
40%	Limestone	Blend	Coarse RAP	1%	465	6.4	4.6	4.6	21%	315.2	376.2	376.2	10%	
40%	Limestone	Blend	Fine RAP	1%	490	13.2	12.5	13.0	3%	134.9	134.9	136.1	1%	
40%	Limestone	Blend	Coarse RAP	1%	490	6.7	6.2	5.5	10%	292.8	311.2	345.5	8%	
40%	Limestone	Blend	Fine RAP	1%	505	14.0	14.7	16.0	7%	126.3	125.8	118.7	3%	
40%	Limestone	Blend	Coarse RAP	1%	505	4.2	7.3	6.9	28%	442.2	267.1	293.4	28%	
40%	Limestone	Blend	Fine RAP	3%	530	10.1	9.9	11.5	8%	200.3	205.4	172.2	9%	
40%	Limestone	Blend	Coarse RAP	3%	530	6.0	3.5	3.3	35%	290.1	509.3	546.0	31%	
40%	Limestone	Blend	Fine RAP	3%	550	11.5	12.3	9.5	13%	176.2	168.2	191.0	6%	
40%	Limestone	Blend	Coarse RAP	3%	550	3.2	2.6	3.0	10%	602.4	717.1	582.8	11%	
40%	Limestone	Blend	Fine RAP	3%	575	12.8	11.7	9.9	13%	163.2	179.3	204.7	11%	
40%	Limestone	Blend	Coarse RAP	3%	575	6.5	3.5	3.2	42%	328.5	514.7	584.0	28%	
40%	Limestone	Blend	Fine RAP	5%	575	8.5	7.7	8.4	5%	211.4	277.5	255.6	14%	
40%	Limestone	Blend	Coarse RAP	4%	575	2.5	3.2	2.8	13%	771.4	584.4	673.5	14%	
40%	Limestone	Blend	Fine RAP	5%	610	10.0	8.5	8.8	9%	228.4	267.7	230.1	9%	
40%	Limestone	Blend	Coarse RAP	4%	610	2.9	2.9	6.4	49%	632.6	584.8	358.7	28%	
40%	Limestone	Blend	Fine RAP	5%	635	8.9	7.3	7.9	10%	242.1	288.3	264.3	9%	
40%	Limestone	Blend	Coarse RAP	4%	635	2.8	5.6	3.2	39%	636.4	799.9	577.4	17%	
10%	Limestone	Fine*	Fine*	3%	325	5.9	5.8	1.6	54%	113.8	114.1	293.4	60%	
10%	Limestone	Coarse*	Fine*	3%	325	13.2	13.8	12.8	4%	55.5	51.2	52.2	4%	
10%	Limestone	Fine*	Coarse*	3%	325	0.8	0.8	0.7	5%	790.9	838.5	848.3	4%	
10%	Limestone	Coarse*	Coarse*	3%	325	1.3	1.9	1.7	20%	552.8	415.7	445.9	15%	
10%	Limestone	Fine*	Fine*	3%	350	1.4	1.4	2.3	28%	335.3	340.4	215.8	24%	
10%	Limestone	Coarse*	Fine*	3%	350	13.4	12.1	10.9	11%	55.5	55.8	64.8	9%	

RAP Content, %	Virgin agg. Source	Virgin agg. gradation	RAP gradation	Moisture, %	Superheated temp, F	<i>H_c. W/C</i>				<i>T_{equi}, sec</i>				Status
						1	2	3	CoV (%)	1	2	3	CoV (%)	
10%	Limestone	Fine*	Coarse*	3%	350	0.8	0.7	0.7	10%	757.2	830.4	906.8	9%	
10%	Limestone	Coarse*	Coarse*	3%	350	2.3	2.2	1.7	15%	337.3	383.0	465.7	16%	
10%	Limestone	Fine*	Fine*	3%	385	2.0	1.4	1.4	22%	261.6	380.9	380.9	20%	
10%	Limestone	Coarse*	Fine*	3%	385	11.0	11.1	10.5	3%	71.4	64.4	67.0	5%	
