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THERMODYNAMICS BETWEEN RAP/RAS AND VIRGIN AGGREGATES DURING ASPHALT CONCRETE PRODUCTION—A LITERATURE REVIEW

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16. Abstract

In hot-mix asphalt (HMA) plants, virgin aggregates are heated and dried separately before being mixed with RAP/RAS and virgin asphalt binder. RAP/RAS materials are not heated or dried directly by a burner to avoid burning of aged binder coating on the materials so they are heated and dried indirectly by the hot virgin aggregates. A literature review shows that virgin aggregate temperature has been predicted for drying and heating RAP at batch plants only. In this study, thermodynamics and heat transfer principles are used to predict virgin aggregate temperature for drying and heating RAP/RAS at a drum plant. Among many results, it was shown that virgin aggregates become superheated (more than 1000°F) when both virgin aggregate and RAP moisture content were in the range of 3% to 5% and the material proportions were in the range of 30% to 50%. The size of virgin aggregates and RAP/RAS, the moisture content of virgin aggregates and RAP/RAS, and the mix proportion of virgin aggregates and RAP/RAS were the major contributing parameters in predicting virgin aggregate temperature in the drum plant. The plant's moisture content data indicate that virgin coarse aggregates hold a lower amount of moisture compared with virgin fine aggregates. However, in comparing same-size virgin aggregates and RAP, RAP contained a higher amount of moisture. The reason might be that the aged binder coating of RAP holds moisture better than virgin aggregates do. Also, RAS contains a higher amount of moisture compared with RAP of the same size.

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EXECUTIVE SUMMARY

In this study, a literature search was conducted on predicting the virgin aggregate temperature required to dry and heat reclaimed asphalt pavement/recycled asphalt shingles (RAP/RAS) in a hot-mix asphalt (HMA) production plant. The study also included an assessment of HMA plant operation and production procedures, application of thermodynamics and heat transfer principles, measurement of moisture content in virgin aggregates and in RAP and RAS, and recording of virgin aggregate temperatures in a drum plant.

It was found in the literature review that virgin aggregate temperatures have been predicted for drying and heating RAP in batch plants, but the study in question did not consider virgin aggregate moisture content. For drum plants, however, previous research noted the use of empirical equations and numerical analysis for predicting the virgin aggregate temperature. In addition, it was found that one attempt had been made to install temperature probes inside the drum to measure the temperature of virgin aggregate. However, the physical parameters of the materials were not considered in the empirical equations, although that study considered the proportions of RAP and virgin aggregates in its analysis. Moreover, numerical analysis and field studies have included the use of thermodynamic principles, but those studies did not include HMA mixes with RAP.

In the current study, thermodynamics and heat transfer principles are used to predict virgin aggregate temperatures necessary to dry and heat RAP. Different proportions of virgin aggregates (50% to 90%) and RAP (10% to 50%) in the HMA mix were used in the calculation. The moisture content of virgin aggregate varied from 1% to 5%, and the moisture content of RAP varied from 1% to 5%. One example is presented for 0.5 in. virgin aggregates and RAP size and another for 0.25 in. virgin aggregates and RAP size. It was observed that for 0.5 in. virgin aggregates and RAP, the virgin aggregates become superheated (more than 1000°F) when the moisture contents for both the virgin aggregates and RAP are in the range of 3% to 5% and the material proportions are in the range of 30% to 50%. For the 0.25 in. virgin aggregates and RAP, the virgin aggregates become very hot (more than 500°F) when the RAP percentages in the HMA mix are in the range of 40% to 50%.

The plant moisture content data indicate that virgin coarse aggregates hold a lower amount of moisture compared with virgin fine aggregates. However, a comparison of same-size virgin aggregates and RAP shows that RAP contains a higher amount of moisture. The reason might be that the binder coating of RAP holds moisture better than do virgin aggregates and because the aged binder coating moisture does not evaporate quickly in the open air. Also, it was found that RAS contains a higher amount of moisture compared with RAP of the same size. Generally, moisture content in virgin aggregates, RAP, and RAS increases after precipitation. However, many other factors—such as evaporation, temperature, and humidity—affect the moisture content of virgin aggregates and RAP/RAS.

Performance of HMA in the field might depend on the superheated virgin aggregate temperature and high RAP proportion in the mix. However, more field studies are needed. The limited literature review shows the importance of additional study about the temperature of virgin and recycled materials inside a drum plant. A future study should take a multi-disciplinary approach, include collection of extensive plant data, and include both computational and numerical modeling as well as laboratory investigations.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Materials such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) have been used in hot-mix asphalt (HMA) for many years to lower consumption of virgin materials to reduce costs and for environmental reasons. RAP has been used in HMA pavement construction for more than 40 years; RAS has been used for fewer than 10 years nationally and for fewer than 5 years in Illinois (Ozer et al. 2012). The Illinois Department of Transportation (IDOT) used approximately 0.6 million tons of RAP in 2001 and 1.7 million tons of recycled materials in 2010 (Al-Qadi et al. 2007; Ozer et al. 2012). However, in HMA mixes, RAP replaced a higher percentage than RAS in virgin materials. In many states, more than 25% RAP is used in HMA pavement, while less than 10% RAS is used (Mannan et al. 2014). In addition, the use of RAS in HMA mix is not commonly practiced in all states.

RAP/RAS materials are coated either partially or fully by aged and oxidized binder. This coating can be extracted and analyzed and a performance grade (PG) of the binder can be determined. These aged and oxidized binders, as well as recycled aggregates or recycled shingles, are mixed with virgin aggregate and virgin binder to produce HMA mix. Virgin binder and aggregate costs are reduced by partial replacement with RAP/RAS materials.

HMA production for mixes that contain RAP/RAS material differs from production of HMA that contains only virgin material. Generally, virgin aggregates are dried and heated inside a dryer at an elevated temperature. Drying is necessary to reduce moisture in the virgin aggregate, while heating is necessary to achieve good bonding between the aggregates and the binder. After the virgin aggregates have been heated, RAP/RAS materials are added separately inside the mixer and mixed with the heated virgin aggregate. Heated virgin aggregates are used to dry and heat the RAP/RAS materials.

It is critical that moisture be removed from the RAP/RAS materials before they are mixed with the asphalt binder because moisture causes adhesive damage (separation of aggregate from the binder) and cohesive damage (disintegration within the binder) in HMA (Hossain 2013). Moisture that remains in the virgin aggregates, the RAP, or the RAS is called residual moisture (Transportation Research Board 2015).

In addition, it is necessary to heat the aged and oxidized asphalt binder coating on the RAP/RAS materials so that they blend properly with the virgin asphalt binder and produce a homogeneous mix. Virgin asphalt binder is added to the mix of virgin aggregate and RAP/RAS to achieve the desired volumetrics of the HMA mix design. HMA is kept heated at a specific temperature in a storage silo until it is transported to the construction location.

RAP/RAS materials are not directly dried and heated inside the dryer/heater at an elevated temperature while the HMA is produced; if RAP/RAS materials are directly heated, then the binder coating will burn off and evaporate from the surface of the recycled material, producing emissions from the mixing plant. If any burned-up binder coating is left on the RAP/RAS materials, the properties of the binder will be significantly changed, resulting in a poorly performing HMA mix. It is necessary, however, to activate the aged and oxidized binder coating by heating it in conjunction with the virgin aggregates.

To prevent the aged and oxidized asphalt binders from being burned, the virgin aggregates are first dried and heated to a particular temperature, and then RAP/RAS is added to the production chamber.

The RAP/RAS is dried and heated indirectly in conjunction with the already heated virgin aggregates as heat is transferred from the virgin aggregates to the RAP/RAS materials. In addition, this heat needs to transfer through the asphalt binder coating to get inside the RAP/RAS materials. Heat is transferred into the recycled materials from the heated virgin aggregates as well as the surrounding heated air inside the mixer. This process continues until the virgin aggregates and recycled materials achieve a uniform temperature. After a specified mixing temperature has been reached, virgin asphalt binder is added and mixed in until the mix is homogeneous.

Figure 1.1 shows a schematic of heat transfer from a virgin aggregate and surrounding heated air into RAP/RAS material. In the dryer/mixer, aggregates randomly come in contact with recycled materials and with each other. This is a dynamic process because the dryer/mixer continuously rotates at a particular velocity. Heat is transferred continuously from the heated air toward the RAP/RAS material. This is known as convection, which is defined as the transfer of energy between a solid surface and the adjacent fluid in motion (Bražiūnas and Sivilevičius 2014).

In contrast, heat is transferred from the virgin aggregate to the RAP/RAS when the heated virgin aggregate is in contact with the cold RAP/RAS material. This is known as conduction, which is defined as the transfer of energy from the more energetic particles of a substance to the adjacent less energetic particles as a result of interaction between particles (Bražiūnas and Sivilevičius 2014).

However, convection phenomena involve the combined effects of conduction and air motion. Moreover, radiation is another heat transfer process, although radiation does not require any media (i.e., fluid or solid) to transfer heat.

In Figure 1.1, it can be seen that heat will be first transferred to the aged and oxidized binder, and then to the RAP/RAS aggregate.

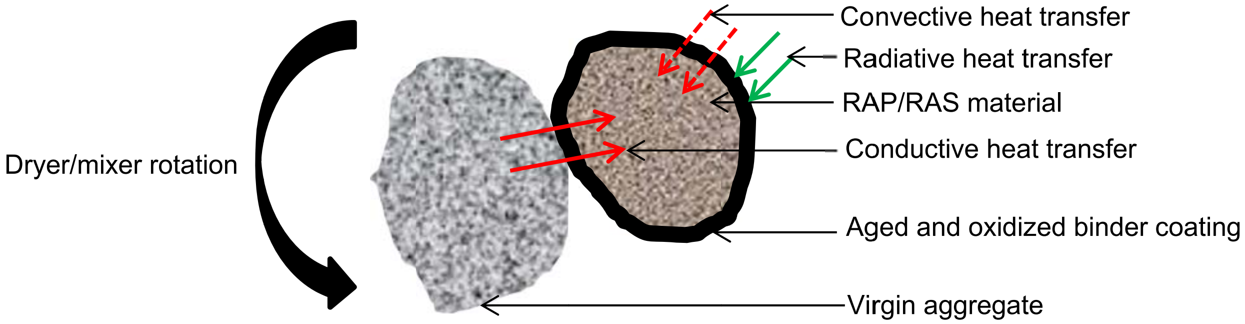


Figure 1.1 Schematic of heat transfer to the RAP/RAS material in a dryer/mixer.

Researchers have observed that RAP/RAS materials have a higher moisture content than virgin aggregates do (Frederick and Tario 2009). The binder coating on the RAP/RAS works as a shield on the aggregate and prevents natural evaporation of moisture from the aggregates. In addition, the moisture diffusion rate is lower for asphalt binder compared with aggregate. For this reason, moisture takes a longer time to evaporate from RAP/RAS materials. It has been observed that additional energy is required in terms of the amount of fuel used to mix cold RAP/RAS with the heated virgin aggregates (Gillespie 2012). Upon heating, the moisture changes from a liquid phase to a gas phase, and this phase change requires additional energy. The phase change from liquid to gas is also part of convective heat transfer. Moreover, additional fuel energy causes higher emission of unwanted gases that cause greenhouse effects. In addition, because of increased fuel price, production costs increase when using additional fuel to dry and heat RAP/RAS materials.

Recently, IDOT officials have become aware of the use of higher virgin aggregate temperatures (approximately 700°F) in HMA production plants. The use of higher temperatures for virgin aggregates has also been observed by several HMA production contractors, plant operators, and paving crews. In addition, IDOT field crews have observed significantly high HMA mix temperatures (over 400°F) while the HMA mix was under the paver. Because of excessive rainfall in 2015, it is possible that the RAP/RAS materials contain a higher amount of moisture than usual. Furthermore, if the ambient temperature of RAP/RAS is very low in winter, then the recycled materials might need additional heat to dry and activate their binder coatings. Consequently, it is possible that virgin aggregates are being overheated inside the drum—and these superheated virgin aggregates might be burning the RAP/RAS coating.

Very few studies have been done on energy consumption in connection with heating virgin aggregate with RAP materials or of the energy required to evaporate moisture from the RAP (Frederick and Tario 2009; Gillespie 2012). In addition, only a limited study has been conducted on the thermodynamic process that takes place inside a dryer/heater to heat virgin aggregates (Hobbs 2009). No study has been done on the thermodynamics of moisture evaporation of RAP/RAS and virgin aggregates, nor has there been any study on energy consumption from the use of RAS materials to produce HMA mix.

Accordingly, an overall understanding of the thermodynamic processes of heat transfer from virgin aggregate to RAP/RAS materials and energy consumption in a mix plant is necessary to reduce energy loss and emissions in a mix plant and to maintain a temperature below that which would cause significant damage to the virgin and recycled asphalt binders.

1.2 RESEARCH OBJECTIVE

The objectives of this project are as follows:

- Conduct a comprehensive literature review on thermodynamics, with special emphasis on heat transfer phenomena between RAP/RAS materials with virgin aggregates when moisture is present in the recycled materials.
- Evaluate the HMA production process specifically in regard to energy use, energy loss, and emissions when mixing RAP/RAS with virgin aggregates in the presence of variable amounts of moisture.
- Determine the virgin aggregate temperature necessary to produce various blends of RAP, RAS, and RAP/RAS mixtures with moisture contents ranging from 0% to 20%.

1.3 RESEARCH APPROACH

Thermodynamics is a vast subject that covers how heat is transferred, how much work is done, and the final state of a system. Heat transfer involves *how* heat is transferred, *at what rate* heat is transferred into a material, and the temperature distribution inside a body. The research approach to accomplish the objectives of the study included the following tasks:

- Study the fundamental principles of thermodynamics and heat transfer and how they apply to virgin and recycled materials. Analyze thermodynamic properties such as thermal conductivity and the heat transfer coefficient of virgin aggregates and recycled materials, as well as the energy required to heat up virgin aggregates, to heat up RAP/RAS materials in conjunction with the hot virgin aggregates, and to evaporate moisture from the aggregate.

- Conduct a comprehensive literature review of published books, journal papers, conference proceedings, National Cooperative Highway Research Program reports, Transportation Research Record journals, National Asphalt Pavement Association publications, National Center for Asphalt Technology reports, and other resources to understand the heat transfer phenomena in aggregates or similar materials. Parameters and typical values required to model heat transfer in aggregates will be collected from the published literature.
- Use generalized heat transfer models that consider the conduction, convection, and radiation processes of heat transfer of virgin aggregates and RAP/RAS materials. Use the developed model to calculate energy consumption and temperature required to evaporate moisture from virgin aggregates and RAP/RAS.
- Collect virgin aggregates, RAP, and RAS from a local HMA production plant to measure moisture content of the materials. Record moisture content data for 3 months and use that information to observe the moisture content variations in the plant's aggregates in a regular production season.
- Visit a drum mix plant to observe the HMA mix process. Collect HMA production data related to type and gradation of virgin aggregates, percentage of RAP/RAS used in the mix, moisture content in virgin aggregates, moisture content in RAP/RAS, heating time of virgin aggregates, mixing time of virgin aggregates with RAP/RAS and binder, virgin aggregate temperature, mixing temperature, etc. These data will provide additional information on heating of virgin aggregates to remove moisture from the RAP/RAS materials and subsequent mixing with the virgin binder.

1.4 REPORT ORGANIZATION

The scope of the research is to understand the energy use and temperature required to evaporate moisture from virgin aggregates and RAP/RAS by studying thermodynamics and heat transfer processes between the aggregates inside a dryer/heater, specifically at a drum plant.

Chapters are organized as follows:

Chapter 2 presents a summary of the HMA plants and effects on plant production related to the presence of moisture in virgin aggregates and recycled materials, especially RAP. Historical and current studies on energy use at drum and batch plants are summarized. In addition, an overview of the different types of plants is provided.

Chapter 3 presents the details of a comprehensive study on thermodynamics and heat transfer principles of materials. Thermodynamics equations are presented, and their application to heating aggregates in a drum plants is explained.

Chapter 4 explains the prediction of virgin aggregate temperature by using values taken from the literature, as well as by using thermodynamics equations. A step-by-step computational process is shown, and two examples are provided.

Chapter 5 presents the moisture content test results of virgin aggregates and RAP and RAS materials collected from a local HMA production plant. Several other field data taken from the plants in other IDOT districts and fields are also documented in this chapter.

Chapter 6 presents the temperature data collected from a HMA drum plant, and a sample calculation to predict virgin aggregate temperature of the plant using the thermodynamics equations is provided.

Chapter 7 discusses the results and provides a recommendation for potential future studies.

CHAPTER 2: HOT-MIX ASPHALT PLANTS

2.1 INTRODUCTION

This chapter summarizes HMA plant types, HMA production processes, and the effects of the HMA production process on virgin aggregates and RAP/RAS moisture. Several illustrations are presented to describe the process of producing HMA using recycled materials.

2.2 HMA MIX PLANTS

There are two types of HMA plants: batch and drum. For a target HMA mix, a batch plant produces the mix in individual batches by proportioning aggregates and binder. Generally, a batch plant is suitable for small paving projects or maintenance work. On the other hand, a drum plant continuously produces HMA mix and it is suitable for large paving projects. Contractors usually prefer drum plants over batch plants for reasons related to production efficiency and quality control. In a previous study, it was estimated that 95% of the newly manufactured plants are drum plants (Kandhal and Mallick 1997).

2.2.1 Batch Plant

Figure 2.1 shows a typical arrangement of a batch plant with the essential plant components. Virgin aggregates are supplied from the aggregate bunker or bins by a conveyor belt under the bins. Bins contain fine and coarse aggregates separated by various gradations. Virgin aggregates are carried to the dryer by a conveyor belt. Upon reaching the dryer, the aggregates are heated and dried by a burner.

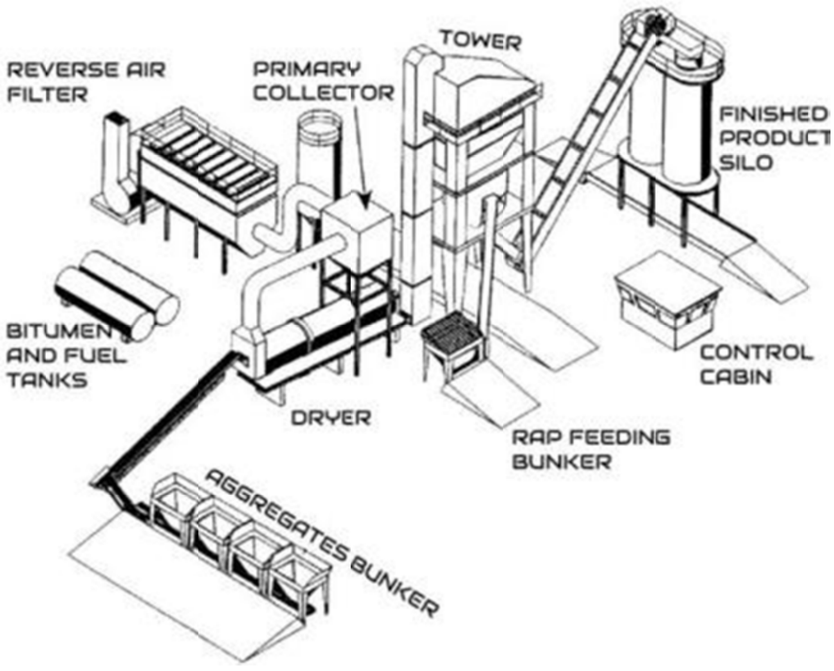


Figure 2.1 Typical arrangement and essential components of a batch plant (http://eu.anadoluekip.com/products/asphalt-plant/batch-asphalt-plant/).

The aggregates are introduced into the dryer at the upper end and are moved down into the drum by the gravity flow, the drum rotation, and the flight configuration inside the rotating dryer (*Hot-Mix Asphalt Paving Handbook* 2000). Figure 2.2 shows the interior of a drum dryer with various types of flight arrangements. The flights are used to make aggregate veils, much like the design of a clothes dryer. These veils dry aggregates by using heat from a burner that passes through the drum through the falling aggregates.

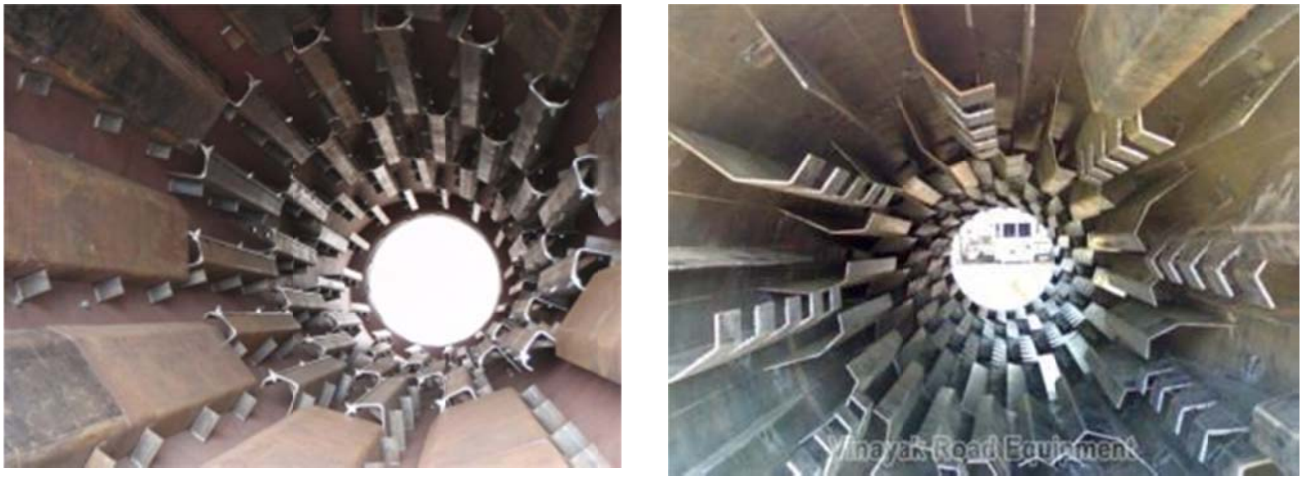


Figure 2.2 Flights inside a dryer drum (http://www.bgeuropa.co.uk/products/aggregate-drying/retro-fit-dryer-drum-shells and http://www.vinayakroadequipment.com/dryer-drum.htm).

Figure 2.3 shows different types of flights used in a dryer. A drum's heating efficiency can be increased by using different flights and placing them in varying arrangements. Some flights are used to make veils and some are used to mix aggregates. For an example, the cup and J-cup flights are used to make veils, while the angle and basket flights are used to mix aggregates.

Aggregates are dried by convective heat while they are falling as a veil and by conductive heat while they are mixing with each other and rotating along the drum wall. The dusts that are generated during mixing and drying aggregates are collected in the primary collector and passed through the baghouse (the reverse air filter in Figure 2.1).

