Innovations Deserving Exploratory Analysis Programs

NCHRP IDEA Program

Development of an Automated and Rapid Conditioning and Testing Device for Cracking and Rutting

Final Report for
NCHRP IDEA Project 224

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July 2023

NATIONAL ACADEMIES Sciences Engineering Medicine

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Development of an Automated and Rapid Conditioning and Testing Device for Cracking and Rutting

NCHRP IDEA Program Final Report

IDEA Project NCHRP 20-30/IDEA 224

Prepared for

The NCHRP IDEA Program
Transportation Research Board
National Academies of Sciences, Engineering, and Medicine

by

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EXECUTIVE SUMMARY

State departments of transportation (DOTs) are currently facing many challenges. Three such challenges involve addressing (a) the cracking and rutting distresses that are costing taxpayers billions of dollars annually, (b) the loss of both the workforce and the skills associated with the workforce, and (c) laboratory safety concerns to prevent worker injury. Many DOTs are addressing the cracking and rutting problems by implementing a balanced mix design (BMD) method to design durable mixes. However, the lack of workforce and workforce skills hinders such efforts. Additionally, the primary safety concern in the laboratory before COVID-19 was preventing worker injury often associated with the hot asphalt, large masonry saws, high-force testing machines, and toxic chemicals typically found in an asphalt material testing lab. While these are still primary safety concerns, COVID-19 has added another layer of safety issues. Automation of certain processes can alleviate all these safety concerns by reducing the number of employees exposed to the different hazards. The innovative solution to addressing these three current issues is to develop an asphalt mixture automated testing system with zero intervention (AMAZE), which was the goal of this research project.

AMAZE includes five components: (a) a rapid cooling subsystem, (b) an air void measurement subsystem, (c) a temperature conditioning subsystem, (d) a material testing subsystem, and (e) a robot arm. During this research project, automation was achieved with a robot arm for air void measurement, temperature conditioning, and cracking and rutting testing. Figure 1 shows the current AMAZE.

FIGURE 1 Asphalt mixture automated testing system with zero intervention (AMAZE).

Figure 2 shows the asphalt mixture properties (cracking tolerance index [CT_{Index}] and rutting tolerance index [RT_{Index}]) measured by AMAZE versus a laboratory technician. The measured asphalt mixture properties are very similar.

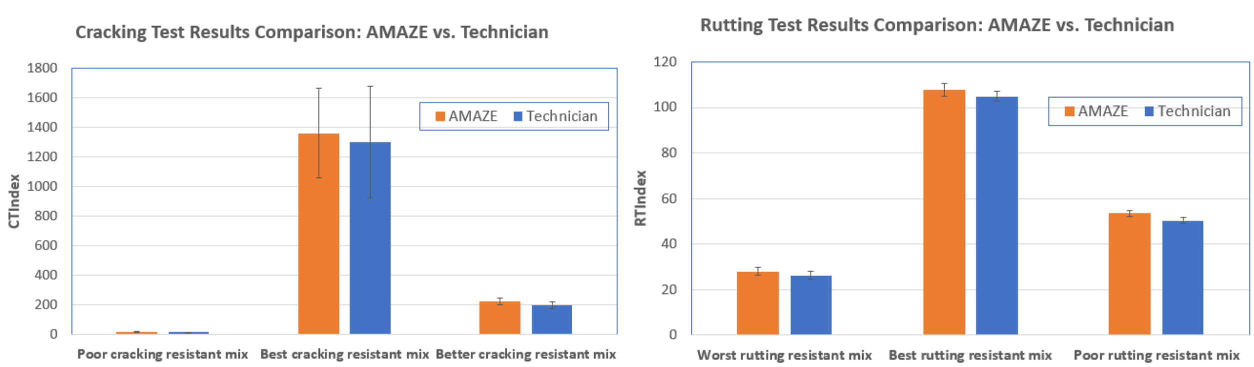


FIGURE 2 Asphalt mixture properties comparison between AMAZE and laboratory technician.

To facilitate implementation, the research team developed a step-by-step plan. Furthermore, an equipment manufacturer is preparing to manufacture the whole system so that highway agencies and asphalt industry professionals can easily purchase it.

Every year, around 360 million tons of asphalt mixes, with a cost of more than $20 billion, are placed on roads in the United States. Repairing pavement distresses and failures (such as fatigue cracking and rutting) associated with asphalt mixes cost taxpayers billions of dollars. Given this large amount of taxpayer money and the unsatisfactory cracking and rutting performance of current asphalt mixtures, implementing AMAZE can help ensure that durable asphalt mixes last 15 percent longer than existing mixes by directly evaluating and verifying both rutting and cracking resistance of the asphalt mixtures. The estimated savings will be significant. Use of this system will also reduce maintenance costs, associated traffic delays, and travel time for every road user.

IDEA PRODUCT

The IDEA product described herein is an asphalt mixture automated testing system with zero intervention (AMAZE), as shown in Figure 1. The system includes five components: (a) a rapid cooling subsystem, (b) an air void measurement subsystem, (c) a temperature conditioning subsystem, (d) a material testing subsystem, and (e) a robot arm. During this research project, automation was achieved with a robot arm for air void measurement, temperature conditioning, and cracking and rutting testing.

Currently, neither cracking nor rutting tests are used at plants to evaluate asphalt mix cracking or rutting resistance during mix production, or to identify and eliminate cracking- or rutting-prone mixes from being paved on the road. This is because the current state-of-practice tests require at least a day to cool, condition, and test hot cylindrical specimens immediately out of a Superpave gyratory compactor mold, which is not practical for controlling mix performance quality during its production. The innovative AMAZE product makes it possible for state departments of transportation (DOTs) and asphalt industry professionals to evaluate asphalt mix cracking and rutting resistances as part of the daily quality control/quality acceptance (QC/QA) testing during mix production. This testing ensures the consistency and performance quality of the mix by identifying and eliminating cracking- or rutting-prone mixes from being placed on roads. Every year, around 360 million tons of asphalt mixes, with an associated cost of around $20 billion, are placed on roads in the United States. It is expected that this new system can increase the life of asphalt mixes by a minimum of 15 percent. The estimated savings is $3.0 billion annually. The system will also reduce maintenance costs, traffic delays, and travel time for every road user.

CONCEPT AND INNOVATION

INTRODUCTION

Every year, around 360 million tons of asphalt mixes, with a cost of more than $20 billion, are placed on roads in the United States. Repairing pavement distresses and failures (such as fatigue cracking and rutting) associated with asphalt mixes cost taxpayers billions of dollars annually. Many DOTs are addressing these problems by employing a BMD method to design durable mixes. However, a good mix designed with balanced cracking and rutting resistance in the lab may not guarantee good performance in the field because of variations in asphalt mix production and placement. Regardless of how well a mix is designed in the lab, if it deviates from its original design during production, which is often the case, its field performance is in jeopardy. Currently, neither cracking nor rutting tests are used at plants to evaluate asphalt mix cracking or rutting resistance during mix production, or to identify and eliminate cracking- or rutting-prone mixes from being paved on the road. This is because the current state-of-practice tests require at least a day to cool, condition, and test hot cylindrical specimens immediately out of a Superpave gyratory compactor mold, which is not practical for controlling mix performance quality during its production. Meanwhile, DOTs are facing another challenge: losing both the workforce and the skills associated with the workforce. Additionally, the primary safety concern in the laboratory before COVID-19 was preventing worker injury often associated with the hot asphalt, large masonry saws, high-force testing machines, and toxic chemicals typically found in an asphalt material testing lab. While these are still primary safety concerns, COVID-19 has added another layer of safety issues. Automation of certain processes can alleviate all these safety concerns by reducing the number of employees exposed to the different hazards. The innovative solution to addressing these three current issues is to use the AMAZE device developed in this project to evaluate asphalt mix cracking and rutting resistance in the lab or at contractor plants. This research is the first step toward defining and implementing automation tools in the laboratory to optimize efficiency and safety.

Literature Review of Laboratory Cracking and Rutting Tests

Currently, QC/QA testing during mix production includes asphalt content, aggregate gradation, and laboratory compaction density. These three characteristics of asphalt mixes are important, but they do not directly characterize mix performance. Both cracking and rutting tests are needed to ensure good quality of mixes produced at asphalt plants. Tables 1 and 2 show common cracking and rutting tests in the literature, respectively. However, most of these tests are not suitable for QC/QA testing because they take days to complete, while QC/QA testing requires results within 2–3 hours (or less). Considering this specific QC/QA testing requirement, the only cracking test suitable for QC/QA is the Ideal cracking test (IDEAL-CT) (*1, 2*) because the IDEAL-CT does not require instrumentation or cutting/notching and can be performed using low-cost test equipment within 2 minutes. Meanwhile, two rutting tests can be used for QC/QA testing: the Marshall stability test and the Ideal rutting test (IDEAL-RT). IDEAL-RT is preferred because it directly measures the shear strength of asphalt mixes and has good correlation with field rutting performance (*3*). Although Marshall stability is widely used, it does not have good correlation with field rutting performance (*4*). In summary, IDEAL-CT and -RT are the best candidates for QC/QA testing. Thus, IDEAL-CT and -RT were selected as the foundation for developing the AMAZE device.

TABLE 1 Common Asphalt Mix Cracking Tests

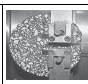
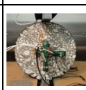
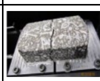
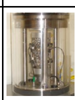
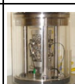
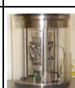
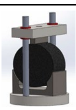
Test standard		**Cracking parameter**	**Test temperature**	**No. of specimens**	**Specimen preparation and testing time**	**Equipment cost**	**Overall practicality for QC/QA**
ASTM D7313 DCT		Fracture energy	PG low+10°C	3	5 cuttings and 2 holes per specimen; Total time: 4-5 days	$50,000	Poor
AASHTO TP105 SCB-low temp.		Fracture energy	PG low+10°C	3	5 cuttings/2 specimens and 2 sensors; Total testing time: 3-4 days	$100,000	Poor
ASTM D8044 SCB-Jc		Jc-Critical strain energy release rate	25°C	12	7 cuttings per 4 specimens; Total testing time: 7-8 days (including 5-day at 85°C aging)	<$10,000	Poor
AASHTO TP124 SCB-FI		Flexibility index	25°C	6	5 cuttings per 2 specimens; Total testing time: 2-3 days (including sample drying)	<$10,000	Fair
IDT-University of Florida method		Energy ratio	10°C	3	2 cuttings per specimen and 4 sensors; Total testing time: 4-5 days	>$100,000	Poor
Tex-248-F OT		Gc, crack resistance index	25°C	3	4 cuttings per specimen and gluing; Total testing time: 3-4 days	$50,000	Poor
AASHTO T321 BBF		No. of cycles	20°C	3	6 cuttings per specimen; Total testing time: 3-5 days	>$100,000	Poor
AASHTO TP107 AMPT cyclic fatigue test		Fatigue damage parameters	Intermediate temperature	4 (+3 for E* test)	1 coring and 2 cuttings/specimen and gluing Total testing time: 4-5 days	$85,000	Poor
ASTM D8225 IDEAL-CT		Crack tolerance index (CT_{Idnex})	25°C	3	No cutting or gluing; Total testing time: 1 day	<$10,000	Good