10%	Limestone	Fine*	Coarse*	3%	385	0.8	0.8	0.9	6%	778.6	754.0	660.5	9%	
10%	Limestone	Coarse*	Coarse*	3%	385	2.0	1.9	1.7	9%	452.1	422.6	479.6	6%	
20%	Limestone	Fine*	Fine*	3%	365	1.8	2.2	6.6	75%	496.1	331.8	160.0	51%	Omitted
20%	Limestone	Coarse*	Fine*	3%	365	7.1	7.6	7.6	4%	132.0	129.2	129.2	1%	
20%	Limestone	Fine*	Coarse*	3%	365	2.6	3.0	2.1	17%	464.1	405.0	569.4	17%	
20%	Limestone	Coarse*	Coarse*	3%	365	2.7	2.7	2.8	2%	514.6	489.4	472.9	4%	
20%	Limestone	Fine*	Fine*	3%	400	2.6	2.4	2.1	9%	389.7	387.6	455.9	9%	
20%	Limestone	Coarse*	Fine*	3%	400	8.6	6.9	9.3	15%	121.5	143.9	123.5	10%	
20%	Limestone	Fine*	Coarse*	3%	400	3.1	3.3	3.7	9%	414.2	395.1	338.5	10%	
20%	Limestone	Coarse*	Coarse*	3%	400	3.0	3.3	3.4	8%	443.0	451.1	427.0	3%	
20%	Limestone	Fine*	Fine*	3%	420	2.9	7.8	8.7	49%	362.2	149.3	128.8	61%	Omitted
20%	Limestone	Coarse*	Fine*	3%	420	8.9	7.7	6.9	13%	132.9	142.3	148.0	5%	
20%	Limestone	Fine*	Coarse*	3%	420	3.6	2.1	2.1	32%	375.0	580.3	580.3	23%	
20%	Limestone	Coarse*	Coarse*	3%	420	3.6	3.9	3.1	11%	423.7	413.7	459.7	6%	
30%	Limestone	Fine*	Fine*	3%	430	7.5	2.7	9.1	52%	148.3	529.7	142.7	81%	Omitted
30%	Limestone	Coarse*	Fine*	3%	430	6.3	6.3	5.7	5%	206.4	206.4	214.7	2%	
30%	Limestone	Fine*	Coarse*	3%	430	2.9	3.0	3.1	4%	623.8	376.1	470.1	26%	
30%	Limestone	Coarse*	Coarse*	3%	430	3.2	3.4	3.1	5%	573.9	505.0	585.0	8%	
30%	Limestone	Fine*	Fine*	3%	465	8.5	2.9	2.7	71%	167.3	499.7	536.5	51%	Omitted
30%	Limestone	Coarse*	Fine*	3%	465	8.1	6.5	5.6	18%	191.3	209.5	240.9	12%	
30%	Limestone	Fine*	Coarse*	3%	465	4.0	3.2	3.2	13%	410.7	499.3	555.4	15%	
30%	Limestone	Coarse*	Coarse*	3%	465	3.4	3.6	3.7	4%	499.8	507.3	515.5	2%	
30%	Limestone	Fine*	Fine*	3%	490	8.3	2.6	8.0	51%	173.1	574.6	166.1	77%	Omitted

RAP Content, %	Virgin agg. Source	Virgin agg. gradation	RAP gradation	Moisture, %	Superheated temp, F	<i>H_c. W/C</i>				<i>T_{equi}, sec</i>				Status
						1	2	3	CoV (%)	1	2	3	CoV (%)	
30%	Limestone	Coarse*	Fine*	3%	490	7.5	8.4	6.6	12%	195.9	178.3	212.8	9%	
30%	Limestone	Fine*	Coarse*	3%	490	3.2	3.0	3.4	8%	526.7	626.6	485.5	13%	
30%	Limestone	Coarse*	Coarse*	3%	490	4.8	4.3	4.7	6%	404.8	426.4	383.8	5%	
40%	Limestone	Fine*	Fine*	3%	530	2.3	2.6	3.0	14%	931.2	732.9	617.5	21%	
