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Turben, T. (2022). Comparing the Stiffness of Cold In-Place Recycled Asphalt Pavement to Hot Mix Asphalt: Determining the Reproducibility of the Stiffness Rebound Test. *Civil Engineering Undergraduate Honors Theses* Retrieved from https://scholarworks.uark.edu/cveguht/72

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COMPARING THE STIFFNESS OF COLD IN-PLACE RECYCLED ASPHALT PAVEMENT TO HOT MIX ASPHALT:
DETERMINING THE REPRODUCIBILITY OF THE STIFFNESS REBOUND TEST

An Honors Thesis submitted in partial fulfillment
of the requirements for Honors Studies in
Civil Engineering

by

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29 April 2022

Contents

Abstract

The Stiffness Raveling Mechanism Test (SRMT) was originally developed as an indirect measure of pavement stiffness to determine a pavement's tendency to ravel, a type of damage. Regarding rehabilitation of existing roadways by Full Depth Reclamation (FDR) Cold In-Place Recycling (CIR), concern of field repeatability was expressed (Hill & Braham, 2016).

An analysis of lab-compacted samples of CIR and Hot Mix Asphalt (HMA) was performed to determine if the results could be reproduced between CIR and HMA. Additionally, the experiment observed the effects of percent air voids, temperature, and moisture conditioning on CIR and HMA. Three samples were prepared for each of 8, 12, and 17 percent air voids for both CIR and HMA. All samples then underwent six sequential tests. The first five tests performed the SRMT on samples at temperatures of 21°C, 40°C, 21°C, 60°C, and 21°C. Following this temperature cycling, the same samples were then saturated under a vacuum in a moisture conditioning process before finally being tested once more at 21°C.

CIR and HMA responded similarly to each condition. Reductions in stiffness were observed for higher percent air voids, higher temperatures, and moisture conditioning. HMA retained higher rebound heights over the course of all testing. CIR had higher standard deviations than HMA. Viewing the test in real-time as opposed to a frame-by-frame analysis did not greatly impact measurements obtained with the SRMT.

The SRMT is a promising as an inexpensive and quick method to obtain a stiffness measurement of asphalt pavement. Due to minor differences observed between CIR and HMA, it is recommended that several more CIR and HMA mixes be tested to determine the full extent to which mixes may affect standard deviation. Modifications to the design of the SRMT may be another way to improve the consistency of the measurements.

Background

Cold In-place Recycling (CIR) of asphalt pavement is a method of pavement rehabilitation that involves milling, processing, and replacing material on an existing asphalt roadway or surface to return it to a smooth, crack-free surface. Using just a single piece of equipment or an equipment "train," a road can be resurfaced without the need to bring in new asphalt concrete mix or the need to dump any removed material off site. This is accomplished by first milling a certain depth of the existing pavement, then mixing new asphalt emulsion into the milled material, and finally profiling and rolling the new surface to compact it (Kandhal & Mallick, 1997).

Cold in-place recycling compared to traditional methods of pavement rehabilitation is beneficial for the environment as well as being logistically simpler. Compared to traditional overlays which involve hauling milled material to a waste site and producing and hauling new asphalt with virgin aggregate, CIR reuses existing aggregate without the need for transit. As such, CIR can decrease global warming by a marginal amount and also reduce the depletion of fossil fuels by nearly 20% (Turk et al., 2016). CIR can also reduce overall energy consumption by 22%, water consumption by 19%, and carbon dioxide emissions by 21% throughout stages of material production, transportation, and construction (Pakes et al., 2018).

Existing Research

There are many ways to compare the performance of a pavement, one being stiffness. If a pavement is less stiff, then the possibility of a pavement to ravel (or wear due to loss of aggregate) is greater. Therefore, having a reliable way to measure stiffness can help engineers understand how likely a road or surface is to ravel. A typical approach to determining the stiffness of a material is using a falling weight deflectometer (FWD), which measures deflections a specified distance from a weight dropped on the material surface (Hill & Braham, 2016). FWDs are large pieces of equipment often built into small trailers which could be a considerable investment for agencies.

Figure 1. Stiffness Raveling Mechanism (Hill & Braham, 2016)

Research previously done at the University of Arkansas involves measuring the stiffness of a pavement with the use of a "Stiffness Raveling Mechanism" as seen in **Figure 1**. The Stiffness Raveling Mechanism (SRM) is a three-foot long hollow PVC tube with a lengthwise viewing window and a base on one end allowing it to stand upright. Beside the viewing window are inch marks that measure up from the base of the tube, marking the height perpendicular to the pavement. To perform the Rebound Test, or Stiffness Raveling Mechanism Test (SRMT), a golf ball is dropped from the top of the tube and its maximum height on the first bounce is considered the "rebound height." This rebound height serves as an indirect measure of the stiffness of the material, as stiffer materials exhibit higher rebounding. Therefore, the SRMT can be used to relate the stiffness of one type of pavement to another or to model the change in stiffness of a pavement over time (Hill & Braham, 2016).

The Rebound Test was developed as one of four methods for quantifying timing of return to traffic for roadways rehabilitated with Full Depth Reclamation (FDR) (Hill & Braham, 2016) FDR is a method of CIR which involves milling and mixing bound and unbound structural layers of an existing roadway (Kandhal & Mallick, 1997). The SRMT is unique from its three counterparts by measuring pavement stiffness in a manner fundamentally similar to that of a FWD. Since structural damage can be caused by allowing excessive traffic or weight within 7 days of performing some CIR rehabilitations, the SRMT can be used to estimate raveling potential of a pavement by measuring its stiffness (Hill & Braham, 2016). This test allows traffic to be returned to a roadway as soon as traffic no longer poses a significant risk of structural damage.