TABLE 2 Common Asphalt Mix Rutting Tests

Test standard		**Cracking parameter**	**Test temperature**	**No. of specimens**	**Specimen preparation and the total time (including specimen preparation and testing)**	**Equipment cost**	**Overall practicality for QC/QA**
ASTM D6927 Marshall stability test		Marshall stability	60°C	3	No cutting or gluing; Total time: 1 day	<$10,000	Good
AASHTO T324 HWTT		Rut depth	50°C (others)	4	1 cutting per specimen; Total time: 2 days	$50,000	Fair
AASHTO T340 APA		Rut depth	64°C (others)	4	No cutting or gluing; Total time: 2 days	>$100,000	Fair
AASHTO TP79 Flow number test		Flow number	High temperature	3	1 coring and 2 cutting per specimen; Total time: 4 days	$85,000	Fair
AASHTO T320 Superpave SST		Permanent shear strain	High temperature	3	Gluing and instrumentation; Total time: 2 days	>$100,000	Poor
AASHTO TP116 iRLPD test		Minimum strain rate	55°C	3	1 coring and 2 cutting per specimen and gluing; Total time: 4 days	$85,000	Poor
AASHTO TP134 Stress sweep rutting (SSR) test		Permanent deformation model	High and low temperature	4	1 coring and 2 cutting per specimen and gluing; Total time: 4 days	$85,000	Poor
ASTM D8360 IDEAL-RT		Shear strength	50°C	3	No cutting or gluing; Total time: 1 day	<$10,000	Good

Objective

The objective of this study was to develop an AMAZE device for evaluating asphalt mix cracking and rutting resistance during BMD and asphalt mix production at asphalt plants. **The key to this entire study was automation.** Thus, the concept of automation is discussed in the following section.

PROGRAMMABLE AUTOMATION TECHNOLOGY

The term *programmable automation technologies* is sometimes used to refer to generalized equipment that is made general purpose through the use of programmable user interfaces like those used for computer numerical control (CNC) machines, programmable logic controller (PLC), and robots. For the purposes of this study, two forms of automation—dedicated and general purpose—were considered candidates for use in the lab and categorized more according to functionality than control interface, as discussed below.

- **Dedicated** solutions tend to be less expensive to implement, but they are more limited in capabilities because they are dedicated to a specific operation in a specific application. This type is basically interchangeable with the industry terminology **fixed automation**. These solutions may or may not be programmable with an electronic interface. Those that are not programmable may rely on limit switches, cams, and/or other types of simple mechanical or electromechanical controls. They tend to be one or two axis devices or cam systems with a motor drive. An example of a dedicated solution without an electronic interface other than an on-off switch would be the older soils/base drop hammer compaction devices that used a guide rod and motor system to semi-automate the compaction process and decrease reliance on a technician manually raising and dropping a weight from a standard height and moving it around between drops.
- **General purpose** devices tend to have higher initial costs, but they are more capable. These include industrial robots with electronic control interfaces that can be programmed to do many different tasks either within one program or by changing programs to suit the task of the day. Therefore, these machines tend to

be better than dedicated solutions for procedures that (a) may change significantly over time, (b) are fairly complex, or (c) need to be portable to move from one location (or operation) to another. They tend to mimic human handling operations, so they are good for relatively complex or hazardous repetitive material handling tasks and have multiple axes of movement (e.g., degrees of freedom, or joints). Figure 3 presents the terminology describing a six-axis robot. The terminology generally follows that of the human body, with the exception of the **end effector**. In this report, the end effector is also referred to as the **gripper** or the **hand**.

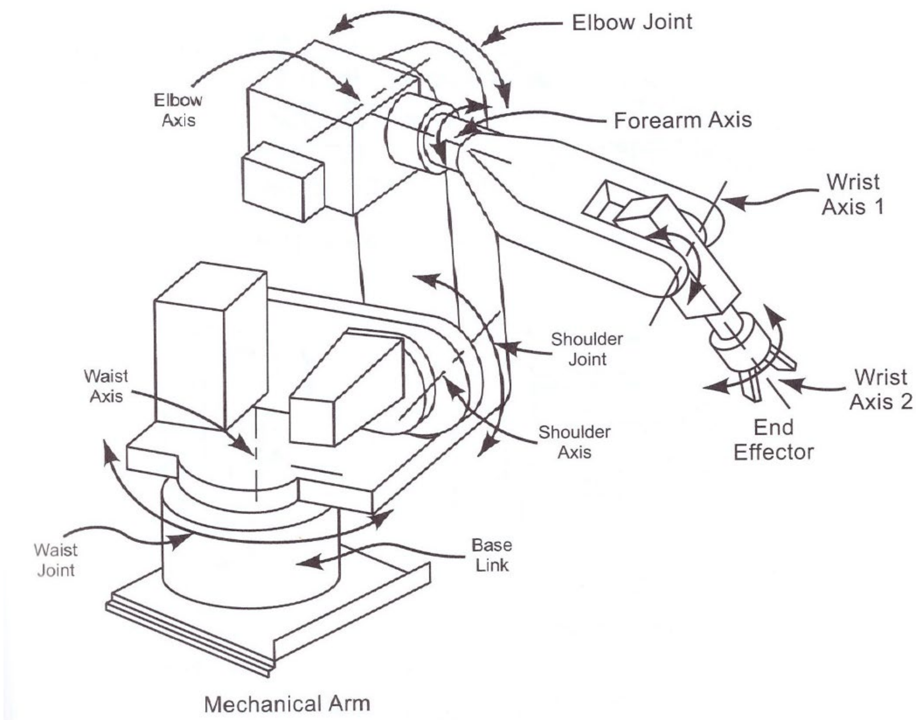


FIGURE 3 Robot terminology (*5*).

Automation Concept for Transportation Construction

When looking at training video productions, any place an operator's hand is shown operating a switch, operating a computer, or handling a specimen is a candidate for automation. Typically, an automation can perform these tasks more quickly, precisely, safely, and consistently than the average human operator. A laboratory production cell is to be developed that:

- produces a report (and/or control signals to other upstream and downstream operations) on the properties of hot mix,
- minimizes the time between molding and reporting,
- uses automation when feasible and appropriate, and
- makes efficient use of employee capabilities while enhancing employee safety.

The focus is on laboratory processes in general and specific test suite(s) in particular. However, the conceptual approach can be extended to field construction and testing operations without much imagination. While a test suite automation is discussed herein, the scope of the concept must be larger than a test suite. An automation concept for transportation construction is shown in Figure 4, where the laboratory test suite, or production cell, might fit in the overall pavement construction process.

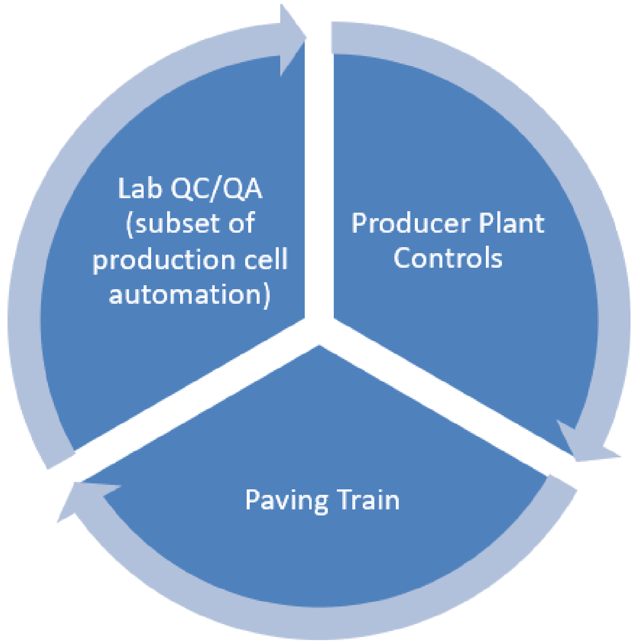


FIGURE 4 Larger scope of automation concept for transportation construction.

Scope of This Study

In this study, programmable automation was the focus. The term *programmable* as used here means that the automation should have at least some components that could be easily adapted to new functionality. This adaptability is intended to make it relatively easy and fast to alter the mechanics of the automation to fit changing tests and processes so that as processes are perfected, the benefits of the initial capital investment in automation may continue to be realized. A three-tiered laboratory automation development process is envisioned (Figure 5).

- **Tier 1: Individual Test Optimization** comprises (a) optimizing tests to take advantage of automation activities, and (b) replacing cumbersome tests with new tests optimized for efficiency. For example, a particular pair of tests might be used to fully evaluate/specify the acceptability of a material. If that pair of tests uses the same basic equipment but different fixtures, automation can be used to take the operator out of the fixture swapping process. Alternatively, if the pair of tests is done on separate host equipment (e.g., the overlay and the Hamburg), optimization may involve an alternative testing system that produces balanced evaluation of rutting and cracking potential.
- **Tier 2: Interfacing Multiple Procedures** comprises all activities appropriate to streamlining full processes from raw material to finished material evaluation. In this category, an example might be the interfacing required to automate a process involving multiple steps, such as wet sawing, drying, inserting in a testing machine, running a test, and disposing of the tested material.
- **Tier 3: Integrating Entire Lab Operations** builds upon the foundations of automation to optimize flow through the lab, from receipt of materials, to engineering measurement and compliance evaluation, to final material disposition.

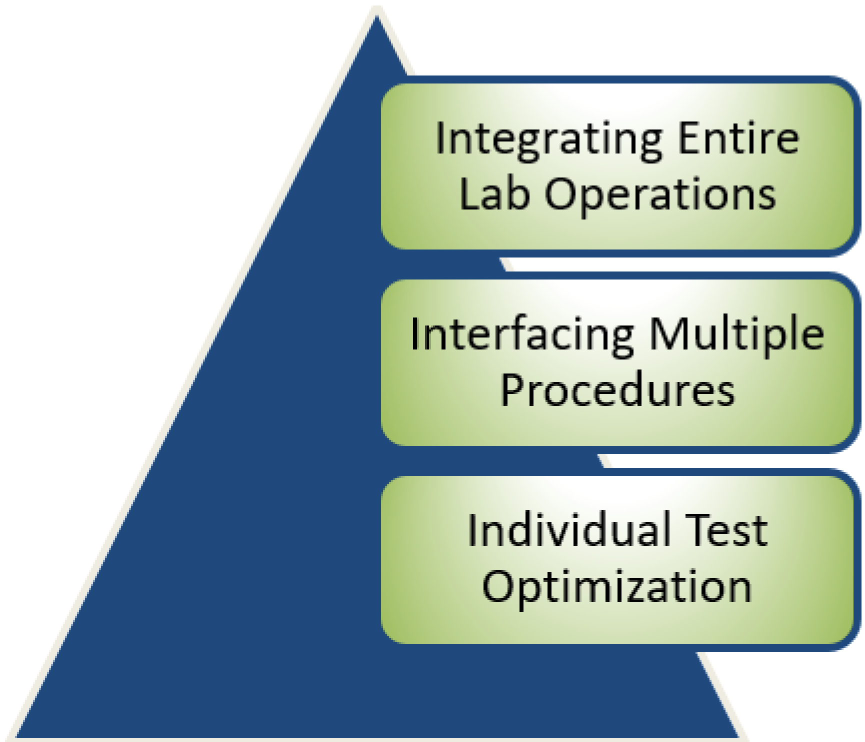


FIGURE 5 Tiered process for laboratory automation implementation.