40%	Limestone	Coarse*	Fine*	3%	530	6.0	6.9	6.4	6%	282.6	238.0	259.2	9%	
40%	Limestone	Fine*	Coarse*	3%	530	3.9	4.1	4.1	3%	564.4	479.4	502.5	9%	
40%	Limestone	Coarse*	Coarse*	3%	530	4.0	4.8	4.5	8%	540.5	446.5	451.2	11%	
40%	Limestone	Fine*	Fine*	3%	550	2.5	8.1	2.6	72%	835.2	225.4	822.5	56%	Omitted
40%	Limestone	Coarse*	Fine*	3%	550	8.3	8.0	8.9	6%	212.6	226.6	203.3	5%	
40%	Limestone	Fine*	Coarse*	3%	550	6.6	4.8	4.8	19%	359.4	414.9	414.9	8%	
40%	Limestone	Coarse*	Coarse*	3%	550	5.3	5.3	4.3	11%	416.1	416.9	492.4	10%	
40%	Limestone	Fine*	Fine*	3%	575	2.2	7.5	7.8	54%	919.3	189.0	239.6	91%	Omitted
40%	Limestone	Coarse*	Fine*	3%	575	9.1	6.9	8.9	15%	200.9	247.2	209.2	11%	
40%	Limestone	Fine*	Coarse*	3%	575	3.5	3.7	3.6	2%	604.1	604.8	604.5	0%	
40%	Limestone	Coarse*	Coarse*	3%	575	5.2	4.9	5.0	3%	401.6	454.0	432.7	6%	
10%	Dolomite	Fine*	Fine*	3%	325	5.9	5.0	5.5	9%	89.1	121.9	109.9	16%	
10%	Dolomite	Coarse*	Fine*	3%	325	12.9	11.2	14.4	12%	60.2	67.0	51.1	13%	
10%	Dolomite	Fine*	Coarse*	3%	325	0.6	0.8	0.8	18%	1006.4	731.6	740.0	19%	
10%	Dolomite	Coarse*	Coarse*	3%	325	1.1	1.0	1.5	22%	641.0	660.6	483.8	16%	
10%	Dolomite	Fine*	Fine*	3%	350	1.7	1.9	2.1	12%	295.5	251.3	244.4	11%	
10%	Dolomite	Coarse*	Fine*	3%	350	12.2	16.7	14.5	15%	58.5	48.7	51.6	9%	
10%	Dolomite	Fine*	Coarse*	3%	350	1.4	1.4	1.7	10%	481.0	471.4	413.6	8%	
10%	Dolomite	Coarse*	Coarse*	3%	350	1.8	2.3	1.8	14%	433.7	379.4	455.4	9%	
10%	Dolomite	Fine*	Fine*	3%	385	5.7	5.9	5.9	2%	103.0	104.5	112.3	5%	
10%	Dolomite	Coarse*	Fine*	3%	385	17.7	16.1	18.9	8%	46.8	47.7	41.2	8%	
10%	Dolomite	Fine*	Coarse*	3%	385	1.5	1.4	1.3	5%	457.2	469.7	474.6	2%	
10%	Dolomite	Coarse*	Coarse*	3%	385	2.7	2.1	2.0	18%	312.8	362.2	387.3	11%	

RAP Content, %	Virgin agg. Source	Virgin agg. gradation	RAP gradation	Moisture, %	Superheated temp, F	<i>H_c. W/C</i>				<i>T_{equi}, sec</i>				Status
						1	2	3	CoV (%)	1	2	3	CoV (%)	
10%	Basalt	Fine*	Fine*	3%	325	1.9	1.7	4.5	59%	256.2	304.2	135.7	37%	
10%	Basalt	Coarse*	Fine*	3%	325	14.4	12.9	12.7	7%	49.8	52.3	58.3	8%	
10%	Basalt	Fine*	Coarse*	3%	325	0.9	0.8	0.7	8%	757.3	811.5	823.4	4%	
10%	Basalt	Coarse*	Coarse*	3%	325	1.2	1.7	1.3	18%	597.3	487.6	542.5	10%	
10%	Basalt	Fine*	Fine*	3%	350	5.0	6.6	5.9	14%	139.9	101.8	110.4	17%	