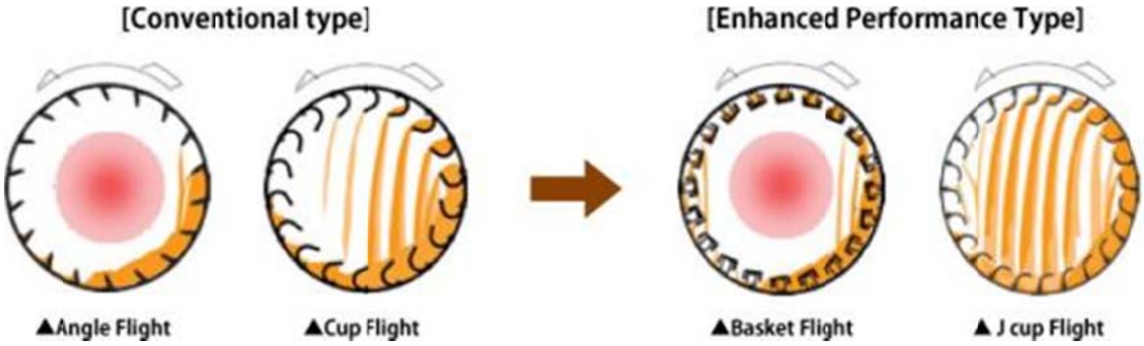


Figure 2.3 Veils inside drum depend on flight type (http://en.nikko-net.co.jp/product/asphalt/combustion_unit.html).

After heating and drying, the virgin aggregates are passed to the tower by means of an elevator. Figure 2.4 shows the batch plant tower, including part of the elevator and the aggregate screener. After reaching the top of the elevator, virgin aggregates are screened out based on their size. These hot-screened virgin aggregates are then ready to be placed into the aggregate weigh bucket, where they are screened and weighed based on the aggregate proportioning for the HMA mix. RAP/RAS, if used, is introduced with the virgin aggregates in the weigh bucket. (Other arrangements or RAP/RAS-feeding techniques in the batch plant are available and are discussed in later sections of this report.) These screened and weighed hot virgin aggregates are ready to mix with hot asphalt binder.

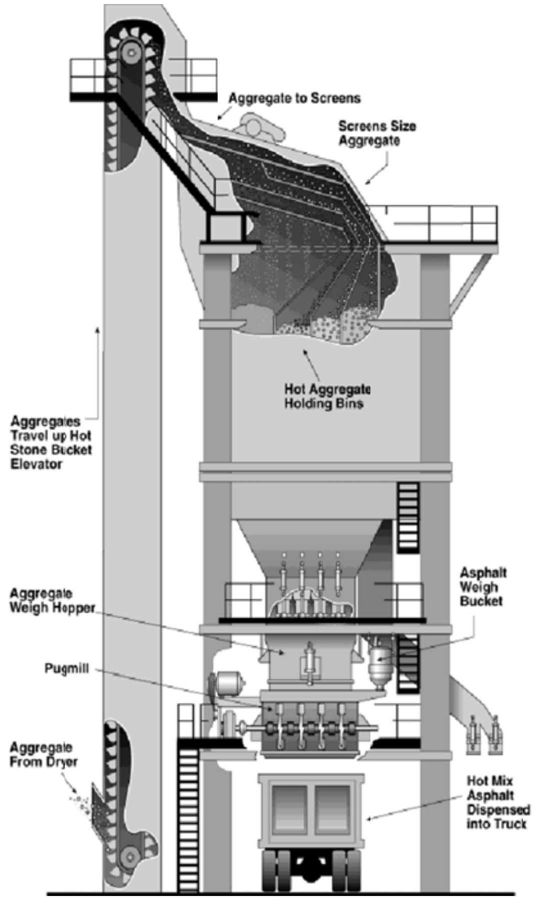


Figure 2.4 HMA production in batch plant
(NCAT Professors Training Course in Asphalt Technology, 2014).

The hot virgin aggregates and binder are mixed inside a pug mill. Figure 2.5 shows a typical twin-shaft pug mill used in a batch plant. A rotating shaft holds levers that are used to mix HMA. The aggregate in the weigh hopper is emptied into the pug mill, and the different aggregate fractions are mixed for a very short period of time-usually less than 5 sec (*Hot-Mix Asphalt Paving Handbook* 2000). This aggregate mixing is called dry mixing.

After dry mixing, hot asphalt binder is weighed and added to the pug mill. The mixing time for blending of the asphalt cement with the aggregate should not be longer than necessary to completely coat the virgin aggregate particles with a thin film of the asphalt cement material—usually in the range of 25 to

35 sec, with the lower end of that range for a pug mill that is in good condition (*Hot-Mix Asphalt Paving Handbook* 2000).

The aggregate mixing with binder is called the wet mixing. Wet-mix time can be as short as 27 sec. If the paddle tips are worn, the wet-mix time will be extended somewhat, but typically should not be more than 33 sec. The total mixing time, which includes dry mixing, wet mixing, and mix discharge, can be as short as 30 to 35 sec (*Hot-Mix Asphalt Paving Handbook* 2000). After mixing, the HMA mix is conveyed to the storage silo or directly dispensed into the truck. The storage silo has an electric heater that keeps the mix warm.

Figure 2.5 Inside of pug mill (NCAT Professors Training Course in Asphalt Technology, 2014).

2.2.2 Drum Plant

A drum plant's essential components and arrangement are similar to those of the batch plant; the only difference is the absence of the tower in a drum plant. Virgin aggregate heating and drying, RAP/RAS mixing, and binder mixing occurs sequentially in the drum. In some HMA production plants, all of those procedures are carried out by a single drum or could be carried out by series of drums. Figure 2.6 shows a typical arrangement of drum plant components.

Virgin aggregates are weighed and conveyed by the weighing belt placed under the aggregate bins. Virgin aggregates are conveyed inside the drum. It should be noted that for drum mixing, virgin aggregates are weighed before entering the drum, while for batch mixing, the virgin aggregates are weighed after they dry in the drum.

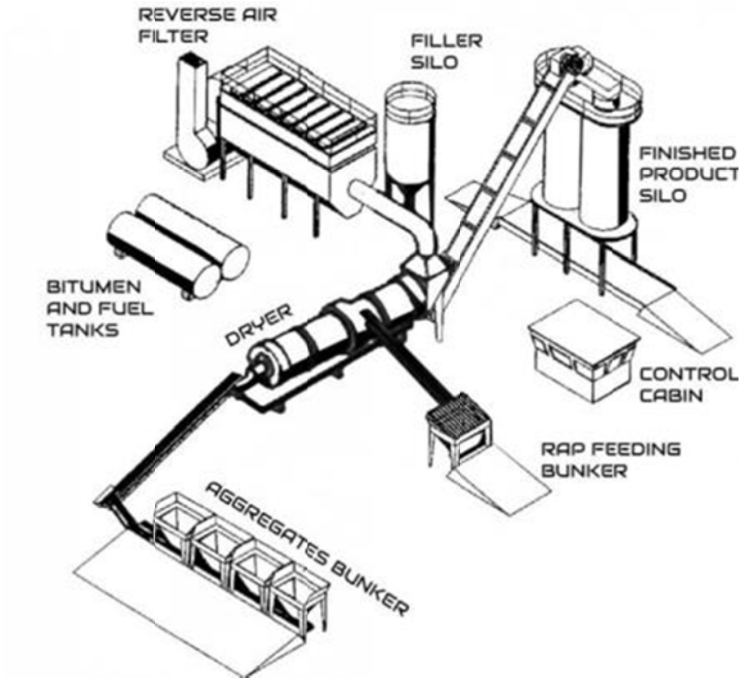


Figure 2.6 Typical arrangement and essential components of a drum plant (http://eu.anadoluekip.com/products/asphalt-plant/drum-mix-asphalt-plant/).

Generally, there are three types of drums used in a drum plant: parallel flow, counter flow, and double barrel. Figure 2.7 shows a schematic diagram of a parallel-flow drum. The term “parallel flow” means that virgin aggregates and heat from the burner enter the drum from the same direction and travel the same path as each other. As shown in the figure, both the dryer burner and the virgin aggregate feeding entrance are on the right end of the drum. Virgin aggregates are heated by the burner and travel down to the middle of the drum, where they come into contact with the RAP/RAS and are mixed thoroughly with it before being mixed with the hot binder. RAP/RAS are kept at an ambient temperature before being fed into the drum.

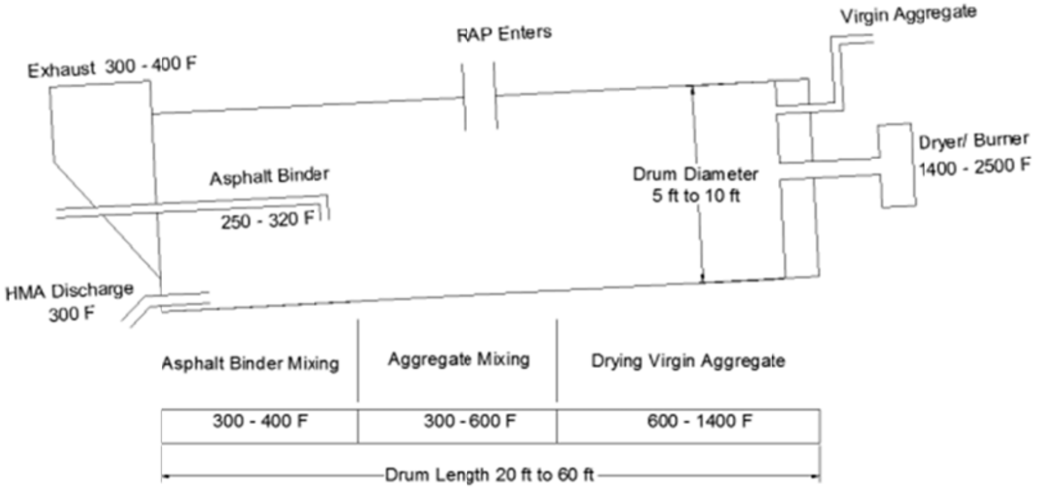


Figure 2.7 Parallel-flow drum.

Figure 2.7 also shows the drying and heating temperature for the virgin aggregates, the mixing temperature for virgin aggregates with RAP, and the mixing temperature for the binder. Because the hot gases and the aggregates move in the same direction within the drum, when it produces a 300°F mix, the lowest obtainable exit gas temperature at the exhaust of the drum is 300°F, regardless of drum length. Even in the most efficient and modern parallel-flow drum mixers, this temperature reaches 310°F to 330°F (Brock n.d.). The virgin aggregate remains in the hot zone of the drum and is superheated to about 500°F (Kandhal and Mallick 1997)**.** The temperature of the burner flame sometime exceeds 2500°F. The exit gas temperature for parallel-flow drum mixers is typically as much as 54°F higher than exit mix temperatures (*Hot-Mix Asphalt Paving Handbook* 2000). Sometimes, special flight design, steel ring drams, or circular steel flame shields are used to force the RAP to mix with the virgin aggregates before being subjected to the high gas treatment (Kandhal and Mallick 1997). In a parallel-flow drum mixer, the stack temperature will almost always exceed the mix temperature. At best, the temperature in a parallel-flow drum mixer will be equal to the mix temperature, regardless of the length and efficiency of the drum. This statement indicates that the heat transfer is completed after the mixing is finished and is probably inside the silo or in the truck or even while HMA is under the paver.

Figure 2.8 shows a schematic diagram of a counter-flow drum. The term “counter flow” means that virgin aggregates and heat enter the dryer from the opposite direction but travel parallel to each other. A counter-flow dryer allows much lower exit gas temperatures to be attained. Exit gas temperatures as low as 180°F have been achieved with this type of dryer. However, with baghouses, temperatures at the dryer exit are usually controlled at about 240°F to prevent condensation of water or acids in the baghouse. When natural gas or low-sulphur fuel oils are used, exit temperatures can be lowered to 220°F (Brock n.d.). Higher exit temperatures cause destruction of baghouse materials. In addition, higher exit temperatures could shut down the plant. The mixing time in the counter-flow drum is typically in the range of 45 to 60 sec (*Hot-Mix Asphalt Paving Handbook* 2000; Hunter et al. 2000). Material discharge or mix temperature from a counter-flow dryer would be as low as 148°F to 392°F (Hunter et al. 2000).

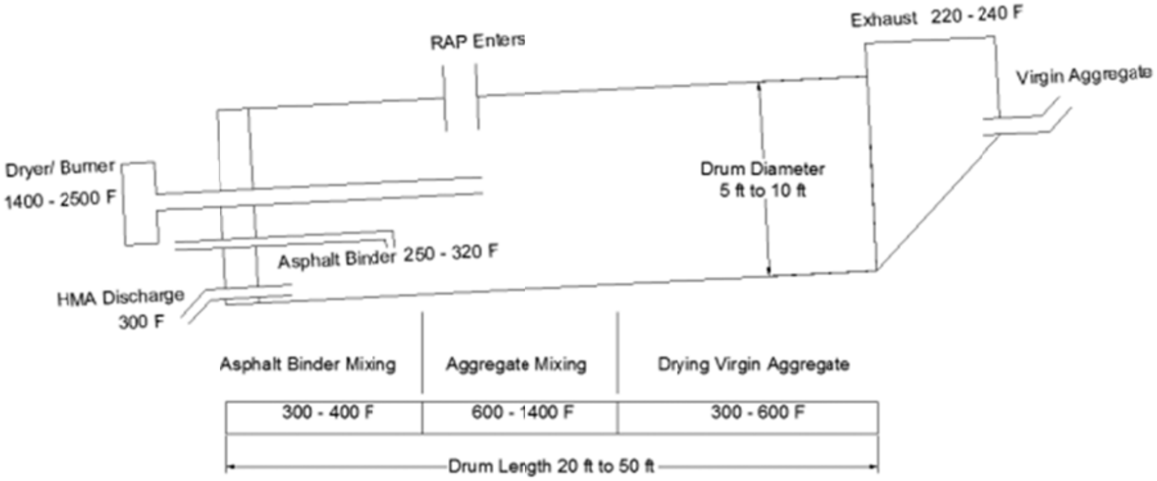


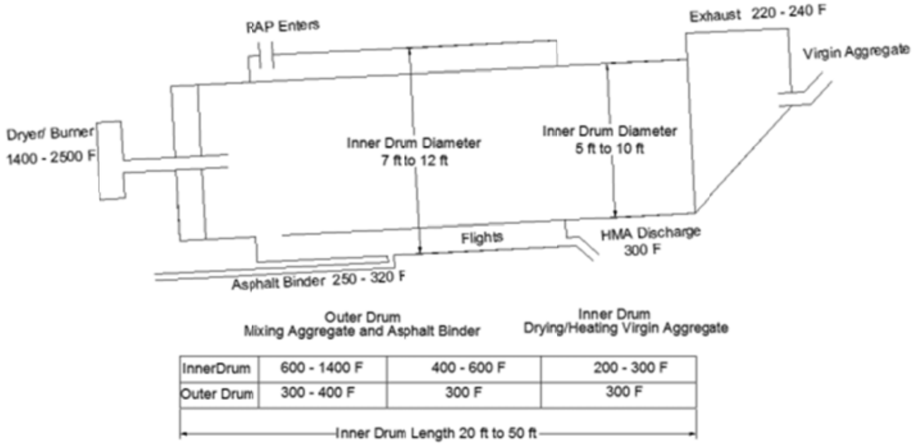
Figure 2.8 Counter-flow drum.

Center entry is the most widely used method for hot-mix recycling in a drum-mix plant (Kandhal and Mallick 1997). RAP/RAS is introduced into the drum downstream of the burner flame to mix with the superheated virgin aggregates. The hot virgin aggregates heat up the RAP materials by conduction. The maximum amount of RAP/RAS that can be used for recycling in a drum-mix plant is about 70%, although the practical limit is about 50%. The use of 50% RAP/RAS would require an extremely high gas temperature; in that case, a relatively smaller amount of virgin aggregates would be available to protect the RAP/RAS from the flame. This may lead to a “blue smoke” problem in some drum-mix plants. Counter-flow dryers or drum mixers, however, can have stack temperatures that are lower than mix temperatures. To prevent condensation in baghouses, however, a stack temperature below 250°F is not recommended. Generally, 50% to 60% RAP can be added to a counter-flow drum mixer (Hunter et al. 2000; Read and Whiteoak 2003).

If RAP/RAS is added to the new aggregates, it is deposited from its own cold-feed bin and gathering/charging conveyor system into an inlet near the center of the drum length. In this process, the reclaimed material is protected from the high-temperature exhaust gases by the veil of new aggregates upstream of the RAP/RAS entry point. When mixes with high RAP/RAS content are used, it is more likely that the RAP/RAS will be overheated in the process (*Hot-Mix Asphalt Paving Handbook* 2000). It is often necessary to screen out and then crush the largest pieces of RAP/RAS to ensure proper heat transfer and mixing of the RAP/RAS and new aggregates inside the drum mixer.

Figure 2.9 shows a schematic diagram of a double-barrel counter-flow drum plant. The term "double barrel" means that there is an outer barrel or drum where the virgin aggregates are mixed with RAP/RAS and binder. The inner barrel or drum is used exclusively for heating and drying of virgin aggregates. The superheated virgin aggregates melt the aged asphalt in the recycled materials, and the aged asphalt coats the virgin aggregates before fresh liquid asphalt is injected into the mix. Mixing time in the outer shell is generally 45 to 60 sec with a maximum of 90 sec (Brock n.d.; *Hot-Mix Asphalt Paving Handbook* 2000; Kandhal and Mallick 1997). The outer shell of the double barrel stays at approximately 120°F at all times, leading to a very efficient plant (Brock n.d.; Kandhal and Mallick 1997).

A triple-drum design uses an outer shell as well, but it also has a stainless steel cylinder that encloses the combustion chamber. This cylinder (without any flight or steps of a regular drum) is believed to be effective in transferring heat to the RAP/RAS material through conduction and radiation (Kandhal and Mallick 1997). The RAP/RAS material is introduced in the annular space formed by the outer shell. The superheated virgin aggregates fall into the annular space and mingle with the RAP/RAS material.



InnerDrum	600 - 1400 F	400 - 600 F	200 - 300 F
Outer Drum	300 - 400 F	300 F	300 F

Figure 2.9 Counter-flow double-barrel drum.

Like the drum dryer in a batch plant, the dryer in a drum plant has flights inside the drum wall. Figure 2.10 shows flights inside a drum. However, the variation of flights in a drum plant differs from that used in a batch plant. Figure 2.10 (right) is the result for a numerical simulation of making veils inside a drum. The numerical simulation is developed using computational fluid dynamics (CFD) and discrete element method (DEM) modeling. This type of simulation is useful in depicting the variations of veils resulting from a change in flight arrangements or from the amount of virgin aggregates and/or RAP/RAS. In addition, heat distribution in aggregates can be visualized by using numerical simulation techniques. As shown in the figure, the aggregates become hotter while falling as a veil and reaching the bottom of the drum. The aggregates are heated primarily by the convective heat transfer process.

Figure 2.10 Flights (left) and veils (right) inside a drum dryer (NCAT Professors Training Course in Asphalt Technology, 2014, and http://www.hotmixmag.com/index.php?option=com_content&view=article&id=375:pushing-the-limits&catid=60:vol-18-num-1-2013).

Figure 2.11 shows the different types of flight use inside a parallel-flow drum. After aggregates enter the drum, the kicker and tapered flights are used to break and separate aggregate chunks. The notched flights create aggregate veils, which help the aggregate dry out by convective heat. The cup and step flights help to mix virgin aggregates with RAP/RAS materials. J-flights are used to mix virgin aggregates, RAP/RAS, and binder. The mix receives radiant heat while mixing using J-flights.

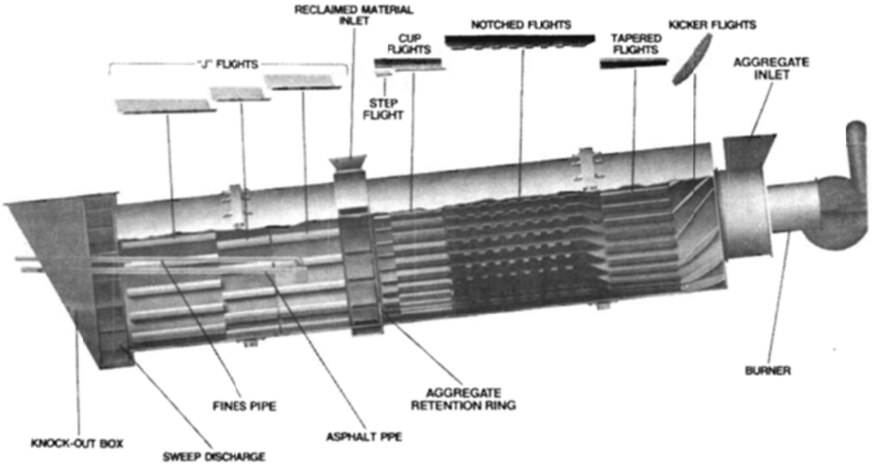


Figure 2.11 Flights inside a parallel-flow drum plant (Kennedy et al. 1986).

Figure 2.12 shows flights inside a counter-flow double-barrel drum. The figure shows the latest flight types and arrangements for mixing virgin aggregates with a high percentage of RAP/RAS content in an HMA mix. A high percentage of RAP/RAS reduces the amount of virgin aggregates, which causes a thinner veil inside the drum. In such a case, the virgin aggregates do not receive sufficient heat because there is less convective heat transfer from the hot air. For this reason, tapered and notched flights are modified. The double barrel retains the kicker flight that breaks the chunk aggregate. However, tapered flights are modified to notched flights so that the virgin aggregate is heated convectively early in the mixing, and V-flights are designed such that the amount of virgin aggregates in the veil increases and receives sufficient convective heat. Combustion flights help virgin aggregates receive radiant heat before they go inside the outer barrel. From beginning to end, the virgin aggregates receive conductive heat from the flights, drum wall, and the aggregate itself. In addition, the virgin aggregates receive radiant heat from the moment of entrance. The outer barrel flights are similar to the bucket flights (shown previously in Figure 2.3). As flights wear, the shell temperature and casing loss to the dryer typically rise, meaning that worn flights have a double effect of further reducing thermal efficiency (Young 2007).