This study focused on Tiers 1 and 2—**individual test optimization** and **interfacing multiple procedures**—as the initial development efforts and proof of concept (Figure 6). The proof of concept is intended to provide a model for developing **laboratory production testing cells**. In this study, the testing and interfacing involved a rapid cooling system to cool specimens after gyratory molding, an automated method of performing air void measurement, a final temperature stabilization station, an integrated test procedure for cracking and rutting, and automated specimen handling equipment (Figure 6). The end result was a cracking and rutting evaluation cell targeting near-real-time QC/QA goals. The model provides a guide for future efforts to establish similar cells for operations such as Hamburg testing, binder rheology testing, and hot-mix mixing and molding, in addition to applications outside the hot-mix lab (e.g., for aggregate, soils, and Portland cement concrete).

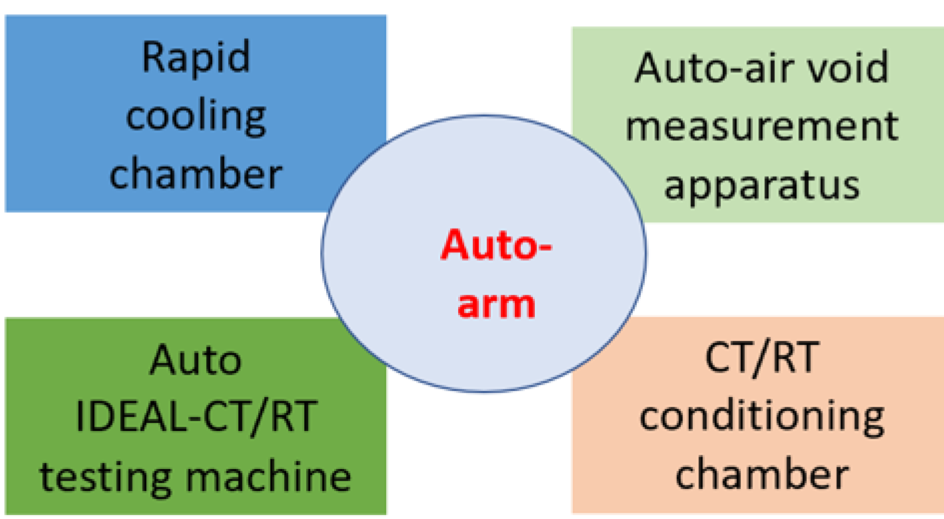


FIGURE 6 Individual test optimization and interfacing.

AMAZE DEVICE OVERVIEW

A schematic example of a lab production cell is presented in Figure 7. Although not presented in a U-shaped arrangement, several of the stations are illustrated as being within reach of the robot arm depicted in the middle with the light yellow circle. There are four major automated workstations in the cell, all of which are fed by material handling processes and controlled by a supervisory function, and at least two of which feed data back to the supervisory function and to engineering/reporting. The current vision is for supervisory work to be done by a PLC, but a PC computer may also be used. The illustration shows a human as part of the supervisory function, but the automation process should reduce the time that human presence is required in the cell. A long-term goal might be lights-out production testing, which means the human supervisor would simply be on call to deal with problems in the cell when notified remotely by the process control functionality in the cell.

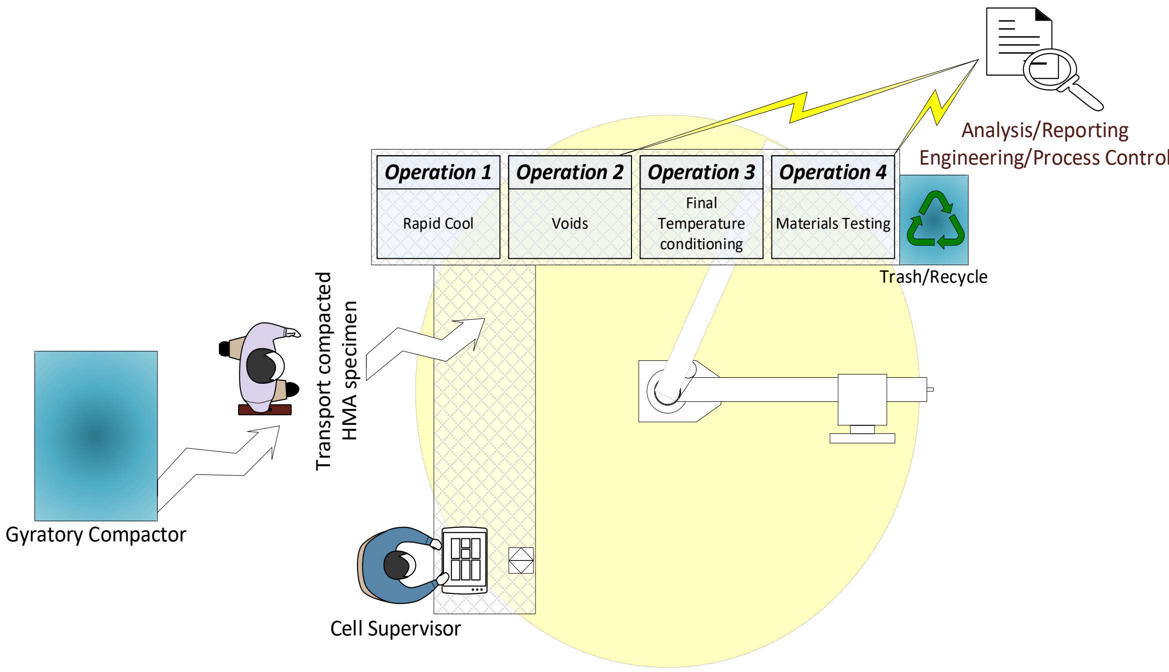


FIGURE 7 QC/QA production cell schematic.

CONCEPTUAL DESIGN OF THE AMAZE SUBSYSTEMS

As previously discussed, the AMAZE device includes at least five subsystems: (a) a rapid cooling subsystem, (b) an air void measurement subsystem, (c) a final temperature conditioning subsystem, (d) a material testing subsystem, and (e) a robot arm. Each of the five subsystems is described below.

Rapid Cooling

Several options have been explored to rapidly cool a recently compacted specimen down to room temperature. Often, the current procedure is to extrude it from the compaction mold, move it to a counter in front of a fan, and let it cool by air movement until it is either tested or put in an environmental chamber. A QC/QA test must do better than this. As noted earlier, it is beyond the scope of this research to address the specimen handling immediately after extrusion. Asphalt specimens are typically very tender at that point and require careful handling. Such handling might be the subject of additional cell development during follow-up studies, and the solution might be a robot with a specialized grip or spatula system that is instrumented for measuring force so that the stresses applied to the hot specimen can be standardized and controlled even better than would be possible with multiple technicians trying to match their grip strengths. Since the full process is beyond the scope of the initial research, the plan is to extrude the specimen, put it in front of a fan for the bare minimum of time to allow human handling, and transport it to the automation cell. In order to rapidly cool the specimen from that elevated temperature state down to room temperature, additional efforts are required. Environmental chambers have been eliminated because they are too slow. The same appears to be true of liquid (e.g., water) baths according to recent testing with a high-end reef tank aquarium refrigeration unit (although the highest horsepower units were not tested, and the recirculating water volume was on the low end, so there may still be a possibility of success with this approach). The approach chosen for further investigation is a plate cooler device (Figure 8). A large commercial version of this concept is found on fishing trawlers that need to process and freeze their catch in a very short time on board the fishing vessel. The unit envisioned for use in the automated lab cell is much smaller than that used by fishing vessels, but the principle is similar. The operational sequence for this workstation is described below:

1. Receive a hot specimen from the upstream process (i.e., compaction and minimal fan cooling) and place it on a surface at the same height as the lower cooling plate.
2. Clamp the specimen with minimal force in the gripper (note: the specimen stays clamped in the gripper until step 6 because the gripper will provide insulation and/or possibly additional cooling).
3. Trigger the horizontal actuator to slide the specimen onto the lower cooling plate.
4. Trigger another actuator (vertical, not shown) to move the top cooling plate down on top of the specimen.
5. When the specimen temperature reaches room temperature (based on sensing and research on time required with various mixtures), raise the top plate and slide the specimen over to the next downstream workstation (void measurement).
6. Release the specimen clamp and retract the actuator to process the next specimen from the upstream process.

Although this scenario might be interpreted to have 3 degrees of freedom (horizontal, vertical, and the grip open/close) and might be easily controlled with PLC logic, it is considered a dedicated automation solution because it is specific to the operation.

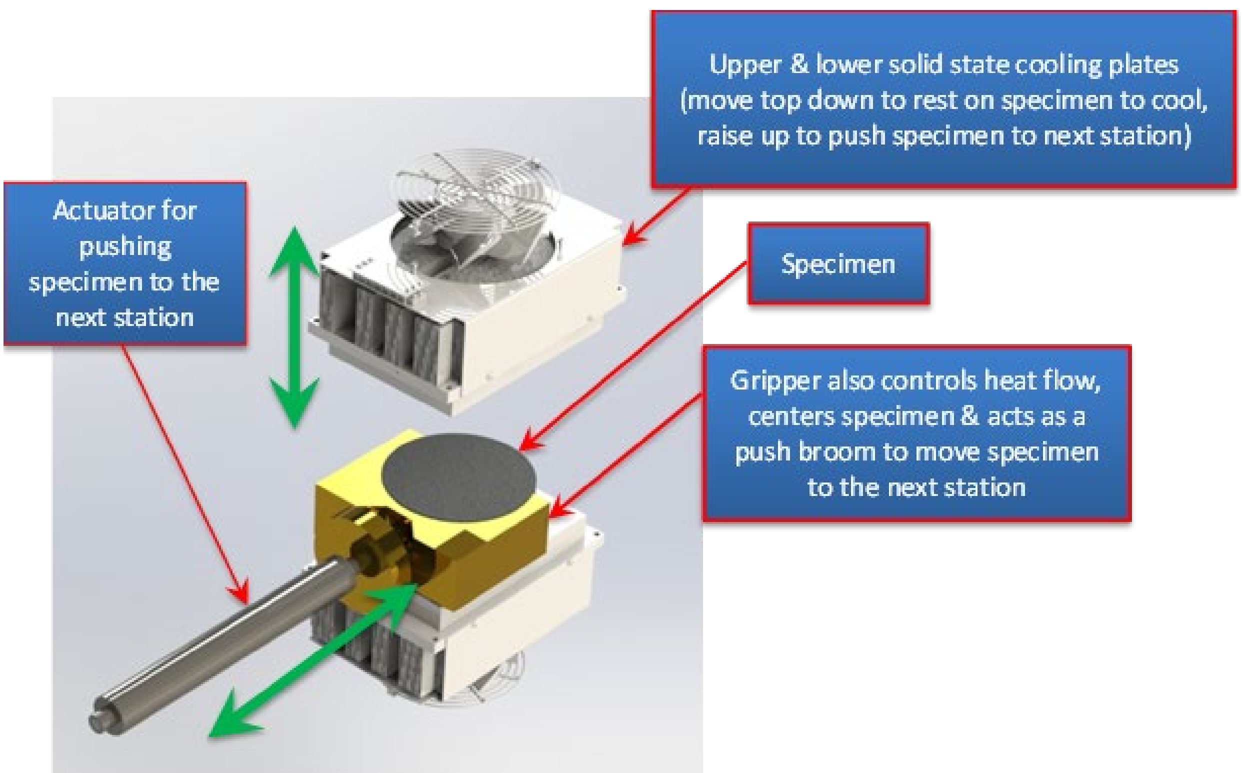


FIGURE 8 Rapid cooling concept.