10%	Basalt	Coarse*	Fine*	3%	350	14.2	17.9	13.4	16%	47.9	43.7	53.1	10%	
10%	Basalt	Fine*	Coarse*	3%	350	1.7	1.2	1.7	17%	416.9	504.7	386.2	14%	
10%	Basalt	Coarse*	Coarse*	3%	350	1.1	1.6	1.5	20%	660.3	450.3	507.1	20%	
10%	Basalt	Fine*	Fine*	3%	385	5.7	6.0	6.0	3%	111.0	103.4	100.1	5%	
10%	Basalt	Coarse*	Fine*	3%	385	9.3	10.7	12.0	13%	69.6	64.9	61.1	7%	
10%	Basalt	Fine*	Coarse*	3%	385	1.7	1.7	1.6	2%	381.2	402.1	420.9	5%	
10%	Basalt	Coarse*	Coarse*	3%	385	1.7	2.9	2.6	25%	466.7	280.7	310.7	28%	
10%	Quartzite	Fine*	Fine*	3%	325	5.3	5.0	3.7	18%	114.3	129.6	162.6	18%	
10%	Quartzite	Coarse*	Fine*	3%	325	11.5	16.7	13.5	19%	56.0	42.7	50.0	13%	
10%	Quartzite	Fine*	Coarse*	3%	325	1.3	1.2	1.2	5%	463.7	498.2	463.3	4%	
10%	Quartzite	Coarse*	Coarse*	3%	325	1.1	0.9	1.1	10%	575.9	669.2	607.3	8%	
10%	Quartzite	Fine*	Fine*	3%	350	4.6	5.3	7.0	22%	130.5	110.8	71.8	29%	
10%	Quartzite	Coarse*	Fine*	3%	350	12.6	10.8	12.5	8%	51.3	60.1	52.3	9%	
10%	Quartzite	Fine*	Coarse*	3%	350	1.2	1.1	1.2	4%	508.6	558.4	506.3	6%	
10%	Quartzite	Coarse*	Coarse*	3%	350	1.4	1.2	1.8	19%	499.6	599.2	394.1	21%	
10%	Quartzite	Fine*	Fine*	3%	385	6.2	6.3	6.0	3%	108.3	99.5	105.5	4%	
10%	Quartzite	Coarse*	Fine*	3%	385	10.0	11.8	14.0	17%	63.1	56.1	49.8	12%	
10%	Quartzite	Fine*	Coarse*	3%	385	1.3	1.2	1.1	9%	481.3	511.0	551.4	7%	
10%	Quartzite	Coarse*	Coarse*	3%	385	2.1	2.1	2.0	5%	352.6	355.3	386.9	5%	
40%	Dolomite	Fine*	Fine*	3%	530	4.0	2.4	2.2	34%	453.3	743.0	899.6	32%	
40%	Dolomite	Coarse*	Fine*	3%	530	7.4	6.7	7.1	5%	234.7	242.0	243.2	2%	

RAP Content, %	Virgin agg. Source	Virgin agg. gradation	RAP gradation	Moisture, %	Superheated temp, F	<i>H_c. W/°C</i>				<i>T_{equi}, sec</i>				Status
						1	2	3	CoV (%)	1	2	3	CoV (%)	
40%	Dolomite	Fine*	Coarse*	3%	530	4.2	4.0	3.3	11%	483.7	562.9	623.0	13%	
40%	Dolomite	Coarse*	Coarse*	3%	530	4.1	4.2	4.5	5%	534.3	514.4	492.0	4%	
40%	Dolomite	Fine*	Fine*	3%	550	2.1	4.9	2.2	53%	923.0	366.4	881.6	43%	Omitted
40%	Dolomite	Coarse*	Fine*	3%	550	7.1	7.1	8.2	9%	242.4	242.4	231.2	3%	
40%	Dolomite	Fine*	Coarse*	3%	550	3.3	4.3	3.6	15%	624.1	507.4	612.0	11%	
40%	Dolomite	Coarse*	Coarse*	3%	550	4.8	4.8	4.9	2%	433.9	435.6	457.5	3%	
40%	Dolomite	Fine*	Fine*	3%	575	2.1	6.2	5.0	48%	863.5	291.6	367.9	61%	Omitted