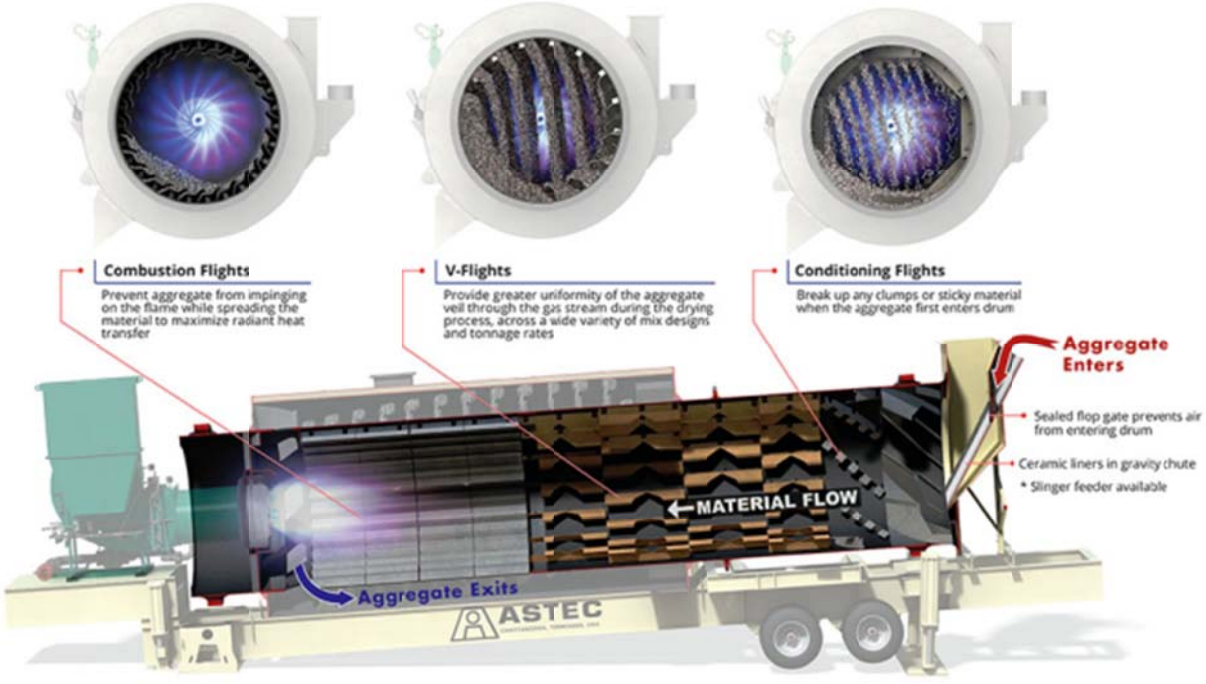


Figure 2.12. Flights and veils inside double-barrel counter-flow drum plant (http://www.astecinc.com/products/drying-mixing/sequential-mixing.html).

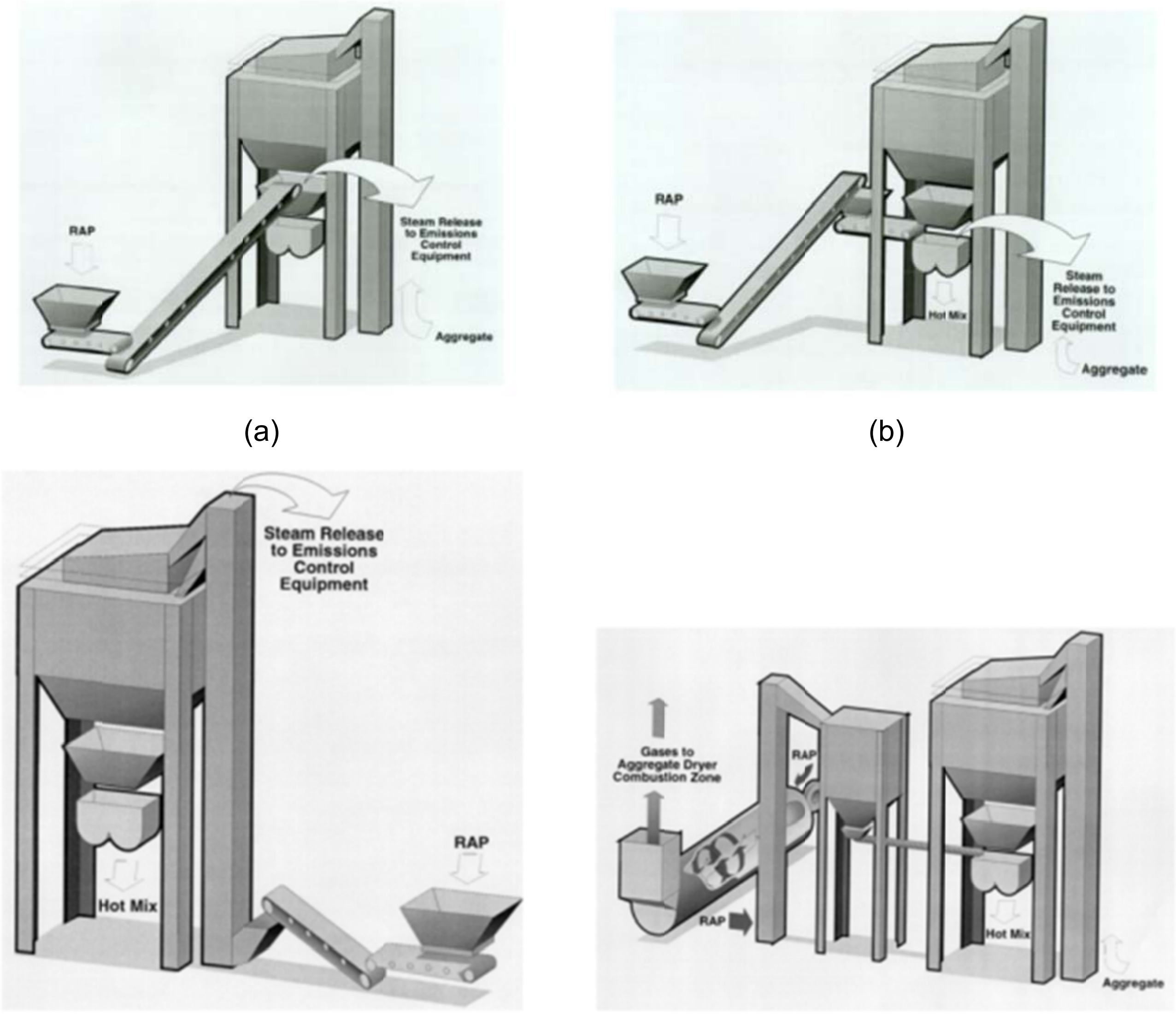
2.3 MIXING OF RAP/RAS IN HMA PLANTS

RAP/RAS mixing in a batch plant is different than in a drum plant because the RAP/RAS is fed in a different way and because of how the plant is configured. RAS is also mixed in the same way as RAP is (to date, there has been no evidence found that there is a different feeding process for RAS). The following sections summarize the current practices of RAP/RAS feeding in batch plants and in drum plants.

2.3.1 Mixing of RAP in a Batch Plant

Figure 2.13 shows the four methods for feeding RAP/RAS in a batch plant (Kandhal and Mallick 1997). As explained earlier, virgin aggregates are weighed in a hopper before entering the pug mill. In Figure 2.13(a), the RAP/RAS is placed in the aggregate weighing hopper by means of a conveyor belt. In Figure 2.13(b), the RAP/RAS is directly added to the pug mill; however, the RAP is first weighed in a separate hopper. In Figure 2.13(c), the RAP/RAS is raised to the top of the tower and then fed through the virgin aggregate bin. In Figure 2.13(d), the RAP/RAS is heated by a separate dryer and then transferred to an individual RAP holding bin; it is then weighed separately and fed directly to the pug mill.

It should be noted that RAP/RAS is generally not heated directly because the RAP binder coating will burn and produce hazardous emissions. RAP/RAS is dried and heated in conjunction with the hot virgin aggregates. Generally 10% to 15% RAP/RAS is used in a batch plant (Hunter et al. 2000).



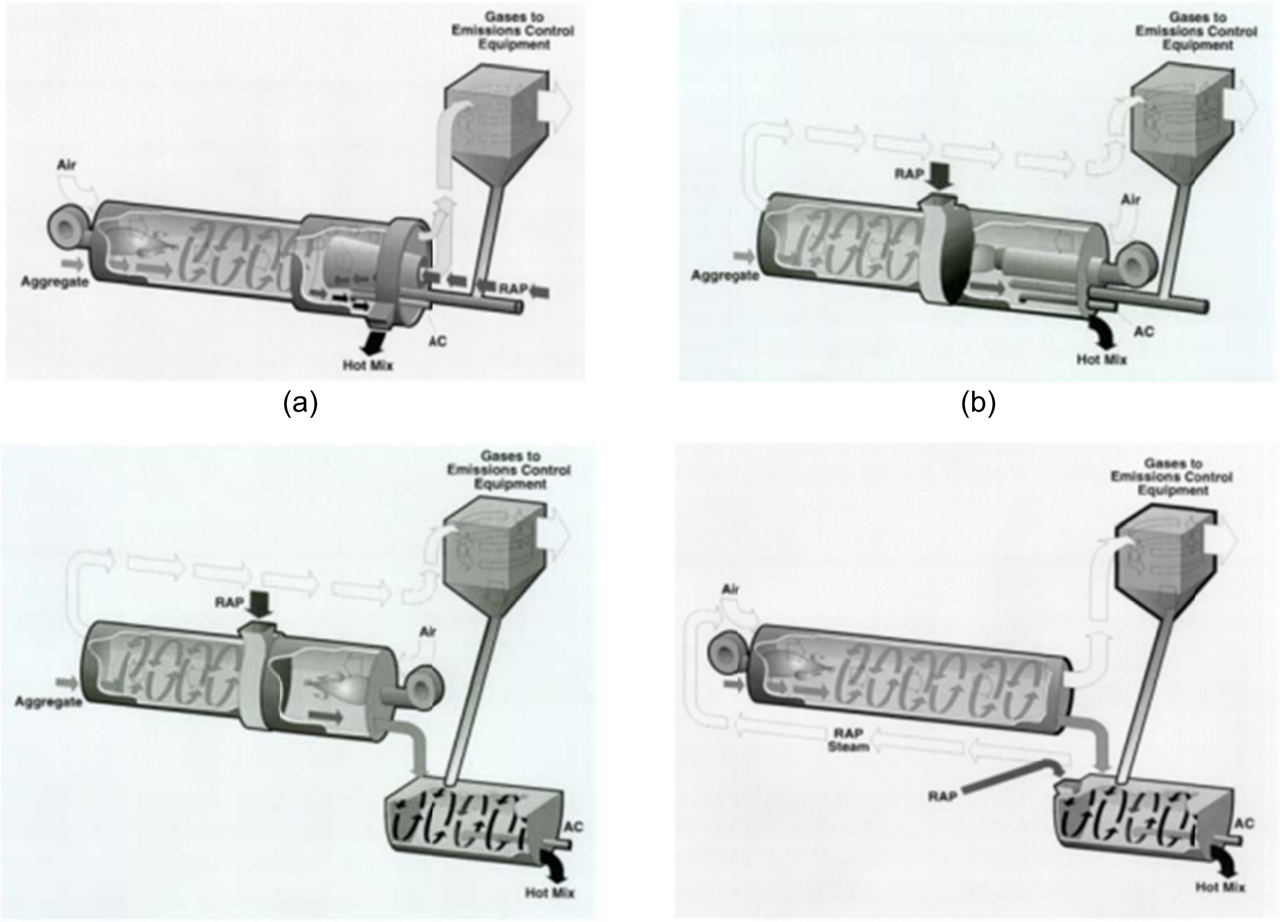
(a) (b)

(c) (d)

Figure 2.13 Options for RAP bins and RAP feeding in a drum plant (Kandhal and Mallick 1997).

2.3.2 Mixing of RAP in Drum Plant

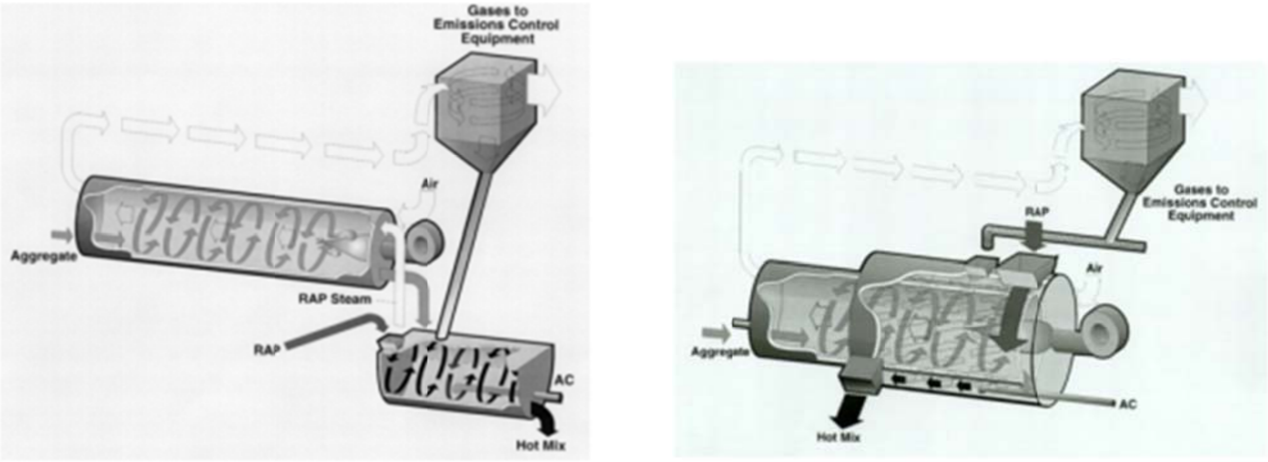
Figure 2.14 shows the options for RAP/RAS entrance and feeding at a drum plant. Figure 2.14(a) shows a parallel-flow drum with a counter-flow arrangement for RAP/RAS feeding. Figure 2.14(b) shows a counter-flow drum with conventional RAP/RAS feeding from the middle of the drum. Figure 2.14(c) shows a counter-flow drum plant with center-fed RAP/RAS (the binder is mixed in a separate drum). Figure 2.14(d) shows a parallel-flow drum; the RAP/RAS and binder is mixed with hot virgin aggregates in a separate drum. Figure 2.14(e) shows a counter-flow drum plant; the RAP/RAS and binder is mixed with hot virgin aggregates in a separate drum. Figure 2.14(f) is the conventional counter-flow double barrel; the RAP/RAS enters via the outer barrel near the burner end.



(a) (b)

(c) (d)

Figure 2.14 continues next page



(e) (f)

Figure 2.14 Options for RAP feeding in a drum plant (Kandhal and Mallick 1997).

Figure 2.15 shows the mixing steps inside the outer drum of the double-barrel drum. RAP/RAS enters via the outer drum, followed by the virgin aggregates that enter inside the outer drum. RAP/RAS is mixed with the virgin aggregates and heat transfer occurs between the aggregates and the RAP. Binder is added in the outer drum after the aggregates are mixed. The fines are then added to the mix.

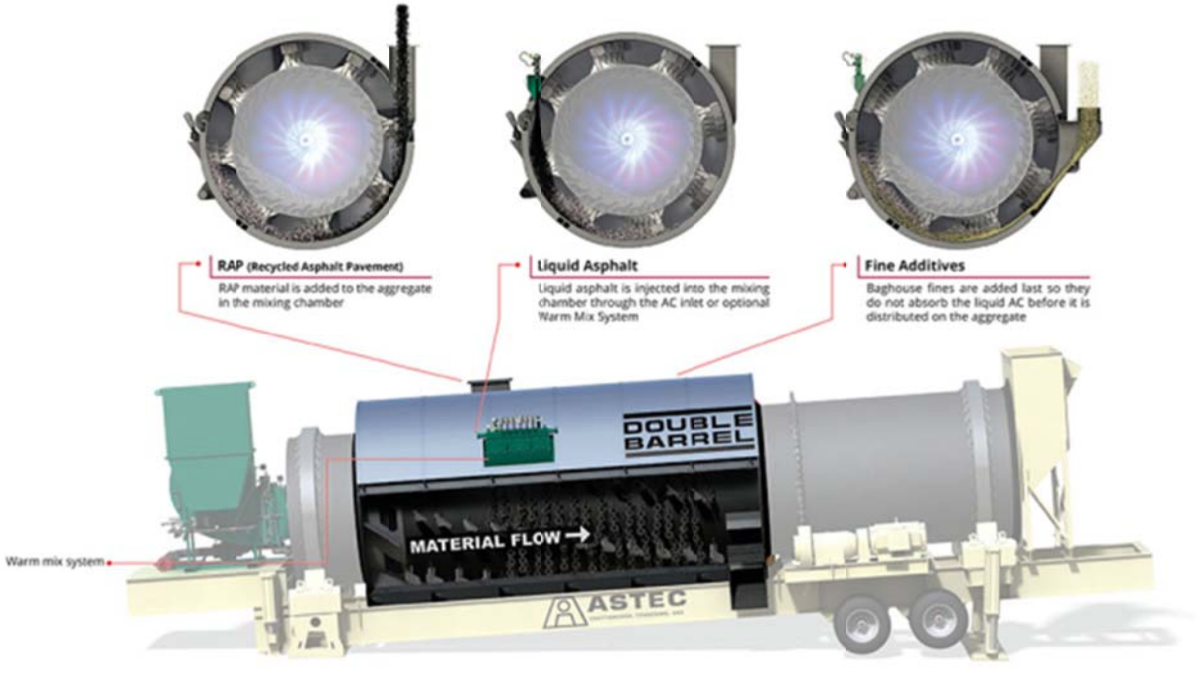


Figure 2.15 Mixing of RAP with virgin aggregates inside the outer drum of a double-barrel drum plant (http://www.astecinc.com/products/drying-mixing/sequential-mixing.html).

2.4 FACTORS AFFECTING HMA PLANT PERFORMANCE

Many factors affect HMA plant performance. Among them are the following:

- size of plant
- moisture content in virgin aggregates and in RAP/RAS
- amount of RAP/RAS in the mix
- HMA mix temperature
- exhaust gas temperature
- baghouse temperature

One study showed that virgin aggregate moisture content and production capacity have the biggest influence on energy consumption (Grabowski and Janowski 2010). Every 1% change in total composite moisture represents a 10% change in fuel requirements. That study found that a 1% increase in moisture per ton of aggregate can result in an additional 0.6 L of fuel being consumed to evaporate it. At 6% moisture, 4 L of fuel are required to dry 1 ton of aggregate. Once the aggregate is dry, heating it to 302°F consumes 3 L of fuel, meaning that more energy is used in drying the aggregate than in heating it (Grabowski and Janowski 2010). For most dryers, the maximum new-aggregate temperature upon discharge should be about 500°F to avoid damaging the dryer (drum warp is a possibility) and to keep from removing internal moisture in the aggregate (*Hot-Mix Asphalt Paving Handbook* 2000).

2.4.1 Effects of Drum Size

Table 2.1 shows the production rate variation in tons per hour (TPH) for a parallel-flow drum plant at various drum diameters and percentages of moisture removal from the aggregates (Brock n.d.). The following analysis assumes 50% excess combustion air in the drum, 10% leakage through RAP/RAS inlet and discharge chute and seals, 110 lb/ft^3 material weight, 4% moisture in RAP, and 5.5% liquid asphalt. CFH stands for cubic feet of gases processed per hour, which is equal to the air intake through the drum. It can be seen that, as expected, the larger the drum diameter, the more hot gas passes through, which provides better drying of the virgin aggregates.

Table 2.1 Parallel-Flow Mixture Production Rates (TPH)

Drum Diameter (ft)	Process Gases Through Drum (CFH)	Percentage of Moisture Removed and Gallons of Fuel per Ton										Total Exhaust Through System (CFH)
		3	4	5	6	7	8	9	10	11	12	
		1.43	1.60	1.80	2.05	2.23	2.45	2.67	2.90	3.14	3.38	
6	28000	253	211	179	153	137	123	111	100	91	83	33600
7	38500	338	285	243	213	187	166	150	137	127	115	46200
8	50000	443	380	317	274	243	216	195	179	164	150	60000
9	63500	564	469	399	348	308	275	248	226	207	190	76200
10	78500	696	574	496	432	380	339	306	280	255	234	94200

Table 2.2 shows the production rate variation in TPH for a counter-flow mixture at various drum diameters and percentages of moisture removal from the aggregates (Brock n.d.). Comparing Table 2.2 with Table 2.1, it can be seen that for any particular drum diameter and percentage of moisture removed, the production rate is higher and the consumption of fuel is lower in the counter-flow drum compared with the parallel-flow drum. The following analysis assumes 50% excess combustion air in drum, 20% leakage through seals, the discharge chute, and tower fugitive air; 110 lb/ft^3 material weight; 4% moisture in RAP; and 5.5% liquid asphalt.

Table 2.2 Counter-Flow Mixture Production Rates (TPH)

Drum Diameter (ft)	Process Gases Through Drum (CFH)	Percentage of Moisture Removed and Gallons of Fuel per Ton										Total Exhaust Through System (CFH)
		3	4	5	6	7	8	9	10	11	12	
		1.37	1.56	1.76	1.95	2.17	2.38	2.50	2.82	3.04	3.27	
6	28000	260	220	187	162	143	129	115	105	97	89	33600
7	38500	355	300	255	223	198	176	159	145	132	123	46200
8	50000	467	390	334	288	257	230	207	188	172	158	60000
9	63500	590	493	423	369	325	291	265	238	219	200	76200
10	78500	730	610	523	465	403	360	325	295	270	299	94200

Table 2.3 shows the production rate variation in TPH for a double-barrel drum mixture at various drum diameters and percentages of moisture removal from the aggregates (Brock n.d.). Comparing Table 2.3 with Tables 2.1 and 2.2, it can be seen that for a particular drum diameter and percentage of moisture removed, the production rate in a double barrel is generally higher and has a lower consumption of fuel. The following analysis assumes 50% excess combustion air in drum, 10% leakage through RAP inlet and discharge chute and seals, 110 lb/ft^3 material weight, 4% moisture, 5.5% liquid asphalt. Comparing all three tables, double-barrel drum is the most efficient in terms of fuel use, moisture removal, and production rate.

Table 2.3 Double-Barrel Drum Mixture Production Rates (TPH)

Drum Diameter (ft)	Process Gases Through Drum (CFH)	Percentage of Moisture Removed and Gallons of Fuel per Ton										Total Exhaust Through System (CFH)
		3	4	5	6	7	8	9	10	11	12	
		1.32	1.51	1.71	1.90	2.10	2.30	2.51	2.72	2.94	3.17	
6	28000	287	239	205	178	157	140	127	115	105	97	33800
7	38500	394	329	281	245	216	193	174	158	145	133	42350
8	50000	512	427	365	318	280	251	226	205	188	173	60000
9	63500	651	542	463	403	356	318	287	261	239	219	69850
10	78500	804	670	573	499	440	393	355	322	295	271	86350

Table 2.4 shows drum capacity for moisture removal considering both drum diameter and length (Kennedy et al. 1986). As expected, as the length of the drum increases, the moisture removal capacity increases as well.