Air Void Measurement

One method of obtaining voids utilizes the saturated surface dry (SSD) weight of the specimen in the computations. This process could benefit from automation. Figure 9 illustrates the sequencing of the tasks performed at this stage along with the immediate upstream and immediate downstream tasks.

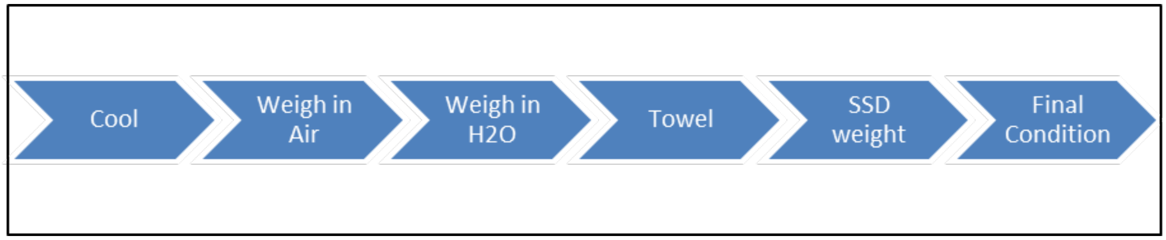


FIGURE 9 Air void measurement sequencing.

Automation of the four tasks shown in the middle of the figure is presented in Figure 10 and Figure 11. The steps involved in this process are:

1. Push the specimen onto the weighing basket plate from the upstream operation (rapid cooling).
2. Weigh the specimen in air and electronically record the weight in the analysis program.
3. Lower the specimen into the water using the actuator.
4. Weigh the specimen in water, transmit the data, and lift the specimen back out of the water with the actuator.
5. Push or pick and place the specimen on the automated SSD towel and close the flat surface dryer disks on the specimen.
6. Roll the towel back and forth for the prescribed time.
7. Put the specimen back on the weighing basket plate, weigh SSD, and transmit the data.
8. Remove the specimen from the weighing basket plate and move it to the next downstream operation.

FIGURE 10 Automated immersion and weighing in water.

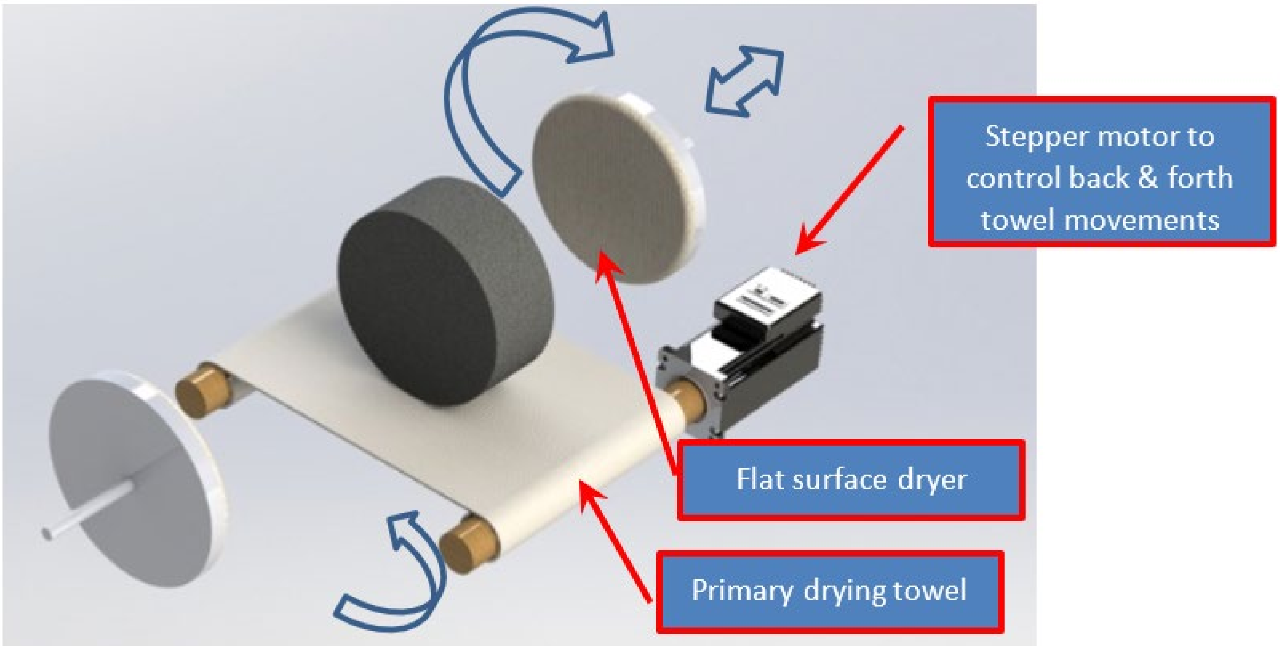


FIGURE 11 Automated SSD concept.

Figure 10 shows the specimen being lowered into the water by the vertically oriented actuator at the top of the figure. The load cell mounted to the rod end of the actuator measures the weight in water and reports that weight to the data acquisition and analysis program to be combined with the weight in air and SSD weight measurements taken in other parts of the sequencing diagram to compute voids.

Figure 11 presents an approach to preparing for SSD weight measurement. The approach is shown with the cylindrical axis of the specimen horizontal, but other orientations may be possible. The model shows two dowel rods with each end of a towel wrapped around them. A stepper motor is attached to one of these dowels, and another device (e.g., another stepper motor, or a constant force spring like a clock spring) is attached to the other dowel. The stepper motor drives the entire drying process for the exact amount of time required by the specification. Also shown in the figure are two flat surface dryers. These are similar to car polishing bonnets, but they freewheel in rotation and have actuators (not shown) that push them in and out along the axis of rotation so that they can be snugged up against the specimen for drying and retracted when the specimen needs to be moved. When the towel is moved back and forth by the stepper motor, the flat disks simply rotate to allow the specimen to rotate, enabling the system to dry both flat surfaces and the cylindrical surface at the same time. For example, when looking at the device from the bottom left corner of the figure, the arrows show a counterclockwise rotation by the stepper motor, which in turn causes the flat surface dryer to rotate clockwise. In order to dry the entire cylindrical surface, the length of the towel must be more than the circumference of the specimen. Techniques to keep the towel and polishing bonnets at the correct level of moisture have not been finalized but could be done with moisture sensors or simply by researching the median time and number of specimens that generate a need to swap out these components for fresh ones. Also, for the towel component, it may be possible to put a large number of wraps on the towel bar and then use the stepper motor(s) to renew the part of the towel that is in contact with the specimen simply by wrapping the old part onto one dowel and rolling the new part off the other dowel.

Final Temperature Conditioning

For the CT test, the specimen temperature should be at or very close to the testing temperature at the end of the SSD operation. However, the RT specimen must go through an additional temperature adjustment to a specified temperature that is based on local conditions and may not be the same for every mix, even at the same lab. In the event that CT specimens do not need any further conditioning before testing, a single-temperature conditioning unit (e.g., a fluid bath [Figure 12]) for the RT specimens may be all that is necessary. If an additional bath is required, a divided system may be used. At present, this final temperature change is planned to be done with a fluid bath, but other options may work, depending on how much different the RT test temperature must be from room temperature. The flowchart for routing the two types of specimens through the cell is given in Figure 13.

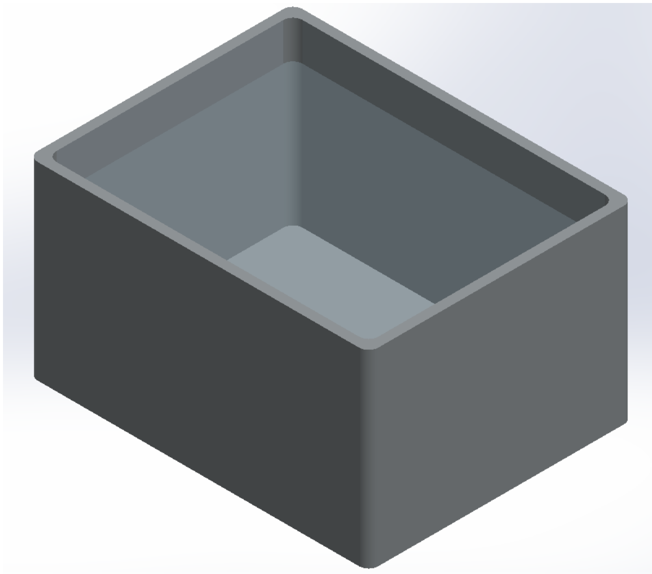


FIGURE 12 Single-temperature bath approach.

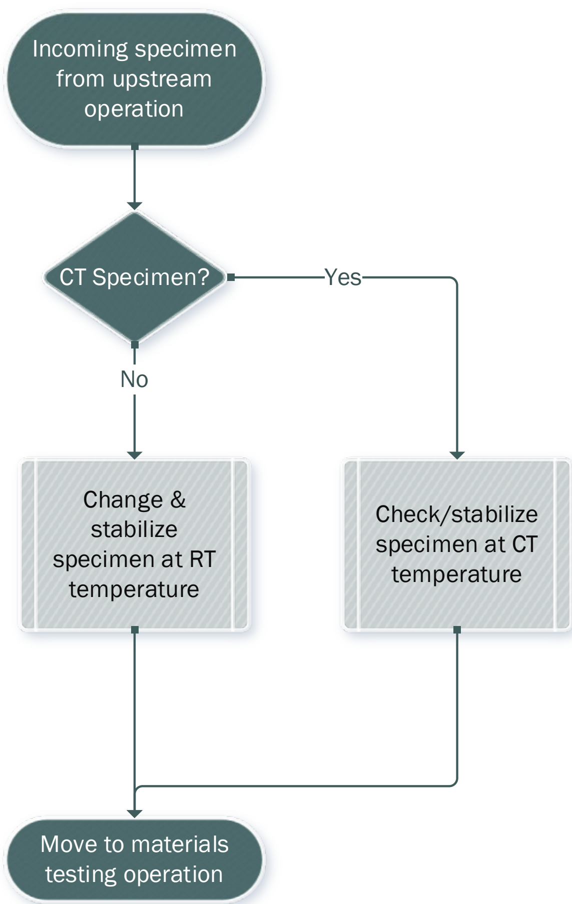


FIGURE 13 Flow of specimens for cracking and rutting tests.