40%	Dolomite	Coarse*	Fine*	3%	575	9.3	9.0	9.5	3%	213.5	221.3	211.1	2%	
40%	Dolomite	Fine*	Coarse*	3%	575	3.1	3.8	2.9	15%	671.0	589.9	685.9	8%	
40%	Dolomite	Coarse*	Coarse*	3%	575	5.1	4.1	5.3	14%	436.5	523.4	399.9	14%	
40%	Basalt	Fine*	Fine*	3%	530	5.7	2.1	5.0	45%	306.8	924.0	368.4	64%	Omitted
40%	Basalt	Coarse*	Fine*	3%	530	7.8	7.2	7.4	4%	230.1	236.9	237.5	2%	
40%	Basalt	Fine*	Coarse*	3%	530	3.8	4.0	3.9	2%	553.5	489.0	493.4	7%	
40%	Basalt	Coarse*	Coarse*	3%	530	4.2	3.7	4.3	7%	530.7	584.1	533.1	5%	
40%	Basalt	Fine*	Fine*	3%	550	2.2	2.1	6.6	71%	902.3	948.6	269.1	54%	Omitted
40%	Basalt	Coarse*	Fine*	3%	550	8.3	7.8	7.4	6%	214.0	212.0	228.8	4%	
40%	Basalt	Fine*	Coarse*	3%	550	4.6	3.8	4.1	9%	505.6	588.6	551.5	8%	
40%	Basalt	Coarse*	Coarse*	3%	550	4.2	4.6	5.2	10%	499.1	483.6	431.6	7%	
40%	Basalt	Fine*	Fine*	3%	575	5.2	4.8	5.9	11%	357.7	402.2	322.2	11%	
40%	Basalt	Coarse*	Fine*	3%	575	8.6	7.5	9.0	9%	225.1	240.3	215.4	6%	
40%	Basalt	Fine*	Coarse*	3%	575	4.3	3.5	3.9	10%	526.7	570.5	559.1	4%	
40%	Basalt	Coarse*	Coarse*	3%	575	5.4	4.3	4.4	13%	428.7	483.8	510.2	9%	
40%	Quartzite	Fine*	Fine*	3%	530	4.2	4.2	4.0	3%	371.2	377.9	410.3	5%	
40%	Quartzite	Coarse*	Fine*	3%	530	8.1	8.0	8.3	2%	216.8	202.4	190.8	6%	
40%	Quartzite	Fine*	Coarse*	3%	530	3.3	3.2	3.1	3%	603.6	601.8	594.5	1%	
40%	Quartzite	Coarse*	Coarse*	3%	530	3.9	3.7	3.9	3%	489.6	534.3	500.2	5%	
40%	Quartzite	Fine*	Fine*	3%	550	4.6	1.8	1.7	60%	367.1	937.4	975.3	45%	Omitted

RAP Content, %	Virgin agg. Source	Virgin agg. gradation	RAP gradation	Moisture, %	Superheated temp, F	<i>H_c. W/C</i>				<i>T_{equi}, sec</i>				Status
						<i>1</i>	<i>2</i>	<i>3</i>	<i>CoV (%)</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>CoV (%)</i>	
40%	Quartzite	Coarse*	Fine*	3%	550	10.0	7.9	8.0	14%	170.3	211.3	208.0	12%	
40%	Quartzite	Fine*	Coarse*	3%	550	3.0	4.1	3.2	16%	630.8	447.1	606.7	18%	
40%	Quartzite	Coarse*	Coarse*	3%	550	4.6	4.5	5.2	8%	440.6	439.7	388.6	7%	
40%	Quartzite	Fine*	Fine*	3%	575	4.2	1.6	3.7	43%	417.0	1051.6	464.7	55%	Omitted
40%	Quartzite	Coarse*	Fine*	3%	575	9.4	9.9	9.7	3%	186.5	183.4	180.1	2%	
40%	Quartzite	Fine*	Coarse*	3%	575	2.7	3.8	3.6	17%	704.2	539.7	555.9	15%	
40%	Quartzite	Coarse*	Coarse*	3%	575	5.5	4.9	5.4	6%	382.7	428.4	390.9	6%	