Table 2.4 Nominal Drum Mix Capacities

Drum Diameter and Length (ft)	Capacity (TPH) for Surface Moisture Removed (%)								
	2	3	4	5	6	7	8	9	10
5 × 22	178	142	116	100	84	79	74	63	58
6 × 24	278	220	178	158	137	121	116	100	89
7 × 30	420	336	273	236	205	184	163	147	137
8 × 32	541	430	352	305	263	236	210	194	173
9 × 36	719	578	478	410	357	315	284	257	236
10 × 40	956	761	630	541	473	420	378	341	315

2.4.2 Effect of RAP Moisture and Exit Temperature

Table 2.5 shows the virgin aggregate temperature needed to dry and heat RAP when RAP moisture content varies from 0% to 5% (*Recycling Hot Mix Asphalt Pavements* 1996). The analysis was done for a batch plant. It should be noted that no literature was found on virgin aggregate temperature required related to RAP moisture content in a drum plant. The result assumes a 20°F loss between the dryer and pug mill. The required temperature of the virgin aggregates is dependent on the amount of RAP and its moisture content (*Hot-Mix Asphalt Paving Handbook* 2000). Also, it should be noted that virgin aggregate moisture content and gradation of virgin aggregates were unknown in the analysis shown in Table 2.5. As expected, virgin aggregates become hotter as RAP moisture content increases. In addition, when the RAP percentage increases in the mix, more heat is needed from the virgin aggregates to remove moisture from the RAP.

Table 2.5 Virgin Aggregate Temperatures Required to Dry and Heat RAP in a Batch Plant (*Recycling Hot Mix Asphalt Pavements* 1996)

Reclaimed Material Moisture Content (%)	Recycled Mix Discharge Temperature 220°F	240°F	260°F	280°F
A. Ratio: 10% RAP / 90% Aggregate				
0	250	280	305	325
1	260	290	310	335
2	270	295	315	340
3	280	300	325	345
4	285	305	330	350
5	290	315	335	360
B. Ratio: 20% RAP / 80% Aggregate				
0	280	310	335	360
1	295	320	350	375
2	310	335	360	385
3	325	350	375	400
4	340	365	390	415
5	355	380	405	430
C. Ratio: 30% RAP / 70% Aggregate				
0	315	345	375	405
1	335	365	395	425
2	360	390	420	450
3	385	415	445	475
4	410	440	470	500
5	435	465	495	525
D. Ratio: 40% RAP / 60% Aggregate				
0	355	390	425	460
1	390	425	460	495
2	425	460	495	530
3	470	500	535	570
4	500	535	570	610
5	545	575	610	645
E. Ratio: 50% RAP / 50% Aggregate				
0	410	455	495	540
1	465	515	550	590
2	520	580	605	650
3	575	620	660	705
4	640	680	715	760
5	690	735	775	820

Another study examined similar moisture content variations in RAP at different exit temperatures *(Hot Mix Asphalt Recycling* 2007). That study was conducted in a batch plant and assumed 10°F loss from dryer to pug mill and a 70°F outside air temperature. A similar trend in increased virgin aggregate temperature was observed. However, in the field, the exit temperature can be very high compared with the theoretical value. An IDOT field crew observed that the exit temperature reached more than 400°F. This high exit temperature indicates that the virgin aggregate becomes very hot and might burn the aged binder and the virgin binder, resulting in a low-quality mix.

Table 2.6 Virgin Aggregate Temperature Required to Dry and Heat RAP in a Batch Plant *(Hot Mix Asphalt Recycling* 2007)

		Recycled Mix Discharge Temperature			
	Reclaimed Material Moisture Content (%)	240°F	260°F	280°F	300°F
10%RAP/ 90% Aggregate	0	269	291	313	335
	1	274	296	318	340
	2	279	301	323	345
	3	284	306	328	350
	4	289	311	333	355
	5	294	316	338	360
20% RAP/ 80% Aggregate	0	292	317	342	367
	1	303	328	353	378
	2	314	339	364	389
	3	325	350	375	400
	4	336	361	386	411
	5	347	372	397	422
30% RAP/ 70% Aggregate	0	324	352	330	408
	1	343	371	599	427
	2	362	390	418	446
	3	381	409	437	465
	4	400	428	456	484
	5	419	447	475	503
40% RAP/ 60% Aggregate	0	366	397	430	463
	1	424	426	459	492
	2	453	455	488	521
	3	482	484	517	550
	4	511	513	546	579
	5	540	542	575	608
50% RAP/ 50% Aggregate	0	420	460	500	540
	1	464	504	544	588
	2	508	548	588	628
	3	552	592	632	672
	4	596	636	676	716
	5	640	680	720	760

To reach the desired output temperature of the HMA, the virgin aggregates are often superheated before being mixed with recycled asphalt materials (RAP and RAS) and new asphalt binder. During superheating, the virgin aggregates can reach temperatures between 500°F and 600°F. Although the recycled asphalt materials are not directly exposed to these hot temperatures, it is estimated that 90% of the recycled materials are heated by the virgin aggregates, while the remainder is heated from the hot gases inside the plant (Daniel and Hall 2014)

Table 2.7 shows results from a study by Frederick and Tario (2009) on measurement of virgin aggregate temperature with RAP content varying from 10% to 50%. For extreme case—50% virgin aggregate and 50% RAP mixture—virgin aggregate temperature increased 44°F for each 1% increase in RAP moisture content.

Table 2.7 Effects of RAP Percentage and Moisture Content, and Discharge Temperature of Virgin Aggregate (Frederick and Tario 2009)

RAP (%)	Increase in Aggregate Temperature (°F)		
	For Same Moisture Content and Discharge Temperature	Per 1% Increase Moisture in RAP	Per 20°F Increase in Discharge Temperature
10	29	5	22
20	52	11	25
30	84	19	28
40	156	29	N/A
50	180	44	40

2.4.3 Effects on Baghouse

If the baghouse is subjected to temperatures above 440°F for extended periods of time, the synthetic fiber bags can char, disintegrate, and burn; therefore, the temperature of the exhaust gases entering the baghouse should not exceed 400°F. To prevent this, a temperature sensor and automatic shutdown devices are installed in the ductwork upstream of the baghouse (*Hot-Mix Asphalt Paving Handbook* 2000).

It follows that if the moisture content of virgin aggregates and RAP/RAS is increased, then a higher temperature would be required to remove the moisture, which would cause an increased baghouse temperature. In addition, when the RAP percentage increases and the virgin aggregate percentage decreases inside the drum, the number of veils decreases and most of the hot air exits to the baghouse, causing the aforementioned damage.

2.4.4 Effects on Exhaust Fan

An exhaust fan is used to transfer hot air from the drum to the baghouse. The capacity of the exhaust fan is affected by the moisture content of the virgin aggregates and RAP/RAS materials. Table 2.8 shows the exhaust fan capacity for batch and drum plants (Young 2007). As shown in Table 2.8, a higher-capacity fan is required while moisture content in the aggregate is increased. Also, as expected, the drum mixture is efficient compared with the batch facility when the heat required to remove moisture is considered.

Table 2.8 Effect of Aggregate Moisture on Exhaust Fan and Heat Demand Requirements (Young 2007)

	Batch Facility 255°F at Exhaust Fan 275°F at Dryer Exit		Drum Mixer 290°F at Exhaust Fan 310°F at Drum Exit	
Aggregate Moisture (% Removed)	Heat Required (1000 Btu/t)	Fan Volume Required (Cubic Ft/Min/TPH Dry Aggregate)	Heat Required (1000 Btu/t)	Fan Volume Required (Cubic Ft/Min/TPH of HMA mix)
1	160.0	60.2	154.1	60.6
2	187.9	79.2	181.2	79.7
3	215.8	98.1	208.4	98.8
4	243.7	117.1	235.5	117.9
5	271.6	136.1	262.7	137.0
6	299.5	155.0	289.8	156.0
7	327.4	174.0	317.0	175.1
8	355.3	192.9	344.1	194.2
9	383.2	211.9	371.3	213.3
10	411.1	230.9	398.4	232.4
11	439.1	249.8	425.6	251.5
12	467.0	268.8	452.7	270.6
13	494.9	287.8	479.9	289.7
14	522.8	306.7	507.0	308.8
15	550.7	325.7	534.2	327.9

2.4.5 Effects on Fuel Consumption

Virgin aggregate temperature increases because of an increase in moisture content in the RAP/RAS material. The plant requires more energy to increase the temperature, which leads to higher fuel consumption in the plant. Table 2.9 shows energy use as it relates to an increase in moisture content and mix temperature. In another study, it was shown that a 40°F reduction in exit gas temperatures will result in an approximately 4% reduction in fuel consumption (Young 2007). That study also found that raising the mix temperature 15°F to 20°F above the target design temperature can result in 4% to 5% energy expenditure.

Table 2.9 Fuel Consumption (gal/t) Versus Moisture
at Various Stack Temperatures (Young 2007)

% Moisture	400°F	350°F	300°F	250°F	200°F
0	0.97	0.95	0.93	0.91	0.89
1	1.18	1.15	1.12	1.09	1.06
2	1.38	1.35	1.32	1.29	1.26
3	1.59	1.55	1.51	1.47	1.43
4	1.79	1.75	1.71	1.67	1.63
5	2	1.95	1.9	1.85	1.8
6	2.21	2.16	2.11	2.06	2.01
7	2.43	2.37	2.31	2.25	2.19
8	2.63	2.57	2.51	2.45	2.39
9	2.84	2.77	2.7	2.63	2.57
10	3.04	2.97	2.9	2.83	2.76
11	3.25	3.17	3.09	3.01	2.93
12	3.45	3.37	3.29	3.21	3.13

2.5 SUMMARY

Drum plants are preferred by HMA producers and contractors for large paving projects because it is efficient in removing moisture from virgin aggregates, RAP, and RAS, and the continuous production provides efficient and faster paving construction.

The temperature required to dry virgin aggregate and RAP/RAS material in a drum plant has not been studied. For batch plants, however, two studies determined the virgin aggregate temperature required to dry and heat RAP to remove moisture (*Recycling Hot Mix Asphalt Pavements* 1996; *Hot Mix Asphalt Recycling* 2007). However, these studies did not consider the moisture in virgin aggregates or the size of virgin aggregates and RAP/RAS. Moreover, it is not known whether that study considered thermal properties of virgin aggregates and RAP/RAS materials. However, the batch plant study did show that virgin aggregates become superheated when the RAP percentage increases to more than 40% and RAP moisture content increases to a range between 4% and 5%. No studies have been done on drying RAS in conjunction with virgin aggregates and RAP. Also, it is not known how superheated virgin aggregate damages the aged binder coating of RAP/RAS and virgin binder.

Now is an ideal time to study the energy consumption and heat required to dry RAP and RAS in a drum plant because the use of RAP and RAS in paving projects is increasing and drum plants are becoming more popular among paving contractors. In addition, fuel costs are increasing, which means HMA mixing costs will increase as well if virgin aggregates must be superheated to dry RAP and RAS.

CHAPTER 3: THERMODYNAMICS AND HEAT TRANSFER PRINCIPLES

3.1 INTRODUCTION

This chapter discusses the laws of thermodynamics and heat transfer principles in materials. Only a drum plant was considered for heating virgin aggregates because use of batch plants has become limited. In addition, for a batch plant, the heat required in virgin aggregates to dry RAP has been determined in previous studies (*Recycling Hot Mix Asphalt Pavements* 1996). However, very limited study has been done on thermodynamics and heat transfer in drum plants, and those studies does not consider the moisture content of virgin aggregates or the physical and thermal properties of virgin aggregates, RAP, and RAS. Thermodynamics principles were used in the current study to predict virgin aggregate temperature in a drum plant.

3.2 HEAT TRANSFER ZONES IN A DRUM PLANT

Figure 2.1 shows typical heat transfer zones in a parallel-flow drum plant. The heat transfer between the gaseous and granular phases and the wall of the baffled-rotary kiln can take place by convection, conduction, and radiation (Lauredan et al. 2014). The temperature is highest in the combustion zone because it is closest to the burner. In that zone, the aggregates are pre-heated while they are broken off from a mass of aggregates. The virgin aggregates receive the most heat in the thermal transfer zone. Veils are produced in thermal transfer zone by notched flights. In the thermal transfer zone, convective heat transfer is more predominant than conductive heat transfer.

Before moving to the coating zone, the virgin aggregates transfer heat to the RAP materials by conduction. However, convection also occurs in RAP as a result of hot air. In the coating zone, hot binder is mixed with virgin aggregates and RAP; conductive heat transfer primarily occurs in that zone. It should be noted that radiation heat transfer takes place in all zones. In the final heat transfer zone, the partial equilibrium of heat transfer occurs between aggregates, RAP/RAS, and binder. It is anticipated that complete heat transfer occurs between materials in the storage silo or at the pavement construction site.

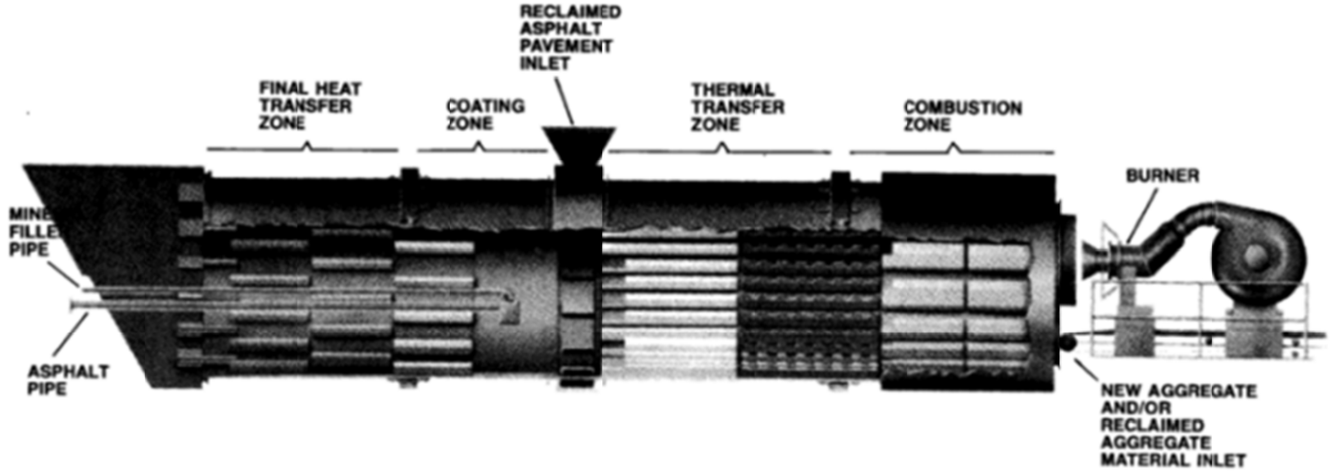


Figure 3.1 Heat transfer zones inside a parallel-flow drum plant (Kennedy et al. 1986).

3.3 PREVIOUS STUDIES ON DETERMINING ENERGY AND TEMPERATURE IN A DRUM PLANT

3.3.1 Empirical Approach

A study was conducted to determine the temperature required in a drum plant (Frederick and Tario 2009). The equation is as follows:

$$\Delta\mathrm{T}_{agg} = (-0.0516 + 0.0143P_{moi} + 0.00034T_{dis})P_{RAP}{}^{2} + (2.1954 + 0.1023P_{moi} + 0.00177T_{dis})P_{RAP} + 2.8P_{moi} + 1.0635T_{dis} - 254.124$$

where $\Delta\mathrm{T}_{agg}$ is the increase in temperature of virgin aggregates caused by RAP (°F), P_{moi} is the moisture content (%), T_{dis} is the discharge temperature (°F), and P_{RAP} is the RAP content (%). Total energy to heat aggregates with moisture can be determined as follows:

$$\Delta\mathrm{H}_{agg} = \frac{M_{Agg}P_{moi}(212 - T_{amb})C_{water}}{100} + \frac{M_{Agg}P_{moi}LH}{100} + \frac{M_{agg}P_{moi}(T_{dis} - 212)C_{vap}}{100} + M_{agg}(T_{dis} - T_{amb})C_{agg}$$

where M_{Agg} is the mass of aggregate (lb), P_{moi} is the moisture content (%), T_{amb} is the ambient temperature (°F), C_{water} is the specific heat of water (1.0 Btu/lb/°F), LH is latent heat to evaporate water (970 Btu/lb), C_{vap} is the specific heat of vapor (0.5 Btu/lb/°F), and C_{agg} is the specific heat of aggregate (0.22 Btu/lb/°F). It should be noted that the above equations do not consider the physical properties of the materials, such as size and shape of aggregates.

3.3.2 Field Measurement

Le Guen et al. (2013) conducted a study in which they placed a temperature probe inside a parallel-flow drum and measured the temperature. The research was solely to analyze convective heat transfer in aggregates. The study did not include RAP or RAS in the drum. The researchers measured gas temperature (T_g) with seven temperature probes on a rod placed along the longitudinal axis of the drum in order to measure gas temperature. Figure 3.2 shows the location of temperature probes inside a drum.

In that study, the temperature of the aggregate mix leaving the drum was measured using a pyrometer. Fuel use was recorded electronically over a wireless connection every half hour. The temperature sensors were protected against granular flow by means of a steel semi-shell; to avoid heat transfer conduction, the sensors were insulated from the support. Because the temperature ranged from 400°K to 1500°K, K-thermocouples were used. The aggregate temperature (T_a) was measured by four inner-wall probes inserted in the drum during a pause in the manufacturing process. Two flaps were machined in order to capture several samples of aggregates so that their temperature and humidity could be measured.

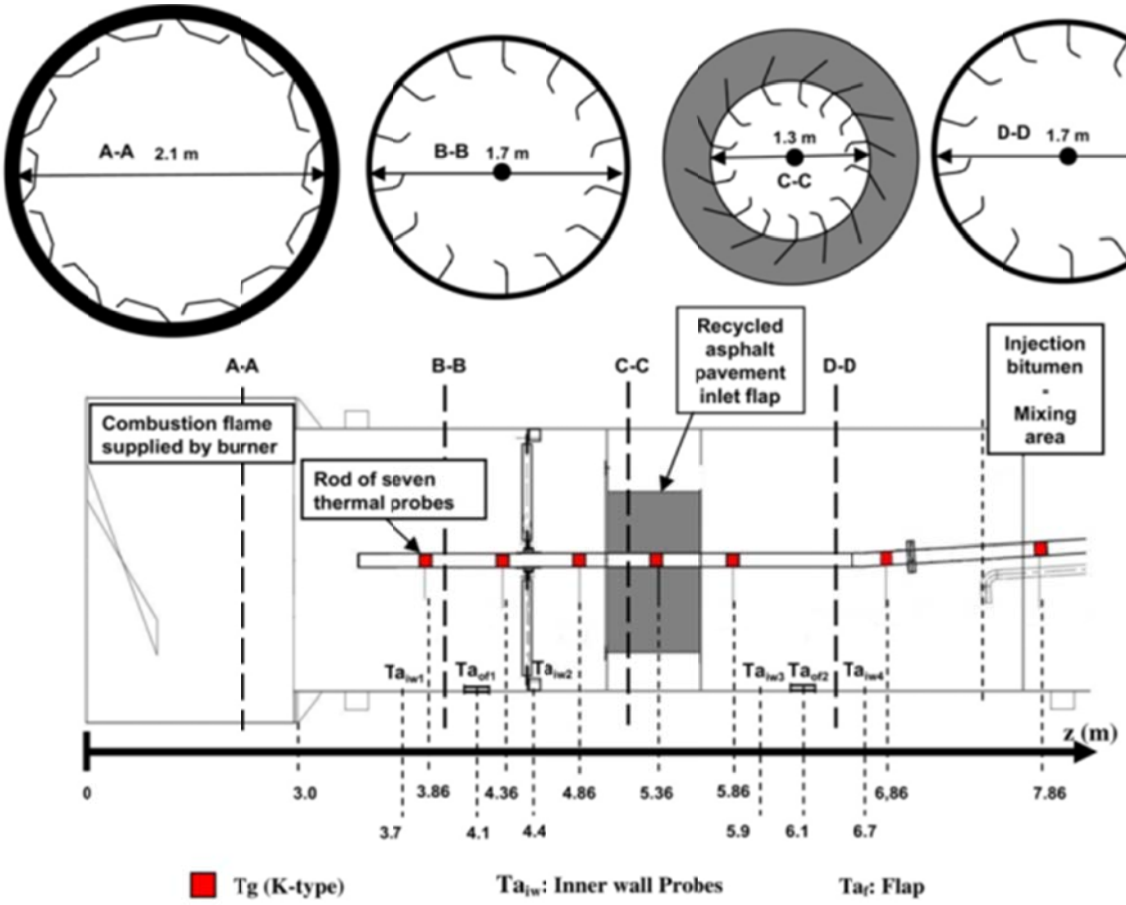


Figure 3.2 Location of heat-measuring probes inside the drum (Le Guen et al. 2013).

3.3.3 Numerical Analysis

Another study used computational fluid dynamics (CFD) and discrete element method (DEM) modeling to predict virgin aggregate temperature inside a drum (Hobbs 2009). That study, until now, was the only advanced numerical analysis available on this subject, other than industry research. However, only virgin aggregates were used in that simulation, and the temperature predicted was considerably high because evaporation was not analyzed. Figure 3.3 illustrates the approach used in the Hobbes (2009) simulation. The figure shows the veils inside a drum and heat flow from the burner toward the exit.