Material Testing

Although a robot arm could be configured to perform testing as well as material handling, use of a load frame (Figure 14) is a more realistic and economical solution for testing the specimen. The CT/RT jig is placed in the load frame to accomplish the tests. One solution to automate the jig is to manufacture the CT load strip with an eccentric shaft location so that when the shaft is turned 180 degrees (e.g., by a stepper motor or solenoid or cam system), the CT loading surface is raised up and supports the specimen above the RT surfaces. When it is rotated back to zero, the CT surface is pointing down and the specimen is resting on the two RT surfaces with a clearance between the CT bar and the bottom of the specimen to allow for development of shear strains and failure deformations.

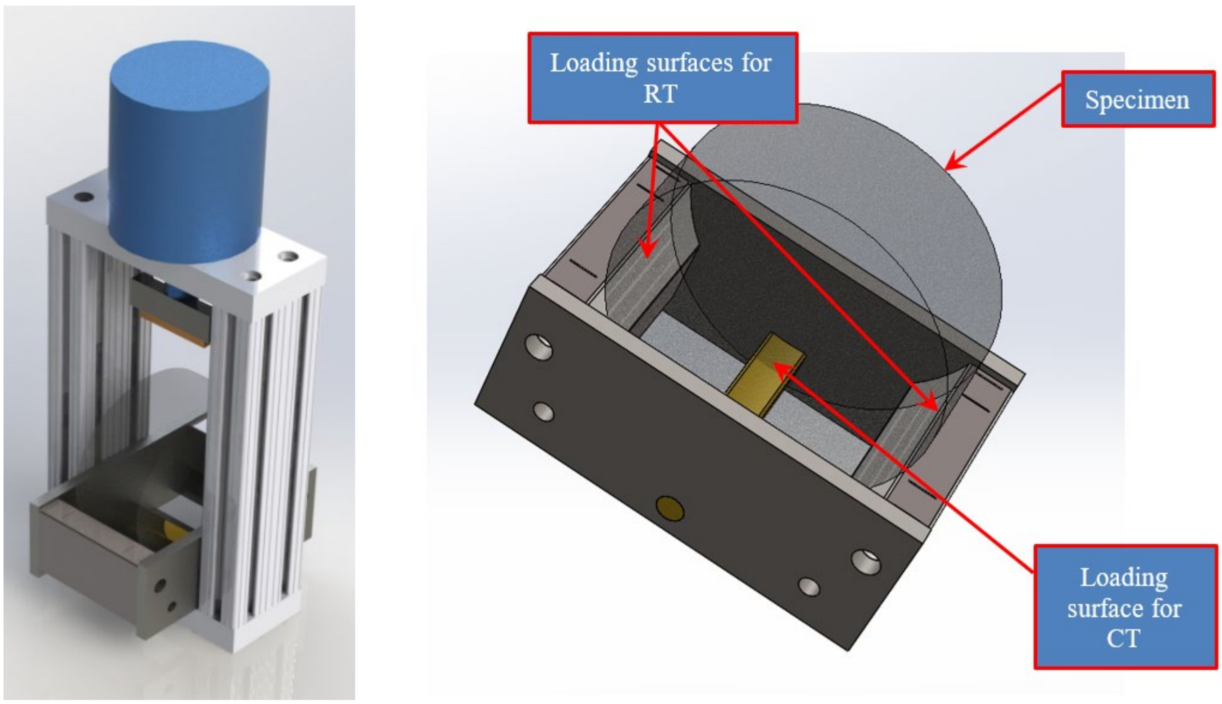


FIGURE 14 Simplified depiction of a CT/RT testing load frame with combined CT/RT fixture.

INVESTIGATION

Once the conceptual designs were completed for the subsystems, the research team started evaluating each one and building individual subsystems. The evaluation and building process was not straightforward but was instead a trial-error process. In some cases, a completely new design had to be developed.

EVALUATION OF RAPID COOLING CONCEPT

Based on the conceptual design of the rapid cooling shown in Figure 8, the research team purchased two thermoelectric coolers and mounted them in a frame (Figure 15). Then a series of tests were conducted. Figure 16 shows an example of the specimen temperature drop with time. It took 15 minutes to drop the specimen temperature at the center of the specimen from 70°C to 25°C. However, the thermoelectric cooler used in the rapid cooling subsystem shown in Figure 15 is relatively expensive. To reduce the cost, the research team is currently evaluating a very simple cooling setup (Figure 17). The new setup only needs two powerful fans. Figure 18 shows the temperature dropping curve. The data shown in Figure 18 are very promising. The research team is improving the rapid cooling setup shown in Figure 17.

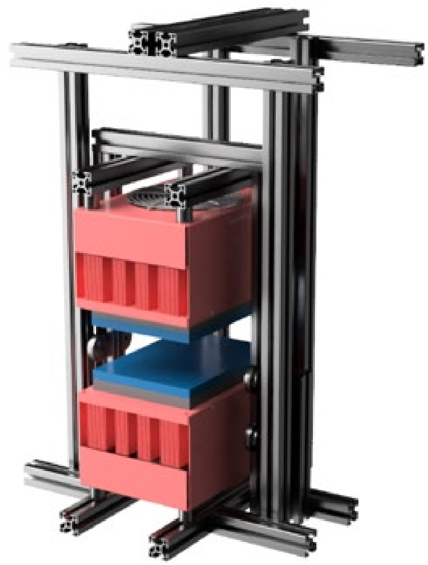


FIGURE 15 Rapid cooling subsystem.

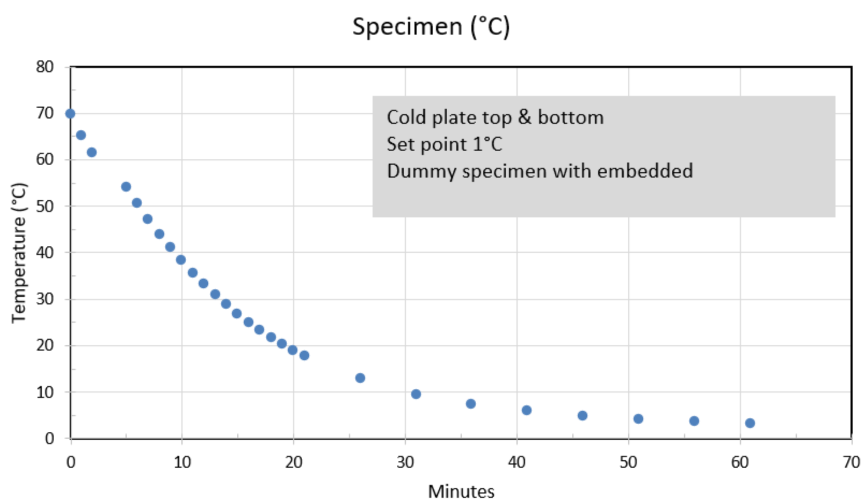


FIGURE 16 Specimen temperature drop with time using the setup shown in Figure 15.

FIGURE 17 Rapid cooling system with two fans.

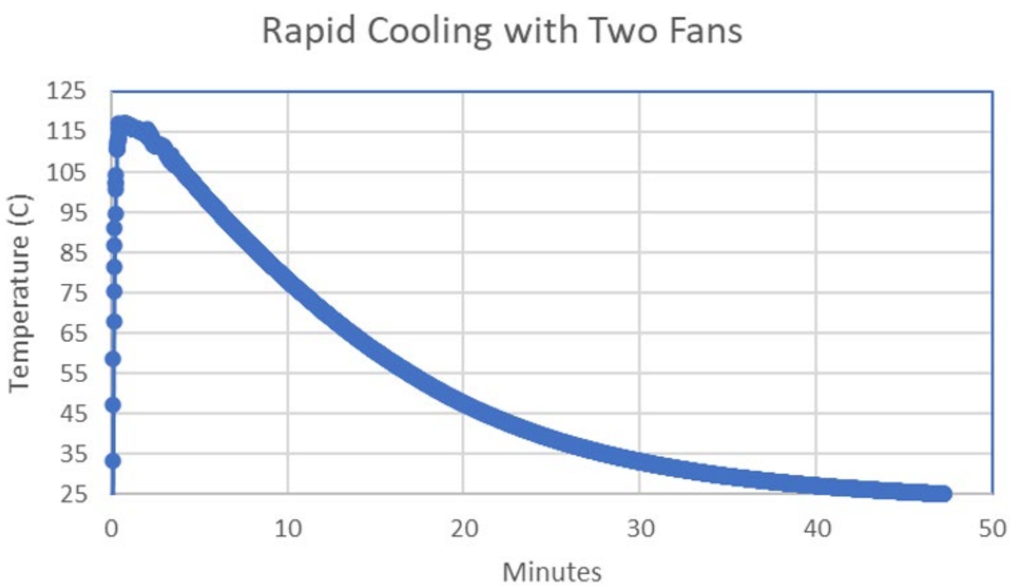


FIGURE 18 Specimen temperature dropping curve using the setup shown in Figure 17.

EVALUATION OF AIR VOID MEASUREMENT SUBSYSTEM

Based on the conceptual design of the air void measurement subsystem illustrated in Figure 9, Figure 10, and Figure 11, the research team purchased some of the components and manufactured a trial setup. However, the trial did not turn out as expected. The research team then went back to the traditional way of measuring the air voids of asphalt specimens using a digital scale and water tank. Figure 19 shows the setup to measure the dry weight and the weight of a specimen in the water. First, the robot arm puts the specimen on the scale to measure its dry weight. Then the robot picks up the specimen and places it on a basket, followed by lowering the basket with the specimen into a water tank through two linear actuators to measure the weight of the specimen in the water. Next, the two linear actuators lift the basket and the specimen. Then the wet specimen is removed by the robot arm to perform the SSD process (Figure 20). After that, the robot arm moves the SSD specimen to the scale to record the SSD weight. Based on the recorded dry weight, weight in the water, SSD weight, and material rice value, the computer automatically calculates and outputs the specimen air voids (Figure 21). The accuracy and consistency of the final air voids measurement subsystem are discussed later.

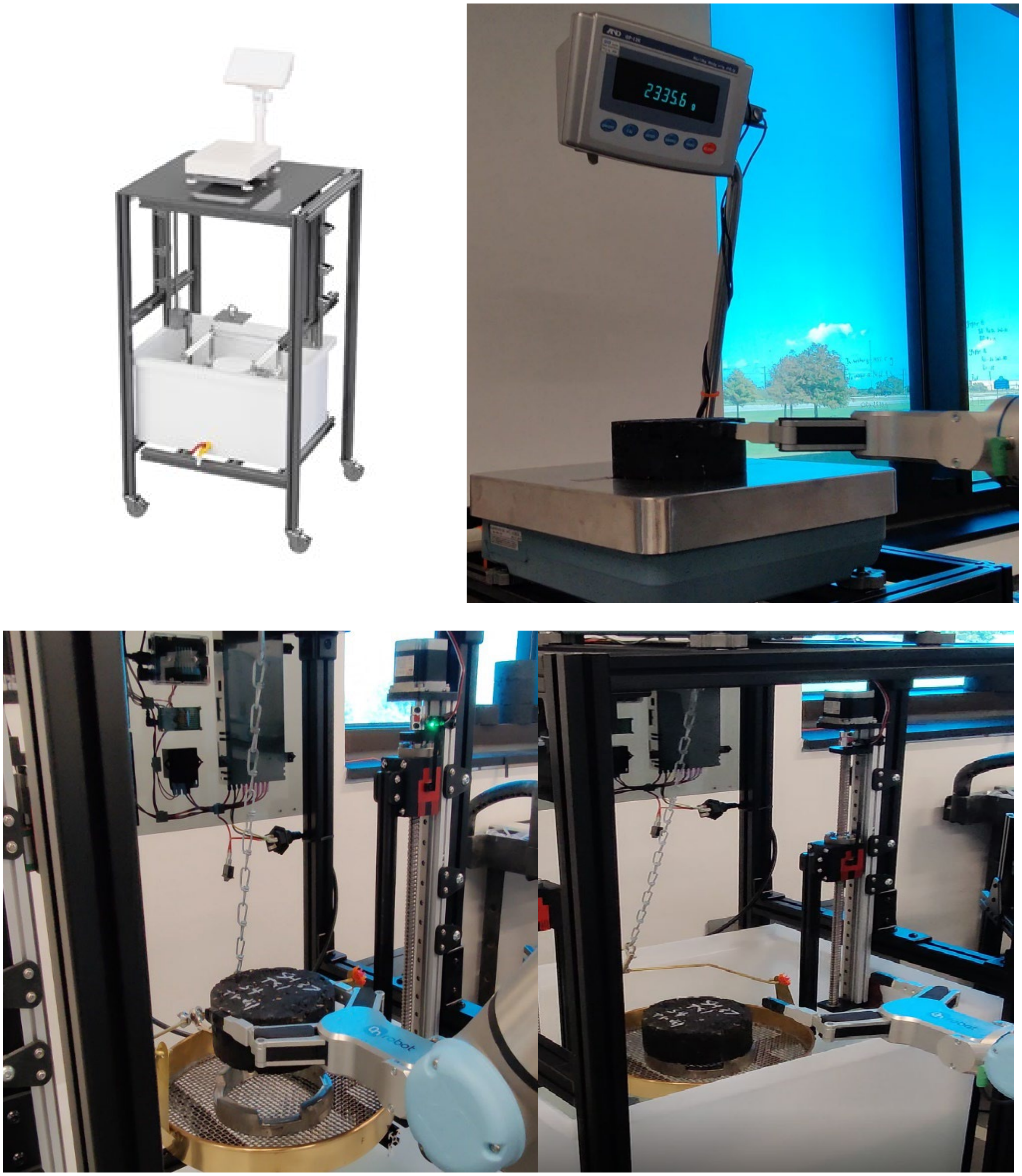


FIGURE 19 Test setup for measuring specimen: Dry weights, weight in the water, and SSD weight.

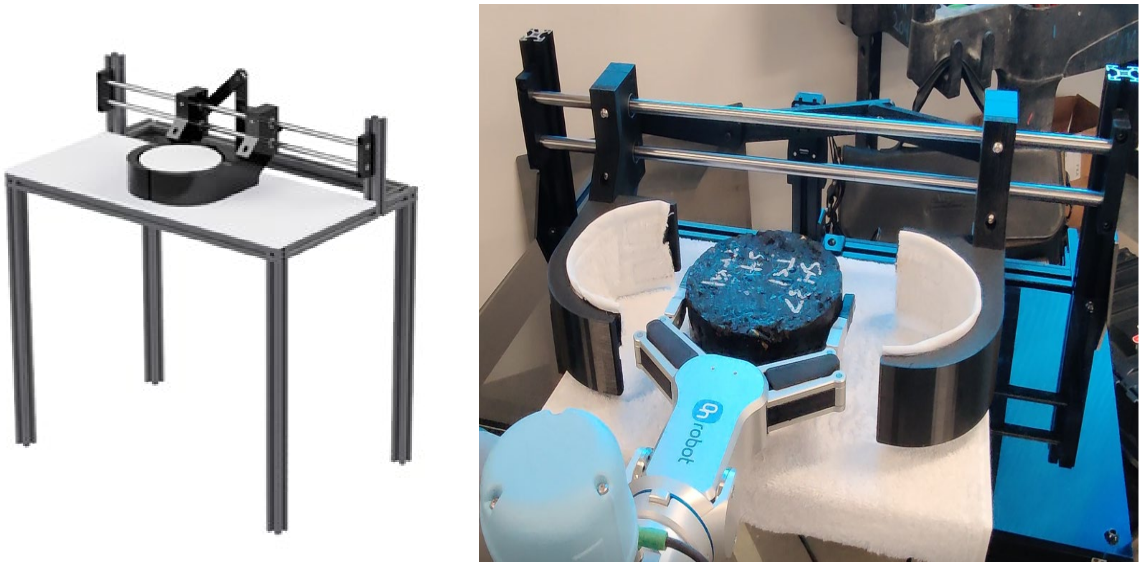


FIGURE 20 Specimen drying unit.

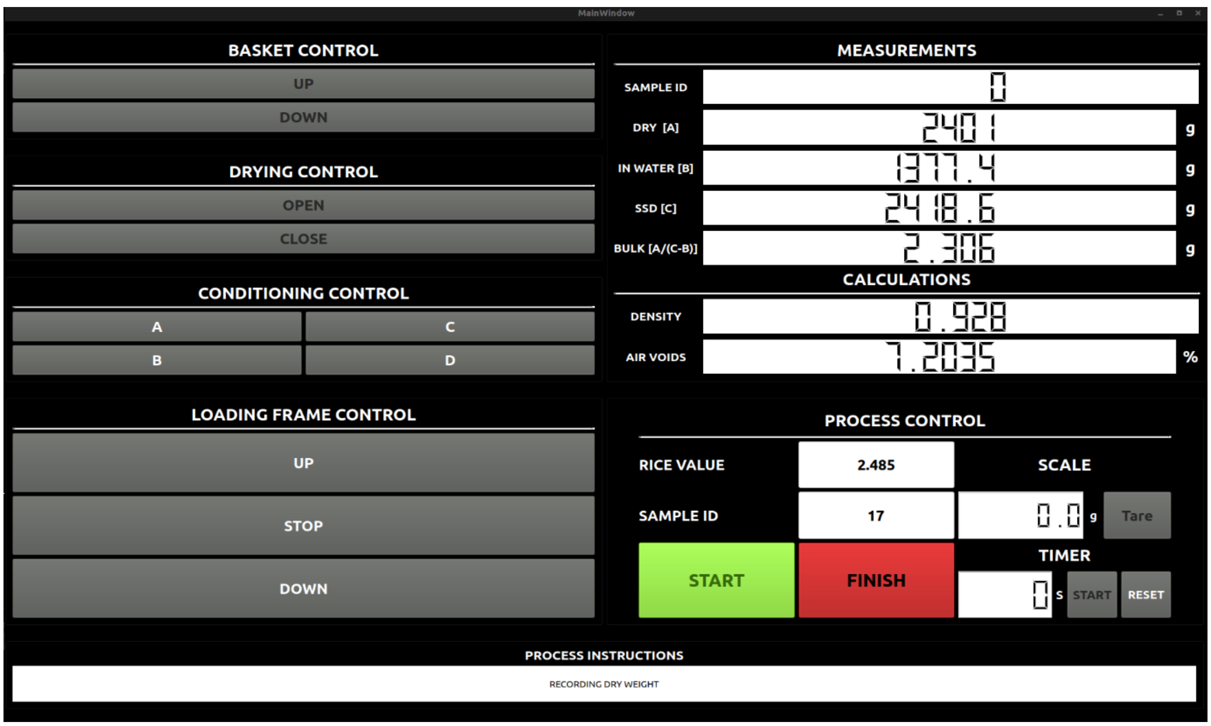


FIGURE 21 Computer control interface for specimen air void measurement.

EVALUATION OF FINAL TEMPERATURE CONDITIONING

Based on the conceptual design of the final temperature conditioning shown in Figure 11, the research team purchased one temperature chamber for conditioning the specimens for IDEAL-CT or IDEAL-RT testing. To accomplish the automation process of conditioning specimens, the researchers designed the automated lowering and lifting mechanism through linear actuators (Figure 22). The final temperature conditioning follows the air void measurement. The robot arm picks up the specimen from the scale and then places it on the lower rack into a water bath to condition the specimens before performing the IDEAL-CT or -RT testing. It was found that it took around 30 minutes for an IDEAL-CT specimen to reach the target temperature of 25 °C and about 40 minutes for an IDEAL-RT specimen to reach the target temperature of 50 °C.

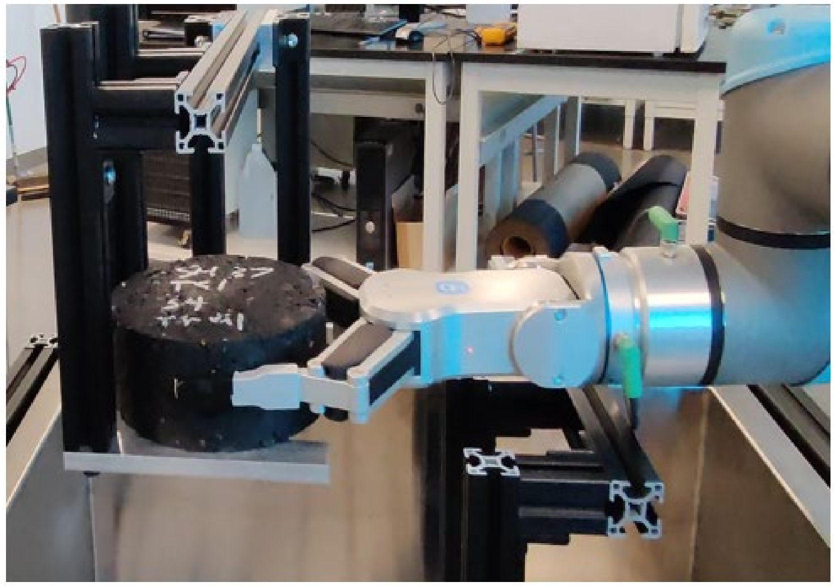


FIGURE 22 Final temperature conditioning subsystem.