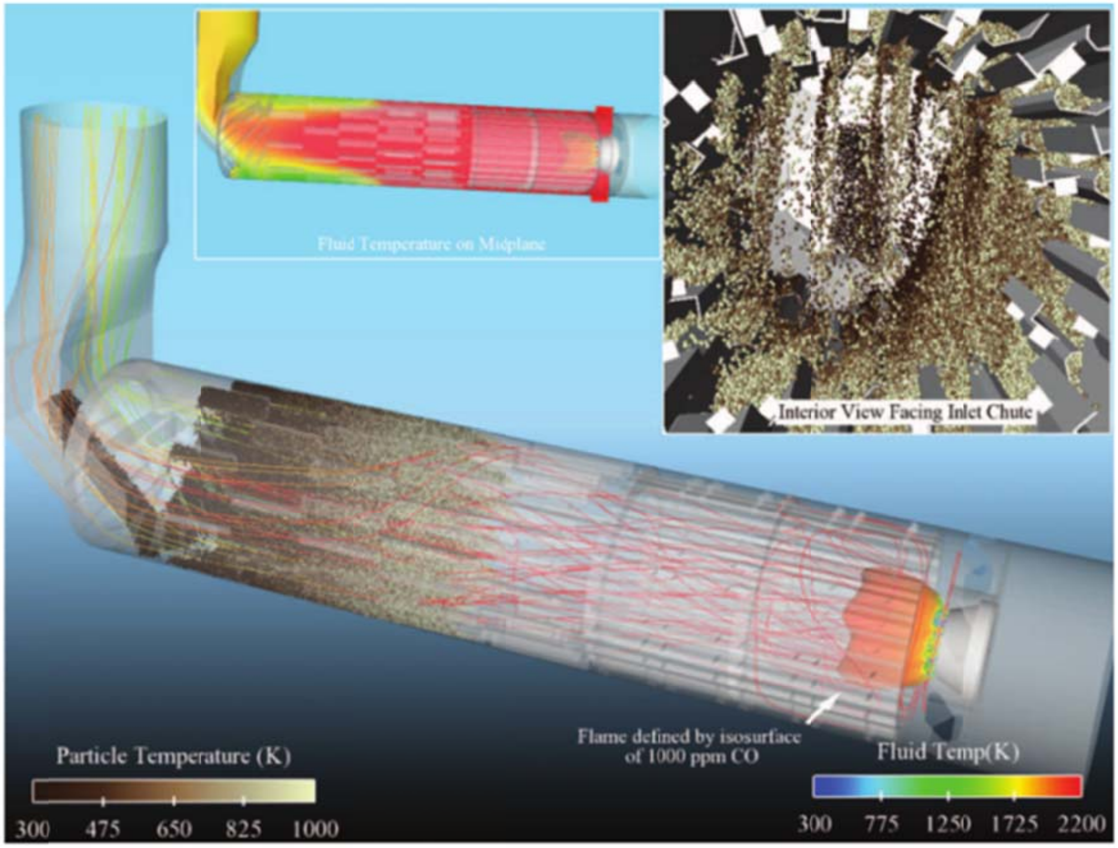


Figure 3.3 A CFD and DEM approach to determine virgin aggregate temperature inside a drum (Hobbs 2009).

3.4 THERMODYNAMIC EQUATIONS

3.4.1 Conduction

Conduction is the transfer of energy or heat from an energetic solid surface to a less energetic solid surface. In the current study, the energetic solid is virgin aggregate and the less energetic solid is RAP/RAS. Virgin aggregates and RAP/RAS are heated by direct contact of aggregate-to-aggregate and aggregate to drum wall. The equation is as follows:

$$Q_{cond} = \frac{kA(T_{hot} - T_{cold})t}{d}$$

where Q_{cond} is the energy required for conduction, k is the thermal conductivity of the material, A is the cross-sectional area, T_{hot} is the higher temperature, T_{cold} is the cooler temperature, t is the heat transfer time, and d is the thickness of the material.

3.4.2 Convection

Convection is the transfer of energy or heat between a solid and the adjacent fluid in motion. In the current study, heat transfer occurred between virgin aggregates and RAP, and in the air inside the drum—primarily the virgin aggregate with air. The equation is as follows:

$$Q_{conv} = H_c A(T_{hot} - T_{cold})$$

where Q_{conv} is the energy required for convection, H_c is the heat transfer coefficient, A is the cross-sectional area, T_{hot} is the higher temperature, and T_{cold} is the cooler temperature.

3.4.3 Radiation

Radiation is the transfer of energy or heat by electromagnetic waves. In the current study, the burner flame causes radiation inside the drum. The equation is as follows:

$$Q_{rad} = \sigma A({T^4}_{hot} - {T^4}_{cold})$$

where Q_{rad} is the energy required for radiation, σ is the Stefan–Boltzmann constant (0.119E-10 Btu/hr/in^2 /°R^4 or 1.712E-9 BRU/hr/ft^2/°F^4), A is the cross-sectional area, T_{hot} is the higher temperature, and T_{cold} is the cooler temperature.

3.5 SUMMARY

Previous research predicted virgin aggregate temperature using empirical equations and numerical analysis. In addition, one attempt has been made to install temperature probes inside a drum to measure virgin aggregate temperature. However, physical parameters of the materials were not considered in the empirical equations, although RAP was not included in the previous analysis. Numerical analysis and field temperature measurement has included thermodynamic principles but did not include RAP.

Thermodynamic equations can be used to predict virgin aggregate temperature given the moisture content of virgin aggregates and recycled materials, incorporating physical and thermal properties of the materials.

CHAPTER 4: DETERMINING VIRGIN AGGREGATE TEMPERATURE

4.1 INTRODUCTION

This chapter provides step-by-step calculations for predicting virgin aggregate temperatures required for drying and heating RAP. Two analyses are presented: one based on values found in the literature for a batch plant and another by applying thermodynamics and heat transfer principles for a drum plant.

The publication *Recycling Hot Mix Asphalt Pavements* (1996) provides the virgin aggregate temperatures required to heat and dry RAP materials containing different moisture percentages. However, the moisture content of RAP varied from 1% to 5%. In addition, the exit temperatures addressed in the literature were limited to 280°F or 300°F.

IDOT has observed higher moisture content in RAP and RAS materials and wanted to determine the virgin aggregate temperature required to remove moisture from RAP. The following analysis addressed RAP only.

4.2 BATCH PLANT

In this exercise, the literature value given for a batch plant was taken as the base value. The data shown in Table 2.5 were used as a base value to predict virgin aggregate temperature for RAP moisture content ranging from 1% to 20% and exit temperatures ranging from 220°F to 400°F.

As a first step, the data shown in Table 2.5 were plotted in MATLAB, and then an equation was used to optimize the data. Five equations were established for five combinations of RAP and virgin aggregates. These equations are given below.

For 10% RAP and 90% virgin aggregates,

$$Virgin\ Aggregate\ Temperature\ (°\mathrm{F}) = -16.07 + 1.229x + 13.43y - 0.02643xy$$

For 20% RAP and 80% virgin aggregates,

$$Virgin\ Aggregate\ Temperature\ (°\mathrm{F}) = -11.43 + 1.327x + 19.07y - 0.01929xy$$

For 30% RAP and 70% virgin aggregates,

$$Virgin\ Aggregate\ Temperature\ (°\mathrm{F}) = -17.38 + 1.5x + 24.29y + (1.841e - 08)xy$$

For 40% RAP and 60% virgin aggregates,

$$Virgin\ Aggregate\ Temperature\ (°\mathrm{F}) = -32.74 + 1.754x + 38.93y - 0.006429xy$$

For 50% RAP and 50% virgin aggregates,

$$Virgin\ Aggregate\ Temperature\ (°\mathrm{F}) = -50.83 + 2.102x + 57y - 0.004286xy$$

In each equation, *x* is the RAP moisture content and *y* is the exit temperature.

After the equations were developed for each combination of RAP and virgin aggregates, virgin aggregate temperatures were determined for RAP with moisture content ranging from 0% to 20% (x-axis) and exit temperature from 220°F to 400°F (y-axis). The results are given in Figures 4.1 through 4.5. Descriptions are provided for only the highest RAP moisture content or when considering the worst-case scenario.

As shown in Figure 4.1, for 90% virgin aggregates and 10% RAP with 10% moisture content in the RAP and at an exit temperature of 400°F, the virgin aggregate temperature must reach 504°F to dry and heat the RAP. For 20% moisture content in the virgin aggregates and at an exit temperature of 400°F, the virgin aggregate temperature must reach 532°F to dry and heat the RAP.

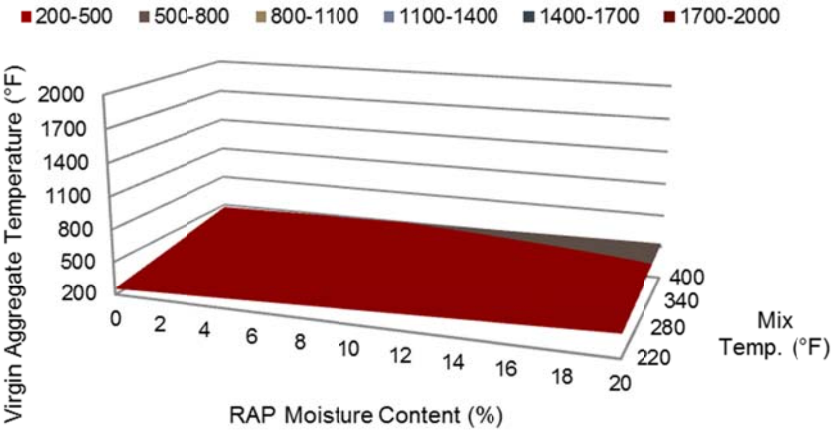


Figure 4.1 Virgin aggregate temperature required for
HMA mix containing 90% virgin aggregates with 10% RAP.

As shown in Figure 4.2, for 80% virgin aggregates and 20% RAP with 10% moisture content in the RAP and at exit temperature of 400°F, the virgin aggregate temperature must reach 632°F to dry and heat the RAP. For 20% moisture content in the virgin aggregates and at an exit temperature of 400°F, the virgin aggregate temperature needs to rise up to 747°F to dry and heat the RAP.

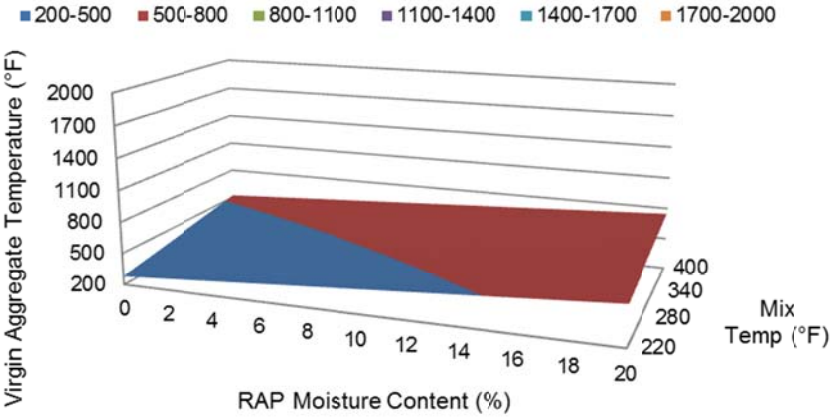


Figure 4.2 Virgin aggregate temperature required for
HMA mix containing 80% virgin aggregates with 20% RAP.

As shown in Figure 4.3, for 70% virgin aggregates and 30% RAP with 10% moisture content in the RAP and at an exit temperature of 400°F, the virgin aggregate temperature must reach 826°F to dry and heat the RAP. For 20% moisture content in the virgin aggregates and at an exit temperature of 400°F, the virgin aggregate temperature must reach 1068°F to dry and heat the RAP.

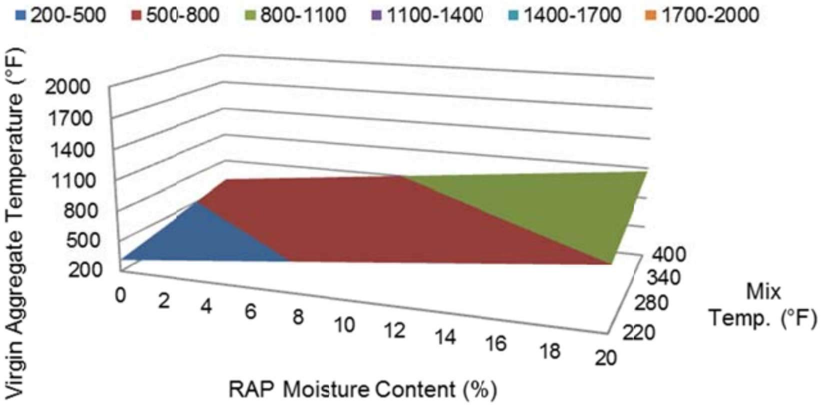


Figure 4.3 Virgin aggregate temperature required for HMA mix containing 70% virgin aggregates with 30% RAP.

As shown in Figure 4.4, for 60% virgin aggregates and 40% RAP with 10% moisture content in the RAP and at an exit temperature of 400°F, the virgin aggregate temperature must reach 1032°F to dry and heat the RAP. For 20% moisture content in the virgin aggregates and at an exit temperature of 400°F, the virgin aggregate temperature must reach 1396°F to dry and heat the RAP.

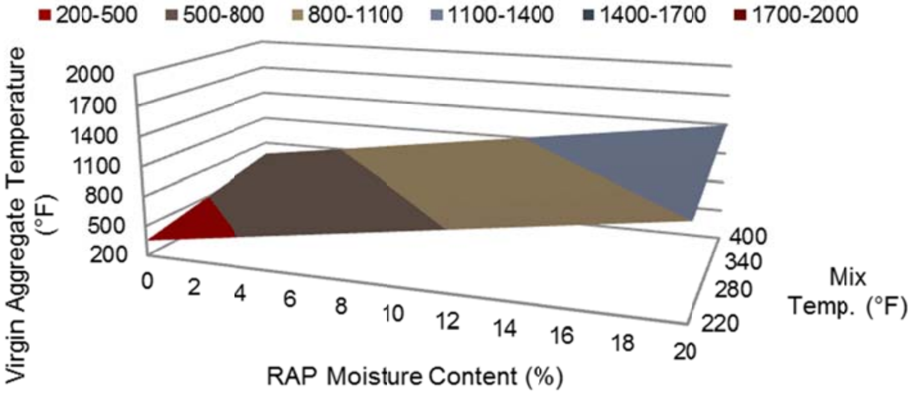


Figure 4.4 Virgin aggregate temperature required for HMA mix containing 60% virgin aggregates with 40% RAP.

As shown in Figure 4.5, for 50% virgin aggregates and 50% RAP with 10% moisture content in the RAP and at an exit temperature of 400°F, the virgin aggregate temperature must reach 1343°F to dry and heat the RAP. For 20% moisture content in the virgin aggregates and at an exit temperature of 400°F, the virgin aggregate temperature must reach 1896°F to dry and heat the RAP.

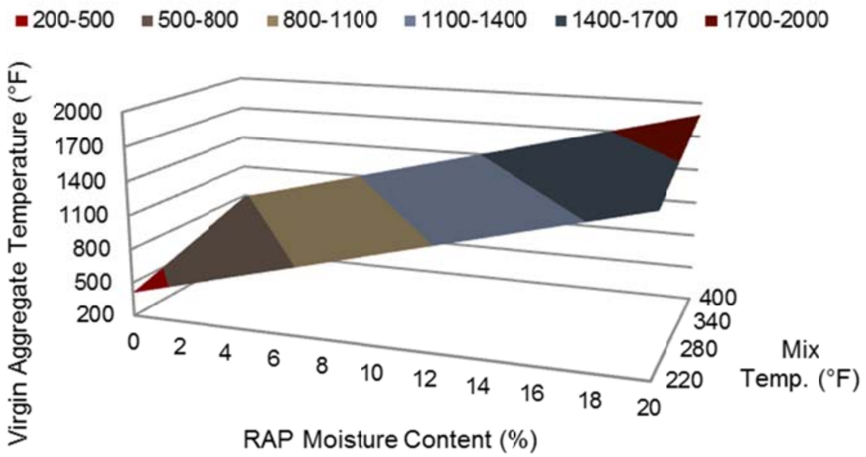


Figure 4.5 Virgin aggregate temperature required for
HMA mix containing 50% virgin aggregates with 50% RAP.

In all scenarios, virgin aggregates become superheated as moisture contents in the RAP and the exit temperatures increase. However, this analysis did not consider moisture in the virgin aggregates. Additional heat is required to dry and heat virgin aggregates. No information was found in the literature for physical and thermal properties of virgin aggregates and RAP.

4.3 DRUM PLANT

The following analysis for a drum plant is done using thermodynamics and heat transfer principles. The heat transfer and energy required to prepare a mix is calculated in three steps: step 1 is the energy required for heating and drying virgin aggregates; step 2 is the energy required for heating and drying RAP/RAS; and step 3 is the heat transfer during the mixing of hot virgin aggregates, hot RAP/RAS, and hot binder.

The exit temperature represents partial equilibrium of heat transfer among virgin aggregates, RAP/RAS, and binder. The final temperature equilibrium is achieved inside the silo.

4.3.1 Energy Required to Remove Moisture from Virgin Aggregates

The energy required to remove moisture from virgin aggregates (Q_1) is determined in two steps: step 1 is the energy required to increase temperature from the ambient condition to 212°F ($Q_{1\text{-}1}$), and step 2 is the energy required to evaporate water at 212°F ($Q_{1\text{-}2}$).

$$Q_{1-1} = Mass\ of\ Water \times Specific\ Heat\ of\ Water \times (T_1 - T_0)$$

where the specific heat of water is equal to 4.186 kJ/kg/°C, T_1 is 212°F, and T_0 is the ambient or atmospheric temperature.

$$Q_{1-2} = Mass\ of\ Water \times Heat\ of\ Vaporization$$

where the heat of vaporization is equal to 2260000 J/kg.

4.3.2 Energy Required to Remove Moisture from RAP/RAS

Energy required to remove moisture from RAP/RAS (Q_2) is determined in two steps: step 1 is the energy required to increase temperature from the ambient condition to 212°F ($Q_{2\text{-}1}$), and step 2 is the energy required to evaporate water at 212°F ($Q_{2\text{-}2}$).

$$Q_{2-1} = Mass\ of\ Water \times Specific\ Heat\ of\ Water \times (T_1 - T_0)$$

where the specific heat of water is equal to 4.186 kJ/kg/°C, T_1 is 212°F, and T_0 is the ambient or atmospheric temperature.

$$Q_{2-2} = Mass\ of\ Water \times Heat\ of\ Vaporization$$

where the heat of vaporization is equal to 2260000 J/kg.

4.3.3 Energy Required to Achieve Exit Temperature

Calculating the energy required to achieve the exit temperature (Q_3) is performed in two steps. Step 1 is the energy required for additional heating of virgin aggregates to achieve the exit temperature after partial equilibrium of heat transfer ($Q_{3\text{-}1}$). If the virgin aggregate temperature is higher than the binder and mixing temperatures, then the virgin aggregates transfer heat to the binder, and partial equilibrium of the exit temperature is achieved. If the virgin aggregate temperature is lower than the binder and mixing temperatures then additional energy is required for heating the virgin aggregates to achieve the mixing temperature ($Q_{3\text{-}2}$). (Heat loss is not considered in this analysis because heat loss varies from one plant from another. However, a significant amount of heat loss could take place inside the drum.)

For example, after the virgin aggregates have been dried and heated, if their temperature (250°F) is lower than the binder temperature (280°F) and mix temperature (350°F), then additional heat (energy) is provided by the virgin aggregates to achieve the mix temperature. In that case, the mix temperature can be controlled and easily maintained. On the other hand, after the virgin aggregates have been dried and heated, if their temperature (500°F) is higher than the binder temperature (280°F) and mix temperature (350°F), then no additional heat (energy) is provided by the virgin aggregates to achieve the mix temperature. In that case, the mix temperature is difficult to control and the HMA mix might become overheated.

RAP/RAS are at ambient temperature. Binder is supplied in the drum at a specific temperature, which depends on the type of PG grade binder. Only the virgin aggregates are heated to achieve the exit temperature. Virgin aggregate temperature increases or decreases depending on the state of the materials and the physical properties of the drum. Q_1, Q_2, and Q_3 are delivered in the virgin aggregates by means of heat transfer (conduction, convection, and radiation) from the burner.

For the following examples, Q_3 is not determined— it is theorized that heat transfer and temperature equilibrium are more complex in the outer drum because binder temperature is involved. However, future studies can incorporate Q_3 in this analysis.

4.3.4 Example of Determining Virgin Aggregate Drying and Heating Temperature

The average temperature to dry and heat virgin aggregate is determined by using thermodynamic heat transfer equations. Only one size of coarse aggregate and RAP is considered in the example. The limitations of this analysis are that (1) no energy loss is considered, and (2) a simplified heat distribution in the virgin aggregates by means of conduction, convection, and radiation is assumed.

Numerical simulations such as computational fluid dynamics (CFD) and discrete element method (DEM) modeling can be used to create a more detailed calculation of heat distribution. Numerical modeling is out of the scope for the current project, but it is recommended for future studies.

4.3.4.1 Analysis Step One

A total of 100 tons of aggregate is used for the analysis. Different proportions of virgin aggregates (90% to 50%) and RAP (10% to 50%) are considered. Likewise, different percentages of moisture content in virgin aggregates (1% to 5%) and RAP (1% to 5%) are considered.

4.3.4.2 Analysis Step Two

$Q_{1\text{-}1}$ and $Q_{1\text{-}2}$ are calculated for virgin aggregates, and $Q_{2\text{-}1}$ and $Q_{2\text{-}2}$ are calculated for RAP using the equations previously shown.

4.3.4.3 Analysis Step Three

Physical properties of the drum were obtained from the available literature: rotational speed of the drum at 7 rpm, drum radius at 5 ft (1.52 m), drum length at 20 ft (6.1 m), and drying and heating time for virgin aggregates at 30 sec.

4.3.4.4 Analysis Step Four

The percentages of conduction, convection, and radiation are calculated as follows:

“One virgin aggregate” is defined as rotating on the drum wall as well as being in contact with neighboring aggregates, climbing on the flight (conduction), traveling half the perimeter of the drum, and then dropping freely (convection) while it reaches at the top of the drum. The amount of time the “one virgin aggregate” is in contact with the drum wall, as well as with the other aggregates (time of conduction) and the time required to free fall (time of convection) when it reaches the top of the drum are calculated from the drum dimension.

It is assumed that “time of radiation” is 5% of the total time; the remaining 95% is “time of conduction” and “time of convection.” Those three times are considered the percentage contribution of heat transfer in virgin aggregates.

It should be noted that a previous study found that 90% of the recycled materials were heated by the virgin aggregates (conduction) and 10% heated from the hot gases (convection) inside the plant (Daniel and Hall n.d.). However, there was no mention of the percentage of radiation in the drum or of the amount of conduction, convention, and radiation for drying and heating the virgin aggregates only.

4.3.4.5 Analysis Step Five

Determine heat transfer coefficient (H_C) for the convective heat transfer equation:

$$H_c = \frac{k \times Nu}{d}$$

where k is the thermal conductivity (Btu/hr/ft^2/°F), and d is the diameter of the aggregates. In this example, k is 2.808 (for silica) and d is 0.5 in. (assumed the same size for virgin aggregate and RAP). Nu is the Nusselt number (no unit) and can be determined using the following equation:

$$Nu = 2 + (4.5 \times 10^{-5} \alpha^{n} Re^{1.8})$$

where α is the thermal diffusivity [k/(density * specific heat); the density of silica is considered 2.648 (gm/cm^3) and the specific heat of silica is 0.5649 Btu/lb/°F], n is 3.5 (generally experimentally determined), and Re is the Reynolds number (1500 is assumed for turbulence flow).

4.3.4.6 Analysis Step Six

Per step 4, 83% conduction, 12% convection, and 5% radiation is calculated. Spherical aggregate shape is considered. The mass of virgin aggregates is determined from the density of virgin aggregates, and total number of virgin aggregates is calculated. Finally, T_{hot} for conduction, convection, and radiation are calculated separately and an average is used.

4.3.4.7 Results for 0.5 in. Nominal Maximum Aggregate Size (NMAS)

Results for one sample are shown in Table 4; other results are shown in subsequent figures.

Table 4.1 Results for One Sample Mix of 90% Virgin Aggregates and 10% RAP

Virgin Aggregate (%)	RAP (%)	Virgin Aggregate Moisture (%)	RAP Moisture (%)	T_{hot} Conduction (°F)	T_{hot} Convection (°F)	T_{hot} Radiation (°F)	T_{hot} Average (°F)
90	10	1	1	116	325	580	340
			2	121	351	594	356
			3	127	378	607	371
			4	133	404	620	386
			5	138	431	631	400

As shown in Figure 4.6, for 90% virgin aggregates and 10% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 400°F to remove moisture from both the virgin aggregates and the RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 524°F; for 3% moisture content in the virgin aggregates, the temperature is 641°F; for 4% moisture content in the virgin aggregates, the temperature is 754°F; and for 5% moisture content in the virgin aggregates, the temperature is 864°F.

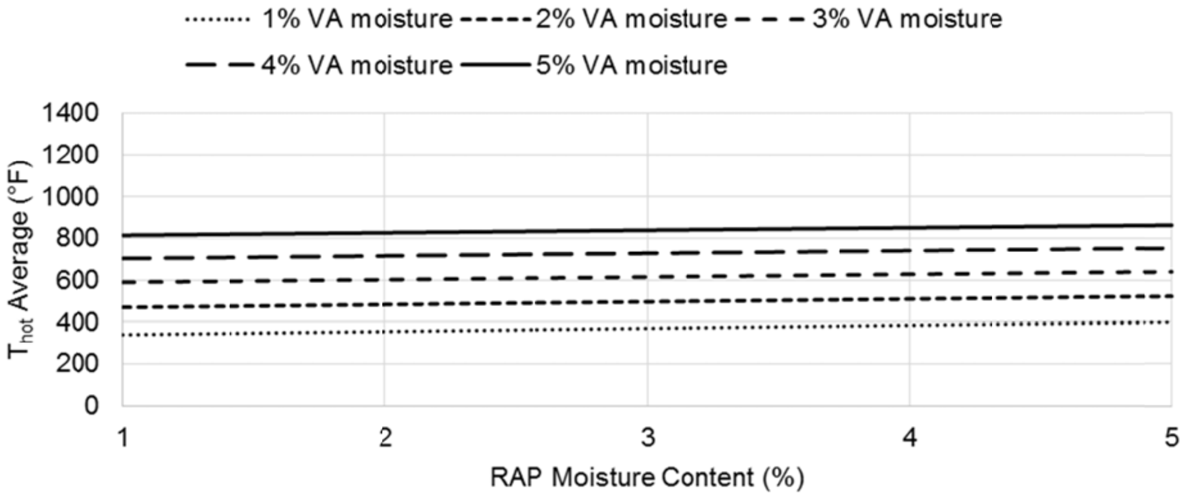


Figure 4.6 Virgin aggregate temperature required for the
HMA mix containing 90% virgin aggregates with 10% RAP (0.5 in. NMAS).

As shown in Figure 4.7, for 80% virgin aggregates and 20% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 487°F to remove moisture from both the virgin aggregates and the RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 606°F; for 3% moisture content in the virgin aggregates, the temperature is 719°F; for 4% moisture content in the virgin aggregates, the temperature is 830°F; and for 5% moisture content in the virgin aggregates, the temperature is 939°F.

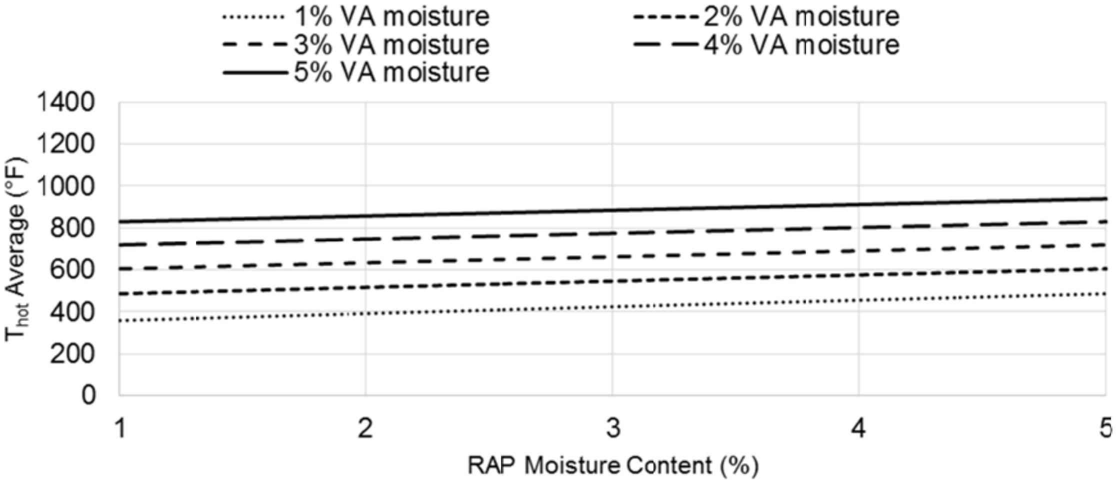


Figure 4.7 Virgin aggregate temperature required for the
HMA mix containing 80% virgin aggregates with 20% RAP (0.5 in. NMAS).

As shown in Figure 4.8, for 70% virgin aggregates and 30% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 593°F to remove moisture from both the virgin aggregates and the RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 707°F; for 3% moisture content in the virgin aggregates, the temperature is 819°F; for 4% moisture content in the virgin aggregates, the temperature is 928°F; and for 5% moisture content in the virgin aggregates, the temperature is 1035°F.

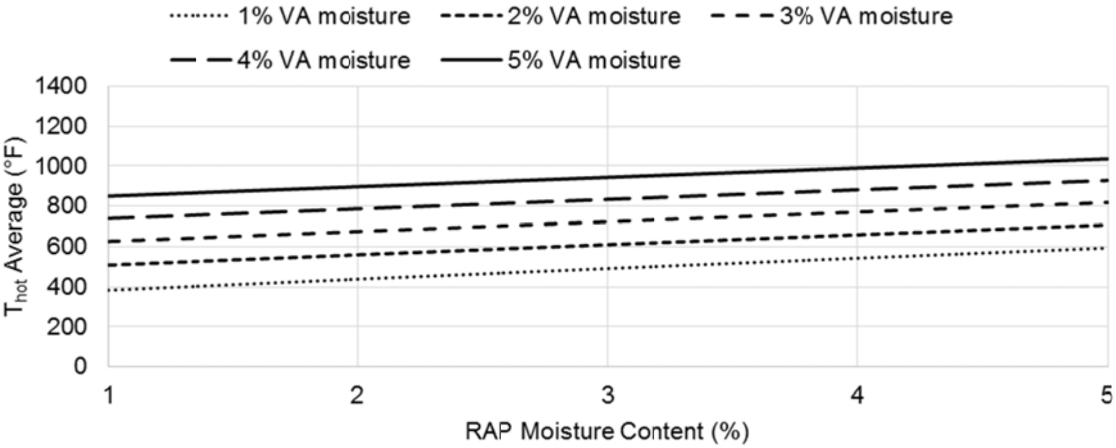


Figure 4.8 Virgin aggregate temperature required for the
HMA mix containing 70% virgin aggregates with 30% RAP (0.5 in. NMAS).

As shown in Figure 4.9, for 60% virgin aggregates and 40% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 729°F to remove moisture from both the virgin aggregates and the RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 840°F; for 3% moisture content in the virgin aggregates, the temperature is 948°F; for 4% moisture content in the virgin aggregates, the temperature is 1056°F; and for 5% moisture content in the virgin aggregates, the temperature is 1162°F.

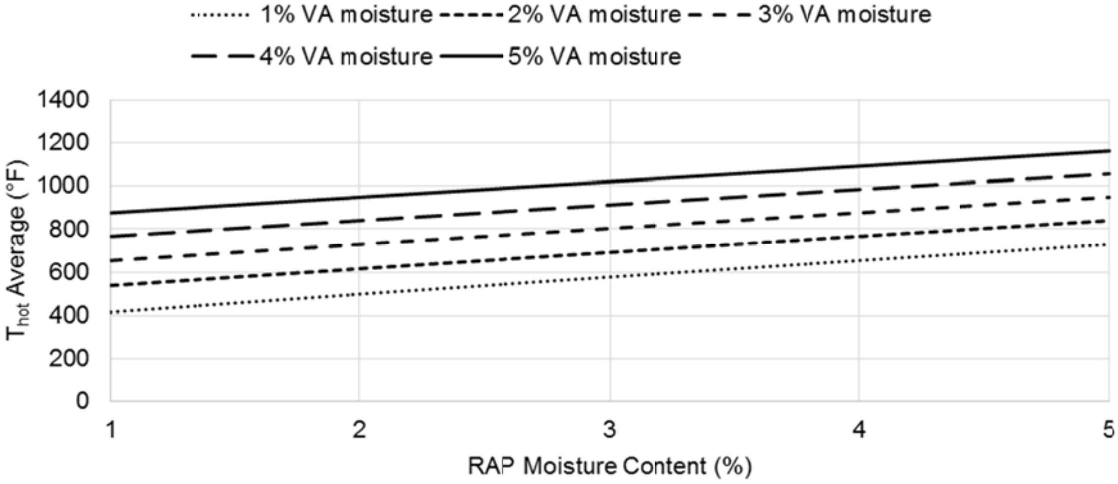


Figure 4.9 Virgin aggregate temperature required for the
HMA mix containing 60% virgin aggregates with 40% RAP (0.5 in. NMAS).

As shown in Figure 4.10, for 50% virgin aggregates and 50% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 912°F to remove moisture from both the virgin aggregates and the RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 1020°F; for 3% moisture content in the virgin aggregates, the temperature is 1127°F; for 4% moisture content in the virgin aggregates, the temperature is 1232°F; and for 5% moisture content in the virgin aggregates, the temperature is 1337°F.

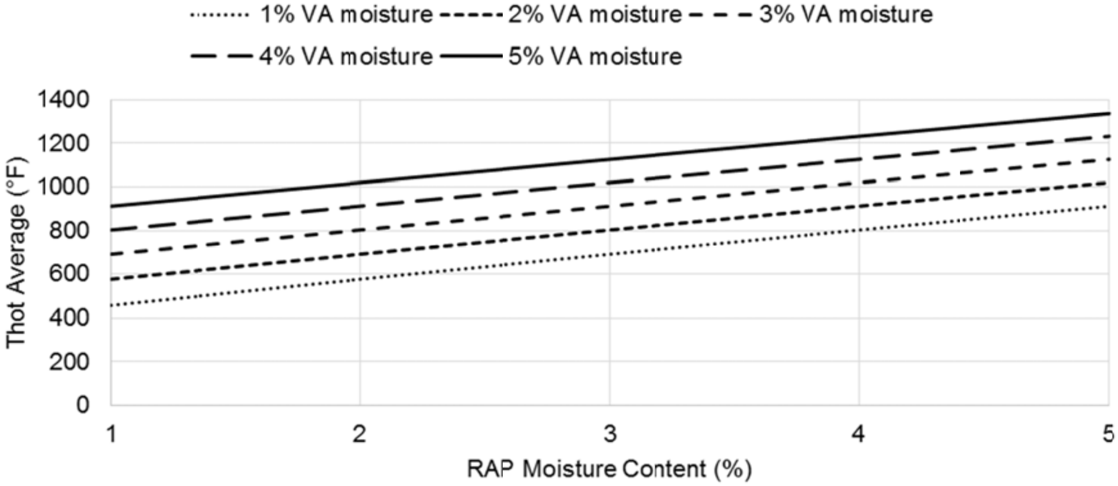


Figure 4.10 Virgin aggregate temperature required for the
HMA mix containing 50% virgin aggregates with 50% RAP (0.5 in. NMAS).

4.3.4.8 Results for 0.25 in. Nominal Maximum Aggregate Size (NMAS)

Another example is presented for virgin aggregates and RAP size of 0.25 in. This analysis was done to determine the changes in the virgin aggregate temperature for smaller virgin aggregates and RAP sizes (0.25 in.) but keeping the same moisture content.

As shown in Figure 4.11, for 90% virgin aggregates and 10% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 254°F to remove moisture from both the virgin aggregates and the RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 302°F; for 3% moisture content in the virgin aggregates, the temperature is 343°F; for 4% moisture content in the virgin aggregates, the temperature is 381°F; and for 5% moisture content in the virgin aggregates, the temperature is 417°F.

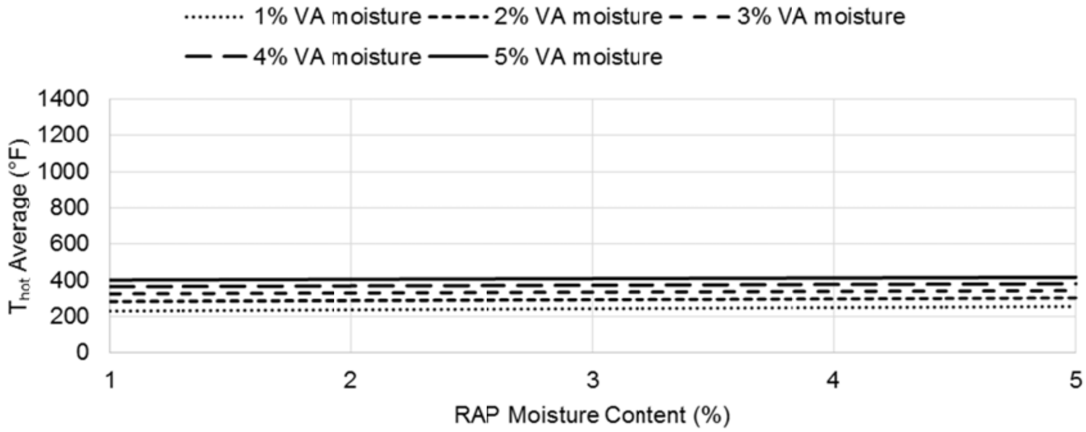


Figure 4.11 Virgin aggregate temperature required for the
HMA mix containing 90% virgin aggregates with 10% RAP (0.25 in. NMAS).

As shown in Figure 4.12, for 80% virgin aggregates and 20% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 288°F to remove moisture from both the virgin aggregates and the RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 331°F; for 3% moisture content in the virgin aggregates, the temperature is 370°F; for 4% moisture content in the virgin aggregates, the temperature is 406°F; and for 5% moisture content in the virgin aggregates, the temperature is 417°F.

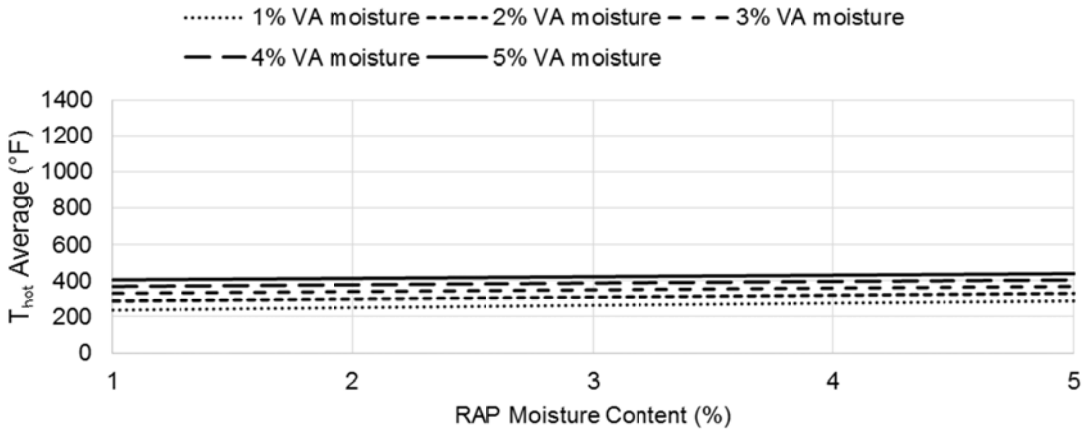


Figure 4.12 Virgin aggregate temperature required for
the HMA mix containing 80% virgin aggregates with 20% RAP (0.25 in. NMAS).

As shown in Figure 4.13, for 70% virgin aggregates and 30% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 327°F to remove moisture from both the virgin aggregates and the RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 366°F; for 3% moisture content in the virgin aggregates, the temperature is 402°F; for 4% moisture content in the virgin aggregates, the temperature is 437°F; and for 5% moisture content in the virgin aggregates, the temperature is 471°F.

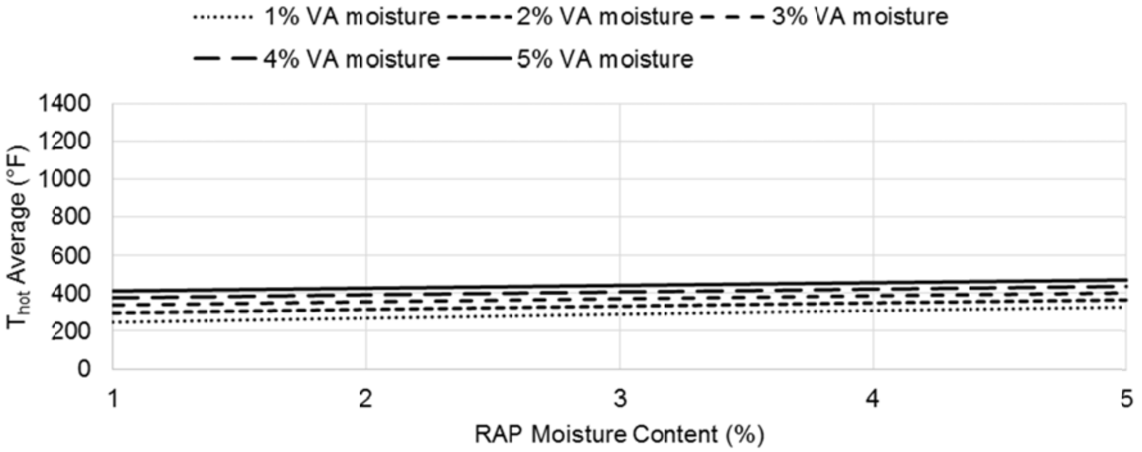


Figure 4.13 Virgin aggregate temperature required for the
HMA mix containing 70% virgin aggregates with 30% RAP (0.25 in. NMAS).

As shown in Figure 4.14, for 60% virgin aggregates and 40% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 373°F to remove moisture from both virgin aggregates and RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 409°F; for 3% moisture content in the virgin aggregates, the temperature is 444°F; for 4% moisture content in the virgin aggregates, the temperature is 477°F; and for 5% moisture content in the virgin aggregates, the temperature is 510°F.

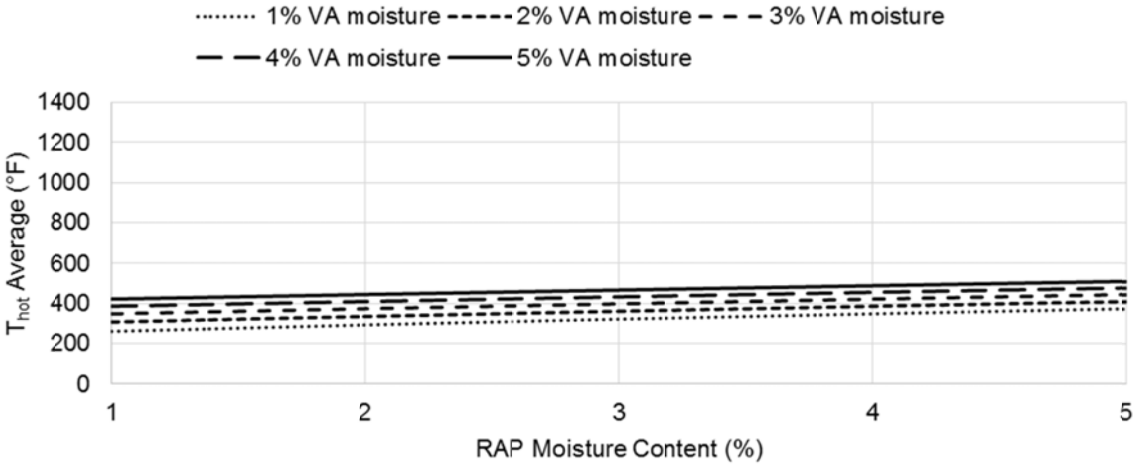


Figure 4.14 Virgin aggregate temperature required for the
HMA mix containing 60% virgin aggregates with 40% RAP (0.25 in. NMAS).

As shown in Figure 4.15, for 50% virgin aggregates and 50% RAP with 1% moisture content in the virgin aggregates and 5% moisture content in the RAP, the virgin aggregate is heated to 432°F to remove moisture from both the virgin aggregates and the RAP. For the same moisture content in RAP (5%) and for 2% moisture content in the virgin aggregates, the temperature is 466°F; for 3% moisture content in the virgin aggregates, the temperature is 499°F; for 4% moisture content in the virgin aggregates, the temperature is 531°F; and for 5% moisture content in the virgin aggregates, the temperature is 562°F.

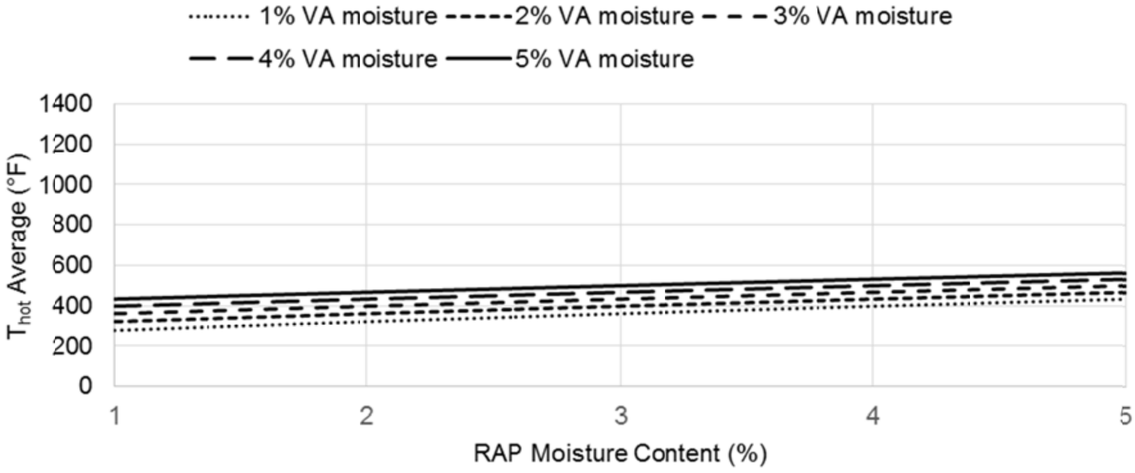


Figure 4.15 Virgin aggregate temperature required for the
HMA mix containing 50% virgin aggregates with 50% RAP (0.25 in. NMAS).