EVALUATION OF MATERIAL TESTING SUBSYSTEM

Ideally, the research team would have designed and built a customized material testing machine. However, that was an unrealistic goal within the limited budget and time for this project. Therefore, the research team worked with one test equipment manufacturer to procure a suitable machine. The first obstacle the research team faced involved externally controlling the test machine to automatically perform the IDEAL-CT and IDEAL-RT testing. It took three months for both the research team and the test equipment manufacturer to realize that it was impossible to externally control the testing machine. Accordingly, the research team had to identify another test equipment manufacturer. Fortunately, the second equipment manufacturer was able to assist the research team with remotely controlling their machine. In the end, the research team could automatically control and perform both IDEAL-CT and IDEAL-RT testing (Figure 23).

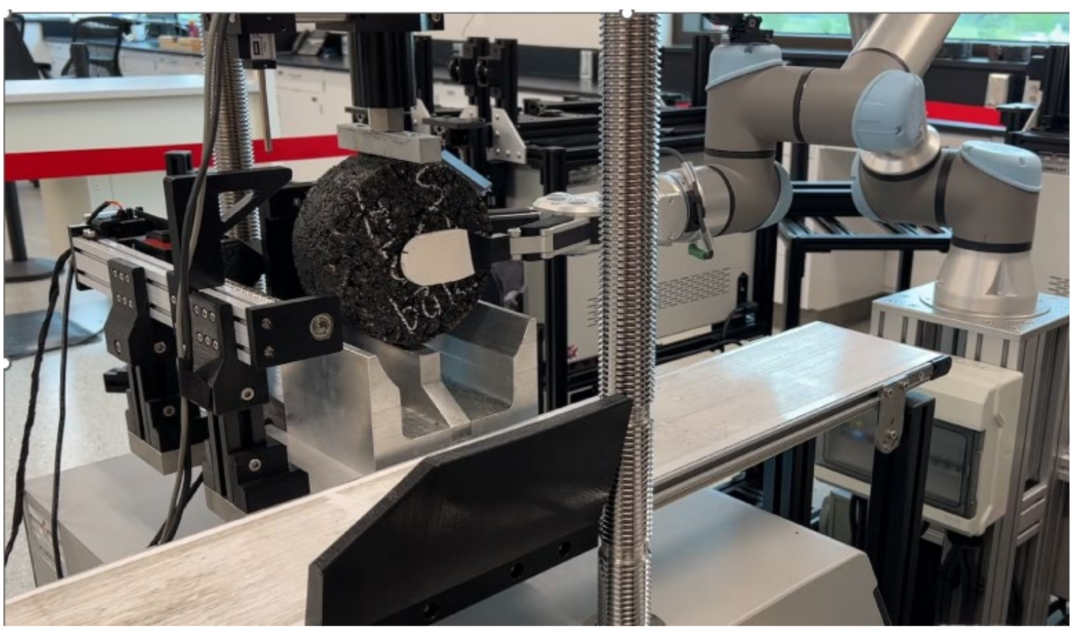


FIGURE 23 Final material testing subsystem with a conveyor belt.

EVALUATION OF ROBOT ARM

The robot arm is a critical component of the whole AMAZE system. The research team evaluated the robot arm market and decided to purchase the UR5e with a payload of 5 kg (Figure 24). The UR5e is an adaptable, collaborative industrial robot that tackles medium-duty applications with ultimate flexibility.

FIGURE 24 Robot arm: UR5e.

FINAL COMPARISON BETWEEN AMAZE AND LABORATORY TECHNICIAN

After building a working system, the research team compared the following measured asphalt mixture properties of various mixes: (a) air voids, (b) CT_{Index}, and (c) RT_{Index}. Figure 24 shows the air voids of seven specimens measured with AMAZE and with a laboratory technician. The measured air void values were very close between the two. Hand and Epps (*6*) reported that the measurement difference of air voids between two different lab technicians within the same lab is around 1.0 percent. The actual differences shown in Figure 25 are less than 0.5 percent. Therefore, the AMAZE-measured air voids are very comparable.

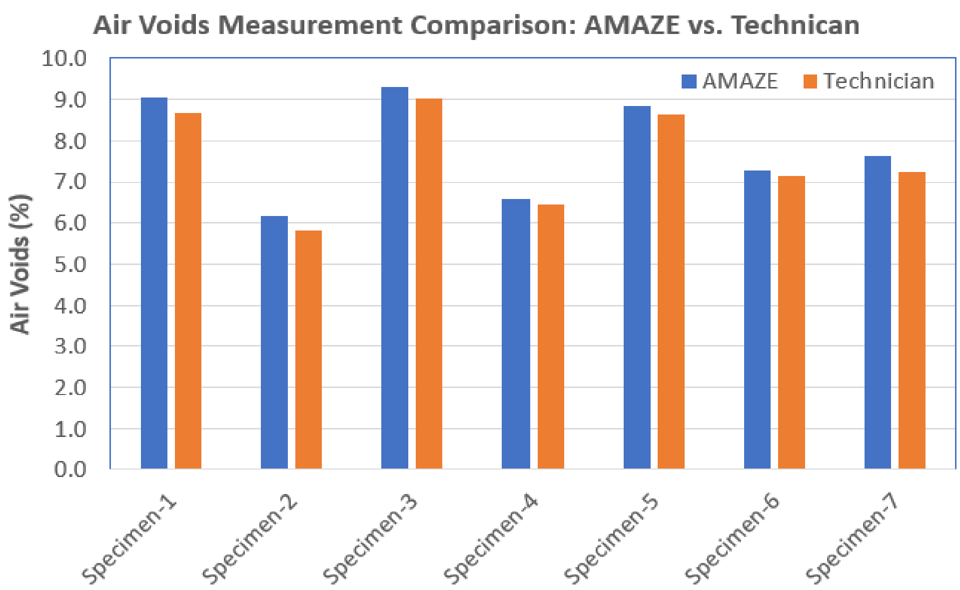


FIGURE 25 Air void measurement comparison.

Furthermore, the research team compared CT_{Index} values of three completely different mixtures: poor, better, and best cracking resistance. For each asphalt mixture, five replicates of specimens were tested. Figure 26 presents the IDEAL-CT results. Not only is the CT_{Index} average value for each mixture similar between AMAZE and the laboratory technician, the standard deviation of each mixture between AMAZE and the laboratory technician is also very close. Similar observations can be made for the IDEAL-RT test, as shown in Figure 27. Note that for the IDEAL-RT test, three replicates were conducted for each mixture.

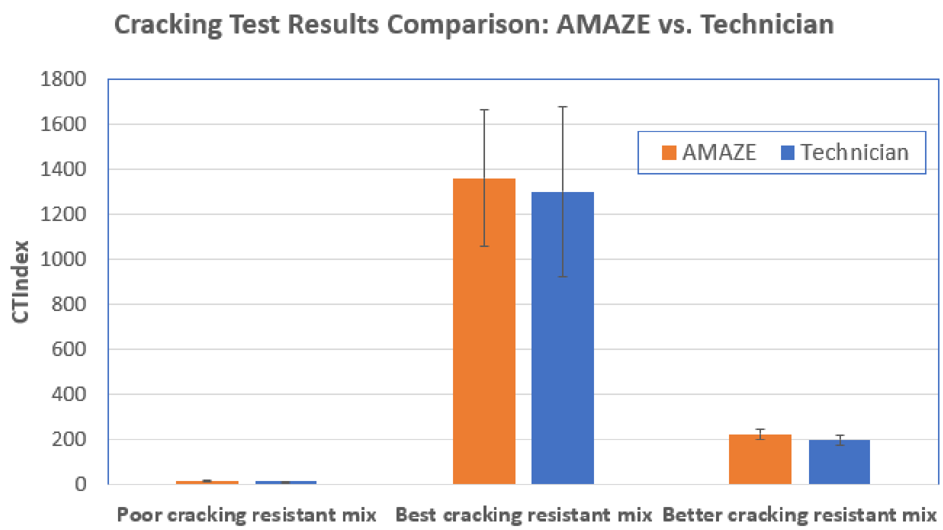


FIGURE 26 Ideal cracking test results comparison.

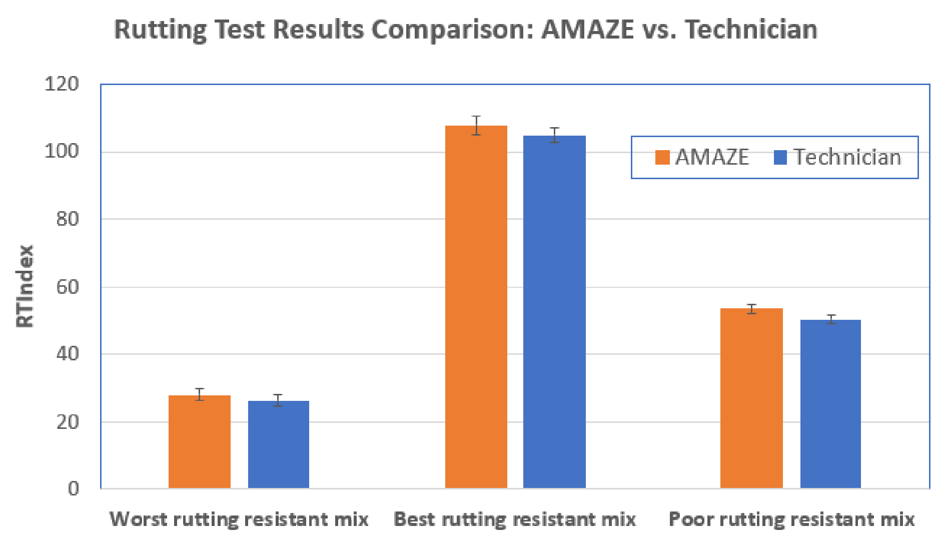


FIGURE 27 Ideal rutting test results comparison.

PLANS FOR IMPLEMENTATION

AMAZE is a cutting-edge research product from this IDEA project. Just like any new product, it takes efforts and time to fully implement it. For example, it took around 20 years for DOTs to fully implement the Superpave binder and mixture design specifications. As an initial step of implementing the AMAZE device, the envisioned activities include the following:

- Shadow projects: A good practice to implement a new device is through a series of shadow projects. Typically, a few shadow projects with the new AMAZE device for information only would help work out sampling and testing logistics for contractors and DOTs, as well as assess how results compare to those of the laboratory technicians. Shadow projects often facilitate early buy-in. This is an essential step in any implementation effort. The research team has discussed the collaboration with Texas DOT and Virginia DOT for a few shadow projects in the stage of implementation. Both DOTs are interested in putting the rubber on the road.