4.4 SUMMARY

Thermodynamic and heat transfer principles were used to predict virgin aggregate temperatures required to dry and heat RAP. Varying proportions of virgin aggregates and RAP in the HMA mix were used for the calculations. Virgin aggregate moisture content varied from 1% to 5%, as did RAP moisture content.

One example was shown for 0.5 in. virgin aggregates and RAP size and another for 0.25 in. virgin aggregates and RAP size. It was observed that for 0.5 in. virgin aggregates and RAP, the virgin aggregates becomes superheated as both the virgin aggregate moisture content and RAP moisture content increased. This superheated temperature was observed for mixes containing RAP at percentages ranging from 30% to 50%. For the smaller virgin aggregates and RAP (0.25 in.), the virgin aggregates become very hot as the RAP percentage in the HMA mix increased to a range of 40% to 50%.

CHAPTER 5: LABORATORY TESTS ON PLANT MATERIALS

5.1 INTRODUCTION

This chapter summarizes the results of laboratory moisture content tests conducted in cooperation with River City Supply, an HMA drum plant contractor in Peoria, Illinois. The lab test was conducted in the IDOT District 4 materials laboratory in Peoria.

Initially, the moisture content for plant virgin aggregates, RAP, and RAS was unknown; therefore, a RAP moisture content in the range of 0% to 20% was assumed based on IDOT field crew experience on selected projects. The analysis presented in Chapter 4 was based on that assumed value. Later, a better and more practical understanding of the moisture content of the plant's materials was gained by collecting virgin aggregates, RAP, and RAS from a plant to determine moisture content. In addition, weather data were collected from the local weather station. The weather data were collected for three consecutive days before the materials were collected from the plant. The weather data collected were cumulative rainfall, maximum relative humidity (RH), minimum temperature, and maximum temperature. All weather data were collected at hourly intervals. The plant materials were collected on the following dates and times.

Table 5.1 Plant Material Collection Dates and Times

Date (2015)	Time
16 April	~8:00 a.m.
22 April	~8:00 a.m.
28 April	~8:00 a.m.
7 May	~8:00 a.m.
13 May	~8:00 a.m.
19 May	~1:00 p.m.
27 May	~7:15 a.m.
6 June	~9:00 a.m.
11 June	~8:00 a.m.
19 June	~8:30 a.m.

5.2 TEST PROCEDURE

The moisture content of the aggregates was determined by means of Illinois Modified Test Procedure 255 (Total Evaporable Moisture Content of Aggregates by Drying). The apparatus used in the test were a balance, a ventilated oven, and a container. The test sample needs to be dried to constant mass in an oven specifically designed for drying, set at and capable of maintaining a uniform temperature of 230°F ± 9°F. Constant mass is defined as the sample mass at which there has not been more than a 0.5 gram mass loss during 1 hour of drying (which should be verified occasionally). After the test sample has been dried to constant mass and cooled down to room temperature, the mass of the sample is determined to the nearest 1 gram for coarse aggregates and to the nearest 0.1 gram for fine aggregates. This procedure provides the total dry mass of the test sample. RAP samples should be air-dried to a constant mass. Aggregate moisture content was determined by the following formula:

$$P = \frac{100(OSM - TDM)}{TDM}$$

where *P* is the aggregate moisture content expressed as a percentage, *OSM* is the original sample mass (grams), and *TDM* is the dried sample mass (grams).

5.3 LABORATORY TEST AND WEATHER DATA

The following tables present the summary of moisture data. The one-day weather data is averaged for the maximum RH, minimum temperature, and maximum temperature. The rainfall shown is cumulative data for 3 days.

The mineral properties (limestone or sandstone) of the aggregates were unknown. Because thermal properties of aggregates depend on their mineral composition, it is recommended to that information on mineral composition of aggregates be recorded as part of a future study.

As shown in Table 5.1(a), the moisture content in coarse aggregates (CA) ranges from 1.74% to 3.57%. The CA supplied by Tri-Con contains a higher amount of moisture. The moisture content in fine aggregates (FA) ranges from 4.58% to 5.49%. For –3/8 RAP, the moisture content is 4.99% and is 6.43% for –3/8 RAS. The negative sign refers that RAP or RAS is less than 3/8 in. Although moisture content is compared between 3/8 in. CA and RAP, the RAP contains 39.77% more moisture. This indicates that aged binder coating helps prevent moisture evaporation from RAP.

Table 5.1(a) Plant Material Moisture Content and Weather Data (16 April 2015, ~8:00 a.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr			Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
		1 hr	3 hr	6 hr			
CA11 (3/4 in.), Lafarge	1.74%	0	0	0	78%	*58.75*	69.25
CA13 (1/2 in.), Tri-Con	3.23%						
CA16 (3/8 in.), Lafarge	2.76%						
CA16 (3/8 in.), Tri-Con	3.57%						
FA01 (Sieve no. #4), Hurley	4.58%						
FA01 (Sieve no. #4), Lowery	4.74%						
FA04 (Sieve no. #16), PS&G	3.38%						
FA20 (Sieve no. #4), Lafarge	4.94%						
FA20 (Sieve no. #4), Pia Conc	5.49%						
–3/8 FRAP	4.99%						
–3/8 RAS	6.43%						

As shown in Table 5.1(b), the moisture content in CA ranges from 0.37% to 2.94%. The CA supplied by Tri-Con contains a higher amount of moisture. The moisture content in FA ranges from 4.46% to 4.78%. For –3/8 RAP, the moisture content is 5.19% and is 7.98% for –3/8 RAS. Although moisture content is compared between 3/8 in. CA and RAP, the RAP contains 76.53% more moisture. It should be noted that rainfall was recorded while collecting these materials, and it is assumed that some FA, RAP, and RAS moisture content increased as a result of the rainfall. However, CA moisture content decreased from the previous week's data.

Table 5.1(b) Plant Material Moisture Content and Weather Data (22 April 2015, ~8:00 a.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr			Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
		1 hr	3 hr	6 hr			
CA11 (3/4 in.), Lafarge	0.37%	0.39	0.11	0.39	67%	44.75	56
CA13 (1/2 in.), Tri-Con	2.79%						
CA16 (3/8 in.), Lafarge	2.51%						
CA16 (3/8 in.), Tri-Con	2.94%						
FA01 (Sieve no. #4), Hurley	4.46%						
FA01 (Sieve no. #4), Lowery	4.44%						
FA04 (Sieve no. #16), PS&G	4.39%						
FA20 (Sieve no. #4), Lafarge	4.57%						
FA20 (Sieve no. #4), Pia Conc	4.78%						
–3/8 FRAP	5.19%						
–3/8 RAS	7.98%						

As shown in Table 5.1(c), the moisture content in CA ranges from 0.33% to 3.20%. The moisture content in FA ranges from 4.19% to 5.08%. For –3/8 RAP the moisture content is 5.45% and is 8.46% for -3/8 RAS. Although moisture content is compared between 3/8 in. CA and RAP, the RAP contained 70.31% more moisture. Excess rainfall increased the moisture content in RAP and RAS from the previous week.

Table 5.1(c) Plant Material Moisture Content and Weather Data (28 April 2015, ~8:00 a.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr			Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
		1 hr	3 hr	6 hr			
CA11 (3/4 in.), Lafarge	0.33%	0.86	0.42	0.87	82%	47.5	59.75
CA13 (1/2 in.), Tri-Con	2.66%						
CA16 (3/8 in.), Lafarge	1.30%						
CA16 (3/8 in.), Tri-Con	3.20%						
FA01 (Sieve no. #4), Hurley	4.19%						
FA01 (Sieve no. #4), Lowery	4.35%						
FA04 (Sieve no. #16), PS&G	2.26%						
FA20 (Sieve no. #4), Lafarge	4.19%						
FA20 (Sieve no. #4), Pia Conc	5.08%						
–3/8 FRAP	5.45%						
–3/8 RAS	8.46%						

As shown in Table 5.1(d), the moisture content in CA ranges from 1.64% to 3.72%. The moisture content in FA ranges from 4.59% to 5.21%. For –3/8 RAP, the moisture content is 4.05% and is 7.54% for –3/8 RAS. It should be noted that less rainfall was recorded (compared with the previous week) while collecting these materials. Less rainfall reduced the moisture content in RAP and RAS from the previous week.

Table 5.1(d) Plant Material Moisture Content and Weather Data (7 May 2015, ~8:00 a.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr			Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
		1 hr	3 hr	6 hr			
CA11 (3/4 in.), Lafarge	1.64%	0.13	0.13	0.13	66%	69.6	81.2
CA13 (1/2 in.), Tri-Con	1.10%						
CA16 (3/8 in.), Lafarge	2.25%						
CA16 (3/8 in.), Tri-Con	3.72%						
FA01 (Sieve no. #4), Hurley	4.59%						
FA01 (Sieve no. #4), Lowery	4.12%						
FA04 (Sieve no. #16), PS&G	3.37%						
FA20 (Sieve no. #4), Lafarge	4.23%						
FA20 (Sieve no. #4), Pia Conc	5.21%						
–3/8 FRAP	4.05%						
–3/8 RAS	7.54%						

As shown in Table 5.1(e), the moisture content in CA ranges from 0.29% to 4.11%. The moisture content in FA ranges from 4.91% to 5.30%. For –3/8 RAP, the moisture content is 3.96% and is 8.74% for –3/8 RAS.

Table 5.1(e) Plant Material Moisture Content and Weather Data (13 May 2015, ~8:00 a.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr			Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
		1 hr	3 hr	6 hr			
CA11 (3/4 in.), Lafarge	0.29%	0.81	0.48	0.69	86%	50.8	58.6
CA13 (1/2 in.), Tri-Con	1.55%						
CA16 (3/8 in.), Lafarge	1.03%						
CA16 (3/8 in.), Tri-Con	4.11%						
FA01 (Sieve no. #4), Hurley	4.91%						
FA01 (Sieve no. #4), Lowery	4.70%						
FA04 (Sieve no. #16), PS&G	5.23%						
FA20 (Sieve no. #4), Lafarge	3.98%						
FA20 (Sieve no. #4), Pia Conc	5.30%						
–3/8 FRAP	3.96%						
–3/8 RAS	8.74%						

As shown in Table 5.1(f), the moisture content in CA ranges from 0.13% to 1.13%. The moisture content in FA ranges from 3.5% to 4.61%. For –3/8 RAP, the moisture content is 5.27% and is 7.77% for –3/8 RAS.

Table 5.1(f) Plant Material Moisture Content and Weather Data (19 May 2015, ~1:00 p.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr 1 hr	3 hr	6 hr	Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
CA11 (3/4 in.), Lafarge	0.13%	0.1	0.02	0.1	79%	56.5	65.75
CA13 (1/2 in.), Tri-Con	1.78%						
CA16 (3/8 in.), Lafarge	2.46%						
CA16 (3/8 in.), Tri-Con	1.13%						
FA01 (Sieve no. #4), Hurley	3.50%						
FA01 (Sieve no. #4), Lowery	3.87%						
FA04 (Sieve no. #16), PS&G	3.59%						
FA20 (Sieve no. #4), Lafarge	4.30%						
FA20 (Sieve no. #4), Pia Conc	4.61%						
–3/8 FRAP	5.27%						
–3/8 RAS	7.77%						

As shown in Table 5.1(g), the moisture content in CA ranges from 1.24% to 2.48%. The moisture content in FA ranges from 4.52% to 5.92%. For –3/8 RAP, the moisture content is 5.37% and is 6.22% for –3/8 RAS.

Table 5.1(g) Plant Material Moisture Content and Weather Data (27 May 2015, ~7:15 a.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr 1 hr	3 hr	6 hr	Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
CA11 (3/4 in.), Lafarge	2.48%	0.95	0.52	0.95	87%	67.75	76
CA13 (1/2 in.), Tri-Con	2.18%						
CA16 (3/8 in.), Lafarge	3.25%						
CA16 (3/8 in.), Tri-Con	1.24%						
FA01 (Sieve no. #4), Hurley	4.52%						
FA01 (Sieve no. #4), Lowery	4.46%						
FA04 (Sieve no. #16), PS&G	2.45%						
FA20 (Sieve no. #4), Lafarge	4.99%						
FA20 (Sieve no. #4), Pia Conc	5.92%						
–3/8 FRAP	5.37%						
–3/8 RAS	6.22%						

As shown in Table 5.1(h), the moisture content in CA ranges from 0.33% to 0.62%. The moisture content in FA ranges from 5.03% to 5.62%. For –3/8 RAP, the moisture content is 5.01% and is 4.54% for –3/8 RAS.

Table 5.1(h) Plant Material Moisture Content and Weather Data (2 June 2015, ~9:00 a.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr			Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
		1 hr	3 hr	6 hr			
CA11 (3/4 in.), Lafarge	0.33%	0.18	0.05	0.19	87%	55.75	64.25
CA13 (1/2 in.), Tri-Con	2.52%						
CA16 (3/8 in.), Lafarge	3.45%						
CA16 (3/8 in.), Tri-Con	0.62%						
FA01 (Sieve no. #4), Hurley	5.03%						
FA01 (Sieve no. #4), Lowery	4.16%						
FA04 (Sieve no. #16), PS&G	3.02%						
FA20 (Sieve no. #4), Lafarge	3.39%						
FA20 (Sieve no. #4), Pia Conc	5.62%						
–3/8 FRAP	5.01%						
–3/8 RAS	4.54%						

As shown in Table 5.1(i), the moisture content in CA ranges from 2.07% to 3.28%. The moisture content in FA ranges from 5.18% to 7.59%. For –3/8 RAP, the moisture content is 3.36% and is 6.65% for –3/8 RAS.

Table 5.1(i) Plant Material Moisture Content and Weather Data (11 June 2015, ~8:00 a.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr			Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
		1 hr	3 hr	6 hr			
CA11 (3/4 in.), Lafarge	2.07%	1.6	0.71	1.6	87%	74.25	85.25
CA13 (1/2 in.), Tri-Con	3.19%						
CA16 (3/8 in.), Lafarge	4.73%						
CA16 (3/8 in.), Tri-Con	3.28%						
FA01 (Sieve no. #4), Hurley	5.18%						
FA01 (Sieve no. #4), Lowery	4.44%						
FA04 (Sieve no. #16), PS&G	4.94%						
FA20 (Sieve no. #4), Lafarge	6.40%						
FA20 (Sieve no. #4), Pia Conc	7.59%						
–3/8 FRAP	3.36%						
–3/8 RAS	6.65%						

As shown in Table 5.1(j), the moisture content in CA ranges from 2.48% to 2.69%. The moisture content in FA ranges from 4.98% to 6.54%. For –3/8 RAP, the moisture content is 5.60% and is 9.04% for –3/8 RAS.

Table 5.1(j) Plant Material Moisture Content and Weather Data (19 June 2015, ~8:30 a.m.)

Aggregate Type (NMAS), Supplier	Moisture Content %	Cumulative Rainfall for 72 hr			Max RH (24 hr)	Min Avg Temp (°F) (24 hr)	Max Avg Temp (°F) (24 hr)
		1 hr	3 hr	6 hr			
CA11 (3/4 in.), Lafarge	2.48%	0.17	0.02	1.03	88%	**70.25**	78.5
CA13 (1/2 in.), Tri-Con	2.84%						
CA16 (3/8 in.), Lafarge	4.13%						
CA16 (3/8 in.), Tri-Con	2.69%						
FA01 (Sieve no. #4), Hurley	4.98%						
FA01 (Sieve no. #4), Lowery	3.63%						
FA04 (Sieve no. #16), PS&G	4.25%						
FA20 (Sieve no. #4), Lafarge	6.60%						
FA20 (Sieve no. #4), Pia Conc	6.54%						
–3/8 FRAP	5.60%						
–3/8 RAS	9.04%						

5.4 OTHER MOISTURE DATA

Other aggregate moisture data collected by IDOT officials in several districts are given in the following tables.

Table 5.2 RAP and RAS Moisture Data Collected by the District 2 Materials Lab

Date Sampled	Producer	Material Code	Sample Weight (g)	Dry Weight (g)	Moisture Content (%)
7/9/2015	6452-02	017CM16	1676.4	1601.3	4.7
7/20/2015	700-16	017CM3804	1892.2	1836	3.1
7/20/2015	700-16	017FM0400	1006.9	967.3	4.1

Table 5.3 RAP Moisture Data Collected by IDOT Officials

HMA Producer/Supplier	RAP Moisture Content
W.L. Miller, Hamilton, IL (1318-02)	5.0%
UCM, Beardstown, IL (5641-05)	4.6%
R.W. Dunteman, Pana, IL (547-05)	4.1%

Table 5.4 RAP and RAS Moisture Data
Collected by the District 1 Materials Lab

Materials Type	Moisture Content
RAS	10.4%
RAP	4.2%
RAP	4.5%
RAP	5.2%

Table 5.5 RAP Moisture Data Collected
by IDOT Industry Representative

Aggregate Type (NMAS)	Moisture Content
CA11 (3/4 in.)	2.3%
CA16 (3/8 in.)	2.9%
CA20 (3/8 in.)	1.0%
–3/8 FRAP	3.4%
+3/8 FRAP	1.4%

5.5 SUMMARY

The plant moisture content data indicates that virgin coarse aggregates hold a lower amount of moisture compared with virgin fine aggregates. However, in comparing same-size virgin aggregates and RAP, it was found that RAP contained a higher amount of moisture. The reason might be that the binder coating on RAP holds moisture better than virgin aggregates do, and the aged binder coating moisture does not evaporate as quickly when it is open to the air. Also, RAS contains a higher amount of moisture compared with RAP of the same size. Generally, moisture content in aggregates increases after precipitation. However, many other factors—such as evaporation, temperature, and humidity—affect the moisture content of virgin aggregates and RAP/RAS.

CHAPTER 6: HMA PLANT VISIT AND TEMPERATURE DATA COLLECTION

6.1 INTRODUCTION

This chapter describes the temperature data collection and analysis of a drum plant. The data were collected from Gallagher Asphalt in Joliet, Illinois, near Chicago and a driving distance of approximately 2 hr and 15 min from Peoria, Illinois. The data were collected on 24 June 2015. Generally, the plant begins operating early in the morning (approximately 6:00 a.m.), and production starts at around 7:00 a.m. The data were collected for approximately 1 hr and 45 min.

6.2 HMA DRUM PLANT VISIT

Gallagher Asphalt has a double-barrel counter-flow drum plant. The drum plant is shown in Figure 6.1(a). The double-barrel drum is shown in Figure 6.1(b). The green box on the right end is the burner and the silver cover is the outer barrel part of the drum plant. The plant has seven virgin aggregate bins and two recycled aggregate bins. One recycled aggregate bin is used for RAP and other is used for RAS. The virgin aggregate bins are showing in Fig 6.1(c) and the recycled bins are shown in Figure 6.1(e).

This double-barrel drum plant has a temperature-measuring unit that records virgin aggregate temperature while it gets inside the outer drum after drying and heating and before mixing with RAP/RAS. There are many other temperatures and parameters recorded automatically by the plant controlling unit. A plant operator or foreman controls and monitors all the measurement taken by the control unit.

The double-barrel drum capacity is 500 t/hr Inner radius of the drum is 10 ft, drum length is 49.8 ft, drum rotation was counted as 6 rpm for that particular mix, and the RAP entrance from the top of the drum and the distance of this entrance is 44 ft away the entrance of the virgin aggregates. RAP entrance is shown in Figure 6.3(d).

(a) Drum plant (b) Double-barrel counter-flow drum

(c) Virgin aggregate bins (d) RAP/RAS entrance in drum

(e) RAP/RAS bins (f) RAP/RAS conveyor belt

Figure 6.1 Drum plant facilities at Gallagher Asphalt.

Figure 6.2 shows the aggregate, RAP, and RAS stockpiles. All stockpiles are open to air. It should be noted that it has been raining for last couple days before the temperature was taken in this plant. Even the paving work has been delayed due the heavy rainfall.

(a) Virgin coarse aggregate (b) Virgin fine aggregate

(c) RAP (d) RAP and RAS

Figure 6.2 Virgin and recycled materials at Gallagher Asphalt.

6.3 DATA COLLECTION

The plant was producing a fine mix or sand mix while the data was collected. Only temperature data was collected for the sand mix. Approximately 300 tons of HMA mix was produced while collecting the data. Temperature data was collected from the computer monitor that shows virgin aggregate temperature data with the other data. Figure 6.3(a) shows the control room that record and monitor temperature data. Figure 6.3(b) shows the monitor that is used to record the temperature data used for this study. Detail of this monitor is shown in the Figure 6.4. In addition to virgin aggregate temperature, the reading is taken for HMA mix temperature, drum pre-heating temperature, and outer drum surface temperature.

(a) Control room (b) Temperature profile monitor

Figure 6.3 Temperature recording from the control room at Gallagher Asphalt.

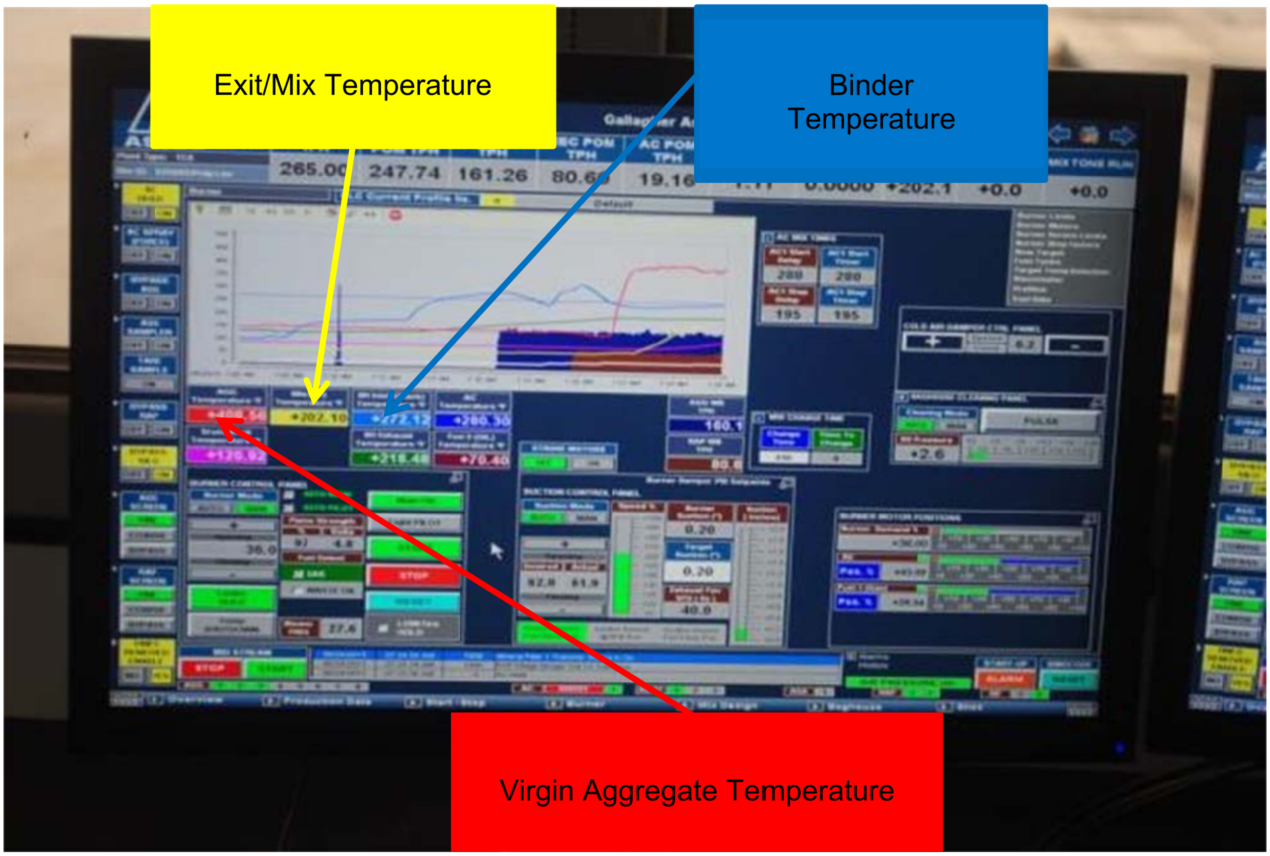


Figure 6.4 Details of temperature profile monitor.

The fine aggregate gradation is given in Tables 6.1 and 6.2. FM02 and FM20 were used in the mix. Thirty-three percent FM02 and 67% FM20 were used in the HMA mix. FM02 contained 5.1% moisture, and FM20 contained 6.3% moisture. The HMA mix contained 31% RAP and 4.75% RAS. The RAP had 6.9% moisture content, and the RAS had 15.2% moisture content. The RAS moisture content recorded in the Joliet plant was higher than the moisture content recorded in the Peoria plant. However, the FM02, FM20, and RAP moisture content in the Joliet plant fell within the range of the data collected from the Peoria plant.

Table 6.1 Gradation of FM02 Aggregate

Sieve Size	% Passing
3/8 in	100
#4 (4.75 mm)	99.6
#8 (2.36 mm)	85.5
#16 (1.18 mm)	63
#30 (0.6 mm)	38.5
#50 (0.3 mm)	10
#100 (0.15 mm)	3.3
#200 (0.075 mm)	2.5

Table 6.2 Gradation of FM20 Aggregate

Sieve Size	% Passing
3/8 in	100
#4 (4.75 mm)	99.7
#8 (2.36 mm)	84.9
#16 (1.18 mm)	56.1
#30 (0.6 mm)	38.8
#50 (0.3 mm)	25.7
#100 (0.15 mm)	13.6
#200 (0.075 mm)	5.5

In the inner drum, the heating time of the fine aggregates was 140 sec. The HMA mix contained 7.8% PG 70-28 polymer-modified binder. In the plant, the binder temperature varied from 278°F to 289°F. In the outer drum, the aggregate, RAP, RAS, and binder mixing time was 40 sec.

The drum was pre-heated at 500°F for more than 30 min before virgin aggregates were fed into it. Generally, the amount of pre-heating time depends on the moisture content of virgin aggregates, RAP, and RAS. The temperature inside the drum was monitored before the virgin aggregates were fed into it. As the virgin aggregates were fed into the drum, the temperature of the aggregates in the drum was continuously monitored by a foreman, and the mix temperature was recorded at the exit before the mix was sent to the silo.

At one point, it was noted that the initial part of the mix was not being heated up to the target temperature (350°F) for the HMA mix. This initial mix was discarded and removed from the conveyor belt before it went into the silo. Figure 6.5 shows the discarded mix being put on the back of a truck. (The discarded material will be used as RAP in other HMA mixes.)

Figure 6.5 HMA mix discarded because it did not achieve target mix temperature.

It should be noted that the outer drum surface temperature was approximately 200°F, which indicates that significant heat loss occurred inside the drum. However, the current study does not consider heat loss in the analysis. Heat loss can be calculated and visualized by the CFD and DEM methods.

6.4 DATA ANALYSIS

Figure 6.6 shows the temperature profile of the virgin aggregates and the HMA mix. Temperature recording began when the HMA mix was taken to the silo after the initial HMA mix was discarded. Time was recorded by taking a picture of the computer monitor. Pictures of the computer monitor were taken for the entire period of mix operation to capture the change in temperature.

It can be seen in Figure 6.6 that virgin aggregate temperatures varied from 615°F to 560°F. After approximately 4300 sec, the virgin aggregate temperature began to drop, as did the mix temperature. That decrease trend indicates the end of mix production.

The mix that came out after the end of production was also discarded by removing it from the conveyor belt. Again, this discarded end-of-production mix will be used as RAP material for the other HMA mixes.

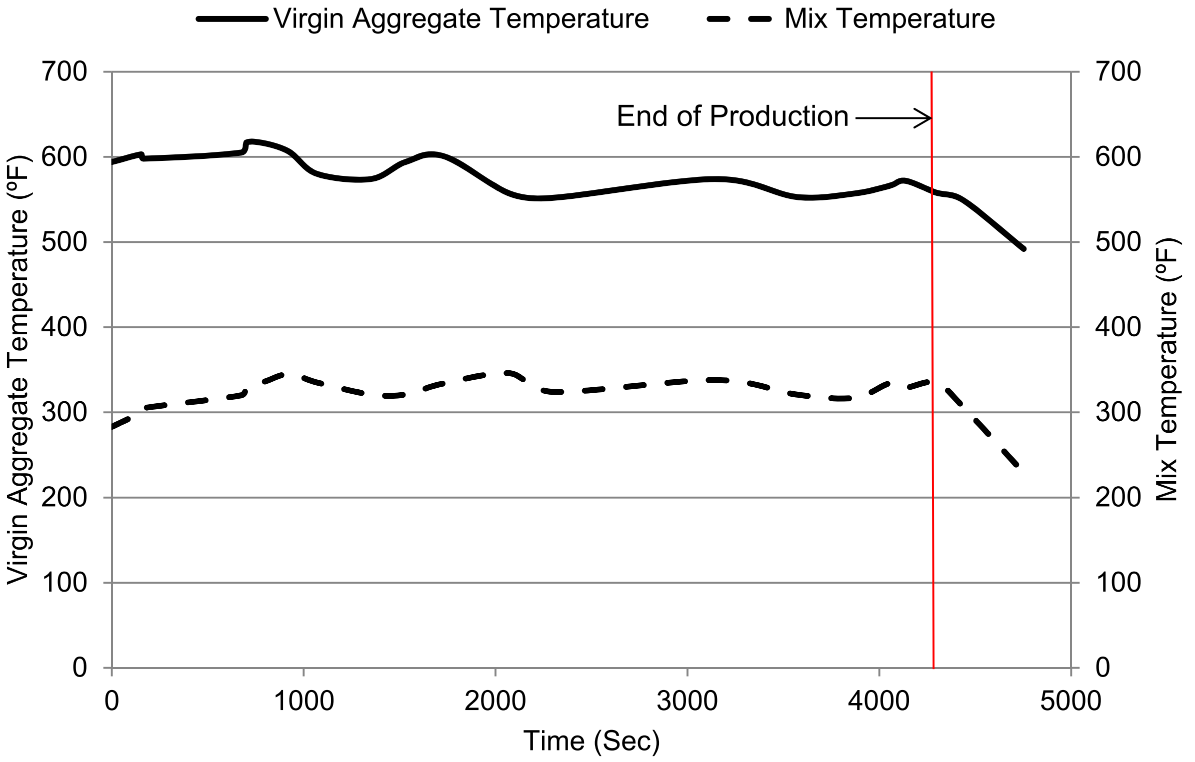


Figure 6.6 Temperature profile of virgin aggregate and mix temperature.

6.5 VERIFICATION OF VIRGIN AGGREGATE TEMPERATURE

The thermodynamic equations used in Chapter 4 were used to validate temperature in this double-barrel drum plant, following these steps:

1. The total amount of virgin aggregates drying and heating in the inner drum for 140 sec was determined, which was 1.98 tons. Of that amount, 33% was FM02 and 67% was FM20.
2. Using the aggregate gradation chart, the total amount of aggregate corresponding to each size was determined.
3. The amount of moisture in each size of aggregate was determined.
4. The energy required (Q_{1-1}) to evaporate water from each aggregate size was determined. The ambient temperature for the virgin aggregate and RAP was 65.3°F. In addition, for each aggregate size, the energy required (Q_{1-2}) to evaporate water was determined.
5. The amounts of RAP and RAS required to mix with 1.98 tons of virgin aggregate were determined. It was calculated that 1.09 tons of RAP and 0.17 ton of RAS was mixed with the virgin aggregates in the outer barrel.
6. The moisture in the RAP and RAS were determined.
7. The energy required (Q_{2-1}) to evaporate water from the RAP and RAS were determined. In addition, for RAP and RAS, the energy required (Q_{1-2}) to evaporate water was determined.

8. The conduction, convection, and radiation percentages in the drum were determined. It was assumed that 5% was radiation. Conduction and convection was found to be 82% 13%, respectively.
9. Thermal conductivity for each aggregate size was determined.
10. T_{hot} conduction, T_{hot} convection, and T_{hot} radiation for each size of virgin aggregate were determined, and average temperature was calculated.

Tables 6.3 and 6.4 show the virgin aggregate temperature calculated using thermodynamic equations. It can be seen that the largest aggregate for both gradations is 0.187 and the temperature is close to the temperature (560°F to 615°F) measured in the drum plant.

Table 6.3 Virgin Aggregate Temperature for FM02

Sieve Size (Aggregate Size)	T_{Hot} Conduction (°F)	T_{Hot} Convection (°F)	T_{Hot} Radiation (°F)	T_{Hot} Average (°F)
#4 (0.187 in.)	285	69	1404	586
#8 (0.0937 in.)	67	65	524	219
#16 (0.0469 in.)	66	65	407	179
#30 (0.0234 in.)	65	65	338	156
#50 (0.0117 in.)	65	65	278	136
#100 (0.0059 in.)	65	65	304	145
#200 (0.0029 in.)	65	65	418	183
Mineral Filler (0.0028 in.)	65	65	315	149

Table 6.4 Virgin Aggregate Temperature for FM20

Sieve Size (Aggregate Size)	T_{Hot} Conduction (°F)	T_{Hot} Convection (°F)	T_{Hot} Radiation (°F)	T_{Hot} Average (°F)
#4 (0.187 in.)	211	68	1267	515
#8 (0.0937 in.)	67	65	476	203
#16 (0.0469 in.)	66	65	374	168
#30 (0.0234 in.)	65	65	330	154
#50 (0.0117 in.)	65	65	288	139
#100 (0.0059 in.)	65	65	245	125
#200 (0.0029 in.)	65	65	218	116
Mineral Filler (0.0028 in.)	65	65	231	121

6.6 SUMMARY

The thermodynamic equations can be used to predict the virgin aggregate temperature required to dry and heat RAP and RAS. However, there are some assumptions in this analysis that require more study. Heat loss is one of the significant parameters to include in the future studies. Moreover, heat distribution by means of conduction, convection, and radiation are not clearly understood and warrant additional study.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

The objectives of this project were to (1) conduct a comprehensive literature review on thermodynamics, with special emphasis on heat transfer phenomena between RAP/RAS materials with virgin aggregates while moisture is present in the recycled materials; (2) evaluate the HMA production process specifically with regard to energy use, energy loss, and emission during mixing RAP/RAS with virgin aggregates with the presence of variable amount of moisture; and (3) determine the virgin aggregate temperature necessary to produce various blends of RAP, RAS, and RAP/RAS mixtures with moisture contents ranging from 0% to 20%.

The following conclusions are drawn on the basis of the literature review, on limited laboratory tests and field investigations, and on calculations made with several assumptions.

7.2 CONCLUSIONS

7.2.1 HMA Plants

A drum plant is preferred by HMA producers and contractors for large paving work because it is efficient in removing moisture from virgin aggregates, RAP, and RAS, and the continuous production provides efficient and faster paving construction. For drum plants, the temperature required to dry virgin aggregate and RAP/RAS material has not been studied.

For batch plants, however, two studies determined the virgin aggregate temperature required to dry RAP only (Recycling Hot Mix Asphalt Pavements 1996; *Hot Mix Asphalt Recycling* 2007). However, those studies did not consider the moisture in virgin aggregates or the size of virgin aggregate and RAP. Also it is not known whether those studies considered thermal properties of the virgin aggregates and RAP materials. The batch plant studies did show that virgin aggregates become superheated when the RAP percentage increases more than 40% and RAP moisture content increases between 4% and 5%.

No study was found in the literature on the topic of drying RAS in conjunction with virgin aggregates and RAP.

In addition, it is not known how superheated virgin aggregate damages the aged binder coating of RAP/RAS and virgin binder.

7.2.2 Thermodynamics and Heat Transfer

Previous research predicted virgin aggregate temperature using empirical equations and numerical analysis (Frederick and Tario 2009; Hobbs 2009). One attempt was made to install temperature probes inside a drum to measure virgin aggregate temperature (Le Guen et al. 2013). However, the physical parameters of the materials were not considered in the empirical equations, although that study did include RAP in the analysis. Moreover, numerical analysis and field temperature measurements have used thermodynamic principles, but those studies did not include HMA mixes with RAP.

7.2.3 Predicting Virgin Aggregate Temperature

Thermodynamics and heat transfer principles are used to predict the virgin aggregate temperature required for drying and heating RAP. Different proportions of virgin aggregates and RAP in an HMA mix were used in the calculations. Virgin aggregate moisture content varied from 1% to 5%, and RAP moisture content varied from 1% to 5%. One example was provided for 0.5 in. virgin aggregates and RAP and another for 0.25 in. virgin aggregates and RAP.

It was observed that for 0.5 in. virgin aggregates and RAP, the virgin aggregates became superheated (more than 1000°F) as the moisture content for both the virgin aggregate and RAP moisture content increased. This superheated temperature was observed for both mid and high RAP percentages (30% to 50%). On the other hand, for the smaller virgin aggregates and RAP (0.25 in.), the virgin aggregates became very hot (more than 500°F) as the RAP percentage increased to a range of 40% to 50% in the HMA mix.

7.2.4 Measuring Moisture Content of Plant Material

The plant moisture content data indicate that virgin coarse aggregates hold a lower amount of moisture compared with virgin fine aggregates. However, in comparing same-size virgin aggregates and RAP, it was found that RAP contained higher amounts of moisture. The reason might be that the binder coating on RAP holds moisture better than virgin aggregates do, and the aged binder coating moisture does not evaporate as quickly when it is open to the air. Also, RAS contains a higher amount of moisture compared with RAP of the same size. Generally, moisture content in aggregates increased after precipitation. However, many other factors—such as evaporation, temperature, and humidity—affect the moisture content of virgin aggregates and RAP/RAS.

7.2.5 Measuring Virgin Aggregate Temperature

Virgin aggregate temperature can be measured in a plant that has temperature-measuring unit inside the drum, but not many plants have the unit. The temperature-measuring unit comes with the drum as an accessory, or it can be installed afterward. Some contractors prefer installing the unit for quality control of the mix. However, other contractors use the exit temperature and baghouse temperature for that purpose.

A significant heat loss through the drum wall was not considered in this analysis, nor was pre-heating.

7.3 RECOMMENDATIONS FOR FUTURE STUDIES

7.3.1 Multi-Disciplinary Study

Studies of thermodynamics and heat transfer in materials and structures are usually conducted by mechanical and industrial engineers. Therefore, a multi-disciplinary collaboration is recommended for a future study. Drying and heating materials in an HMA plant is a complex operation, and a multi-disciplinary study will help provide an understand of the broader relationship between aggregate heating and drying in conjunction with virgin and recycled materials.

7.3.2 Extensive Data Collection

Many types of drum plants are available. Operation of plants varies based on RAP feeding, virgin aggregate feeding, and other material considerations. Other factors that have an effect on achieving a properly heated mix are age of the plant, operator experience, and lack of temperature-measuring units, which requires operators to rely on judgment when heating and drying virgin aggregates.

Accordingly, extensive data collection is necessary to understand plant operation when a temperature-measuring unit is not available and to determine how plant operators control the temperature.

The current study collected only one type of data for one single mix. A solid conclusion cannot be made based on one sample calculation. However, this study helps bring this issue to the attention of the intellectual and professional community. Several HMA mixes with varying aggregate sizes, mix proportions, and other properties (coarse, fine, etc.) are recommended for future study.

7.3.3 Computational Modeling

It is impossible to see what is going on inside the drum while it is operating. However, temperature probes can be embedded inside the drum, and a temperature reading can be obtained from outside the drum. Generally, it is possible to measure the input (moisture content) and output (mix temperature) parameters. In some cases, not all the outputs (such as virgin aggregate temperature) can be observed. For this kind of situation, computational predictive modeling such as artificial neural network (ANN) or genetic algorithm (GA) can be used. Those models provide output based on “data training.” However, a significant amount of data is required in order to use those ANN or GA. The computational modeling can be done in parallel with extensive data collection from the plants.

7.3.4 Numerical Analysis

Finally, numerical analysis such as computational fluid dynamics (CFD) and discrete element method (DEM) modeling can be used to simulate the heating and drying process. Limited study has been done in this field, but recycled materials have not been used in the simulation. Numerical analysis helps provide an understanding of the complete heat transfer phenomenon in drying and heating materials.

7.3.5 Laboratory Study

Damage or burning caused by the superheated virgin aggregate to the virgin asphalt binder, aged binder coating on the RAP/RAS, and to the HMA is unknown. Further study can be done in the laboratory by heating virgin aggregates to a superheated temperature and then mixing them with virgin binder and/or with RAP/RAS. Such a study would supplement our understanding of the adverse effect of superheated virgin aggregates in the plant.

REFERENCES

Al-Qadi, I.L., Elseifi, M., and Carpenter, S.H. (2007). *Reclaimed Asphalt Pavement—A Literature Review*. Illinois Center for Transportation, Rantoul, IL.

Bražiūnas, J., and Sivilevičius, H. (2014). "Heat Transfer and Energy Loss in Bitumen Batching System of Asphalt Mixing Plant." 9th International Conference on Environmental Engineering. Vilnius, Lithuania.

Brock, J. D. (n.d.). Dryer Drum Mixer (T-119).

Daniel, J.S., and Hall, K. (Feb. 2014). "Research Project Proposal NETC 13-2 : HMA Mixtures Containing Recycled Asphalt Shingles (RAS): Low Temperature and Fatigue Performance of Plant-Produced Mixtures."

Frederick, G., and Tario, J.D. (2009). *Quantify the Energy and Environmental Effects of Using Recycled Asphalt and Recycled Concrete for Pavement Construction: Phase I Final Report*. New York State Department of Transportation, Albany, NY.

Gillespie, I. (2012). *Quantifying the Energy Used in an Asphalt Coating Plant*. M.S. thesis, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, UK.

Grabowski, W., and Janowski, Ł. (2010). "Issues of Energy Consumption During Hot Mix Asphalt (HMA) Production." 10th International Conference on Modern Building Materials, Structures and Techniques, Vilnius, Lithuania, pp. 89–92.

Le Guen, L., Huchet, F., Dumoulin, J., Baudru, Y., and Tamagny, P. (2013). "Convective Heat Transfer Analysis in Aggregates Rotary Drum Reactor." *Applied Thermal Engineering*, 54(1), pp. 131–139.

Hobbs, A. (2009). "Simulation of an Aggregate Dryer using Coupled CFD and DEM Methods." *International Journal of Computational Fluid Dynamics*, 23(2), pp. 199–207.

Hossain, M.I. (2013). *Modeling Moisture-Induced Damage in Asphalt Concrete*. Ph.D. dissertation, Department of Civil Engineering, University of New Mexico, Albuquerque, NM.

Hot-Mix Asphalt Paving Handbook (2000). AC 150/5370-14A. U.S. Army Corps of Engineers, Washington, DC.

Hot Mix Asphalt Recycling. (2007). Alaska Asphalt Pavement Summit, Anchorage, AK.

Hunter, R., Woodward, D., Lancaster, I., Brown S., Rockliff, D., Moore, J., Cluett, C., Hindley, G., Richardson, J., Whiteoak, D., and Farrington, J. (2000). *Asphalts in Road Construction*, 1st ed., Thomas Telford, London, UK.

Kandhal, P.S., and Mallick, R.B. (1997). *Pavement Recycling Guidelines for State and Local Governments Participants Reference Book*. Federal Highway Administration, Auburn, AL.

Kennedy, T.W., Scherocman, J.A., and Tahmoressi, M. (1986). *Drum Mix Plants—Equipment and Operations*. Center for Transportation Research, Austin, TX.

Lauredan, L.G., Florian, H., and Jean, D. (2014). "A Wall Heat Transfer Correlation for the Baffled-Rotary Kilns with Secondary Air Flow and Recycled Materials Inlet." *Experimental Thermal and Fluid Science*, 54, pp. 110–116.

Mannan, U.A., Faisal, H.M., and Tarefder, R.A. (2014). *Mechanical and Rheological RAP Characterization of NMDOT Mixes: Interim Report*. New Mexico Department of Transportation, Albuquerque, NM.

Ozer, H., Al-Qadi, I.L., and Kanaan, A. (2012). *Laboratory Evaluation of High Asphalt Binder Replacement with Recycled Asphalt Shingles (RAS) for a Low N-Design Asphalt Mixtures*. Illinois Center for Transportation, Rantoul, IL.

Plant, A. (2000). *Hot-Mix Asphalt Paving Handbook*.

Read, J., and Whiteoak, D. (2003). *The Shell Bitumen Handbook,* 5th ed., Thomas Telford, London, UK.

Recycling Hot Mix Asphalt Pavements. (1996). Information Series 123. National Asphalt Pavement Association, Lanham, MD.

Transportation Research Board. (2015). *Moisture Damage to Hot-Mix Asphalt Mixtures: Synopsis of a Workshop*. Transportation Research Circular E-C198. Washington, DC.

Young, T.J. (2007). *Energy Conversion in Hot-Mix Asphalt Production*. National Asphalt Pavement Association, Lanham, MD.

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