- Pilot projects: A further step of implementation is pilot projects. Unlike shadow projects, where testing is for information only, pilot projects use the test results to approve and accept asphalt mixtures. Generally, the pilot projects start on a small scale, such as just a few in the first year, then one to two projects in most districts in the second year, and so on. Adjustments may be necessary to each round based on the information and lessons learned. The pilot projects would enable more stakeholders to become more familiar with the new AMAZE device and how its results could influence mix design and production acceptance. TexasBit (an asphalt mix producer and construction company) is interested in using the AMAZE device in a few pilot projects for production quality control.
- Flyers and videos: Two one-page flyers along with videos could be developed to disseminate the information. One flyer for DOT senior management could describe the benefits and the cost implications. A second flyer could be developed for DOT bituminous engineers, hot-mix specialists, consultants, and the asphalt industry with more technical information on test setup and a step-by-step test process. Short, high-definition, professionally produced videos could also be provided to accompany the flyers.
- Transportation Research Board (TRB) webinars and national (or regional) in-person workshops: TRB webinars are another effective way to disseminate the research findings from this critical project. Furthermore, national or regional in-person workshops, ideally with hands-on experience, are a great way for attendants to learn, adopt, and implement the AMAZE device.
- Commercialization of the AMAZE device: Test equipment commercialization is a critical step for implementation. Currently, Humboldt Mfg. Co. is interested in manufacturing the AMAZE device.
- DOT–asphalt industry working group: To implement anything new or make changes, it is crucial to get every party involved in the process as early as possible so that every party is aware of and prepared for what is coming. One way is to establish a DOT–asphalt industry working group through NAPA or a local asphalt pavement association.
- Training and certification: Training engineers and technicians on the use of the AMAZE device is vital to successful implementation. DOTs also need to coordinate with local asphalt pavement associations to get QC personnel trained.
- Statewide implementation: Full implementation should occur after the pilot projects in every district and stakeholder buy-in are complete. It may take 5–7 years or longer to successfully implement a new cracking or other test.

CONCLUSIONS

This innovative research developed a robot-based device: AMAZE. The system includes five components: (a) a rapid cooling subsystem, (b) an air void measurement subsystem, (c) a temperature conditioning subsystem, (d) a material testing subsystem, and (e) a robot arm. During this research project, automation was achieved with a robot arm for air void measurement, temperature conditioning, and cracking and rutting testing. Additionally, a step-by-step plan was developed for implementing the AMAZE device.

Every year, around 360 million tons of asphalt mixes, with a cost of more than $20 billion, are placed on roads in the United States. Repairing pavement distresses and failures (such as fatigue cracking and rutting) associated with asphalt mixes cost taxpayers billions of dollars annually. DOTs and asphalt industry professionals can benefit from the AMAZE device in at least three ways: (a) produce high-quality asphalt mixes with long-lasting life, (b) remedy the loss of the workforce and the skills associated with the retired workforce, and (c) improve test consistency and the safety of the working environment.

INVESTIGATORS' PROFILES

Dr. Fujie Zhou, Principal Investigator

Dr. Zhou is a registered professional engineer in the state of Texas and a senior research engineer at the Texas A&M Transportation Institute (TTI). He has over 25 years of research experience in the field of asphalt pavement. His professional interests include laboratory test development and automation, balanced mix design (BMD), asphalt pavement mechanistic-empirical design, performance modeling (rutting, fatigue cracking, reflection cracking, low-temperature cracking, top-down cracking), asphalt overlay design, and laboratory characterization of asphalt binders. He has led multiple Texas Department of Transportation (TxDOT) projects, such as BMD, Texas Asphalt Overlay Design (TxACOL), and Texas Flexible Mechanistic-Empirical Pavement Design (TxME). He served as PI of NCHRP 09-57, 09-57A Phases I–III, and three NCHRP IDEA Projects: 195, 224, and 242. Dr. Zhou's research projects have also been sponsored by other DOTs and private sectors. His work on upgrading TTI's overlay tester was recognized as TxDOT's Top Innovation Award in 2004. His research on asphalt overlay design and analysis was nationally recognized as one of the 12 state department of transportation high-value research projects at TRB 2011. Additionally, Dr. Zhou is a three-time recipient of the AAPT Emmons award.

Mr. Jorge Roa, Key Researcher

Mr. Roa is an assistant research scientist at TTI, with a comprehensive background in software, electronics, and electromechanical systems. Fueled by a passion for promoting the integration of automation and robotics in the transportation industry, Mr. Roa actively collaborates with industry pioneers and esteemed researchers to revolutionize laboratory testing procedures. As a critical member of this research team, Mr. Roa spearheaded the development and implementation of the groundbreaking AMAZE device, which has been well received by the NCHRP IDEA Advisory Committee and DOTs. Currently, his professional interests encompass the application of robotics and machinery in laboratory testing environments, the design and deployment of autonomous robotic systems, and the incorporation of artificial intelligence in the realm of automation.

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APPENDIX: RESEARCH RESULTS

WHAT WAS THE NEED?

State departments of transportation (DOTs) are currently facing many challenges. Three such challenges involve addressing (a) the cracking and rutting distresses that are costing taxpayers billions of dollars annually, (b) the loss of both the workforce and the skills associated with the workforce, and (c) laboratory safety concerns to prevent worker injury. Many DOTs are addressing the cracking and rutting problems by implementing a balanced mix design method to design durable mixes. However, the lack of workforce and workforce skills hinders such efforts. Additionally, the primary safety concern in the laboratory is preventing worker injury often associated with the hot asphalt, large masonry saws, high-force testing machines, and toxic chemicals typically found in an asphalt material testing lab. Automation of certain processes is critical to alleviate these safety concerns by reducing the number of employees exposed to these hazards.

WHAT WAS OUR GOAL?

The goal of this research project was to develop an asphalt mixture automated testing system with zero interference (AMAZE) to be used for mix design and quality control and quality acceptance during asphalt mix plant production.

WHAT DID WE DO?

The research team developed an AMAZE device, as shown in Figure 28. AMAZE includes five components: (a) a rapid cooling subsystem, (b) an air void measurement subsystem, (c) a temperature conditioning subsystem, (d) a material testing subsystem, and (e) a robot arm. During this research project, automation was achieved using a robot arm for air void measurement, temperature conditioning, and cracking and rutting testing.

FIGURE 28 AMAZE device.

Figure 29, Figure 30, and Figure 31 show the comparisons of test results measured by AMAZE versus laboratory technicians in terms of air voids, cracking tolerance index (CT_{Index}), and rutting tolerance index (RT_{Index}), respectively. The asphalt mixture properties measured by AMAZE are comparable to those measured by laboratory technicians.

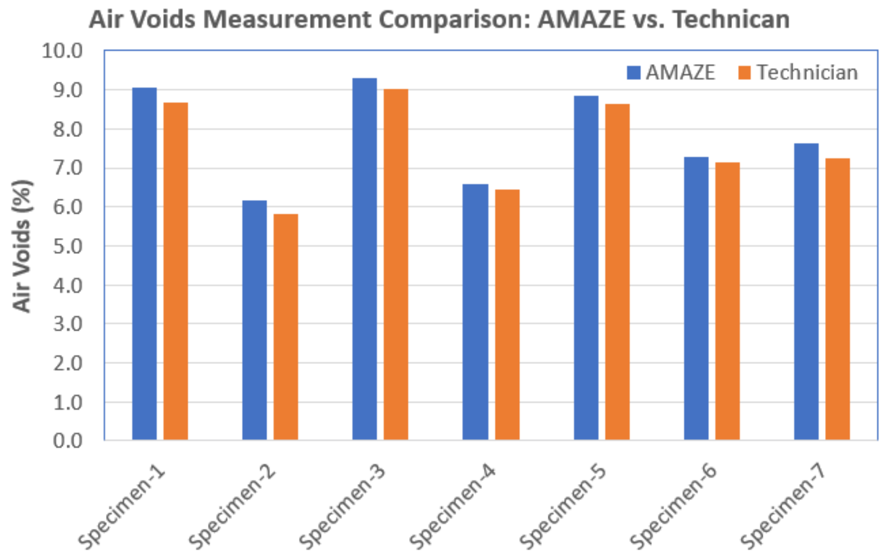

FIGURE 29 Air void measurement comparison.

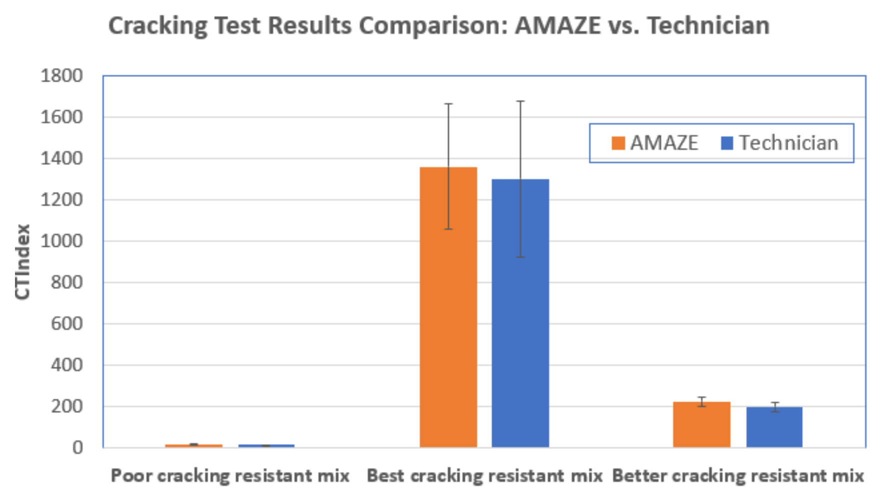

FIGURE 30 Cracking resistance comparison.

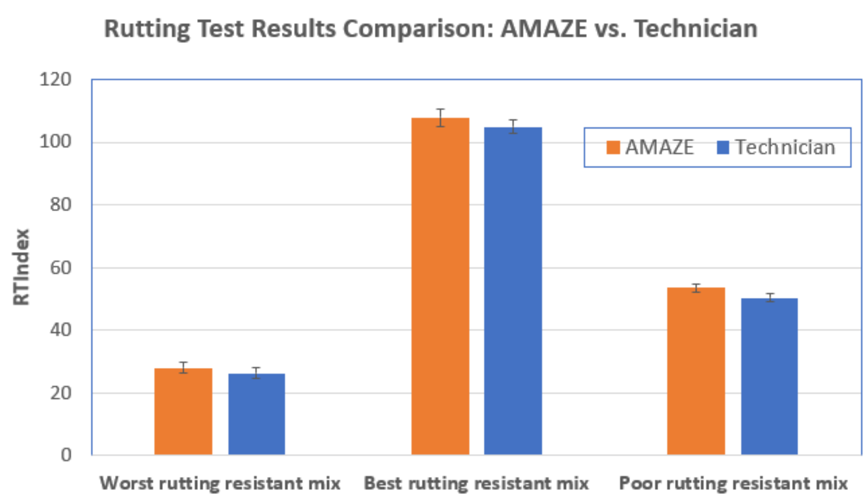

FIGURE 31 Rutting resistance comparison.

WHAT WAS THE OUTCOME?

The outcomes of this research project are the AMAZE device and a step-by-step implementation plan for DOTs.

WHAT IS THE BENEFIT?

Every year, around 360 million tons of asphalt mixes, with a cost of more than $20 billion, are placed on roads in the United States. Repairing pavement distresses and failures (such as fatigue cracking and rutting) associated with asphalt mixes cost taxpayers billions of dollars annually. It is expected that the AMAZE device can increase the life of asphalt mixes by a minimum of 15 percent. The estimated savings is $3.0 billion annually. The device will also reduce maintenance costs, traffic delays, and bad publicity associated with premature failures.