The Rebound Test benefits from being an inexpensive and simple way to compare the stiffness of pavements without the need for cumbersome, specialized tools like the FWD. Its construction is simple and could be built with parts from a hardware store. Since FWDs are often mounted on trailers, they are much more difficult to transport from site to site and navigate into position on site. Conversely, the rebound test can be performed anywhere on flat pavement by only two individuals with minimal free area. Additionally, the Rebound Test requires little training to perform while using and maintaining an FWD is more involved. As such, the SRMT serves as a cheaper and easier method for agencies to monitor the likelihood of damage.

Purpose

The Rebound Test has been developed at the University of Arkansas as a measure of indirect asphalt pavement stiffness and applied to CIR (Hill & Braham, 2016). To gauge the repeatability of the test across a greater variety of material properties, this study will perform the SRMT on CIR and HMA lab compacted samples of three different air voids.

Methods

Rebound Tests were performed on cylindrical lab specimens using the Stiffness Raveling Mechanism from **Figure 1**. Observations were made for one CIR mix and one HMA mix. For each mix, 8%, 12%, and 17% air voids were tested. Each mix received 3 samples per air void and 3 trials per sample. Each sample would then undergo 6 identical tests. The experimental design is shown in **Table 1**. The flowchart detailing the testing procedure is shown in **Figure 2**.

Table 1. Experimental Matrix

Variable	*Levels*	*Description of Levels*
Asphalt Type	2	CIR, HMA
Air Voids	3	8%, 12%, and 17%
Repeatability	9[1]	3 lab samples with 3 replicates per air void per type

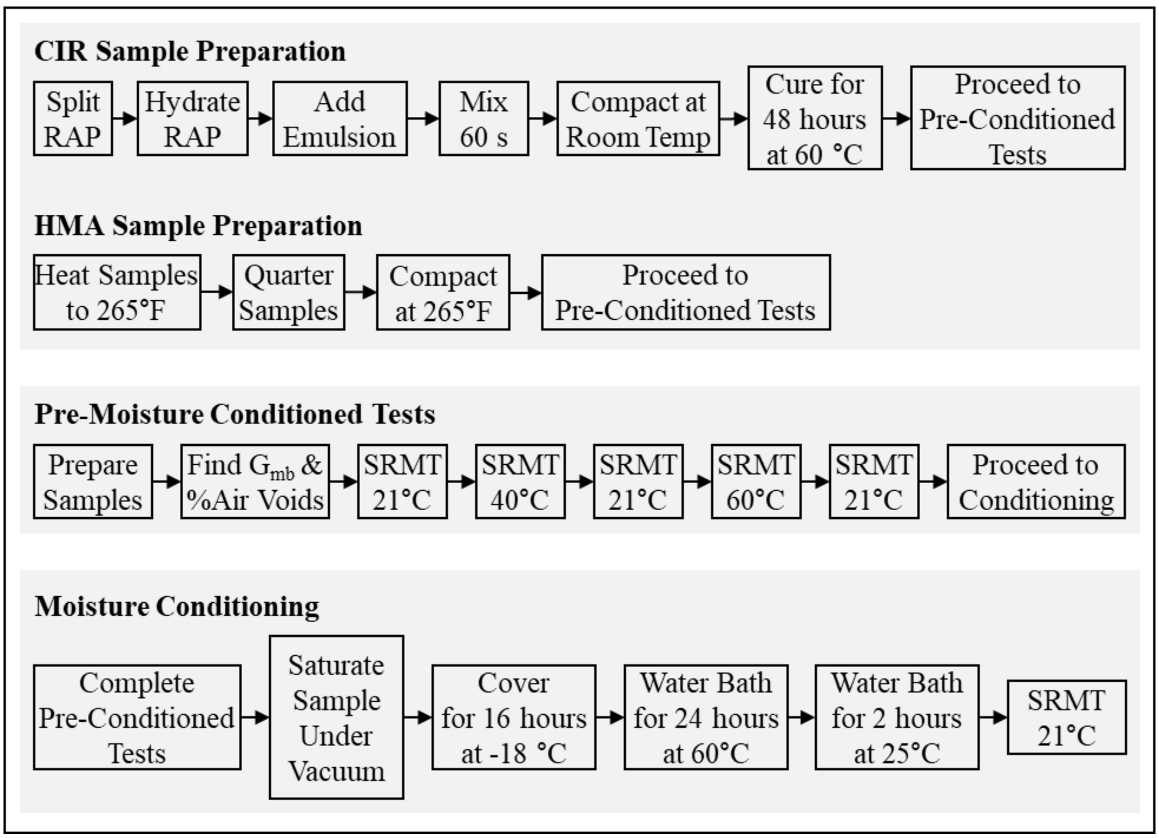

Figure 2. Flowchart of Sample Preparation, Testing Procedure, and Moisture Conditioning

[1] Exceptions: 6 levels (2 lab samples) for 8% HMA, 12 levels (4 lab samples) for 12% HMA

Sample Preparation

CIR samples were prepared from Recycled Asphalt Pavement (RAP) milled from a Kansas site. The RAP was split to obtain 4000-gram samples using Method A, “Mechanical Splitter,” of ASTM C702-18. The samples were then hydrated with 60 grams of water and mixed for 60 seconds in a bucket with 112 grams of CSS-1 emulsion in accordance with AASHTO PP 86-20. After mixing, the samples were placed in a 150 mm diameter mold and compacted at room temperature with a Pine gyratory compactor using sufficient gyrations to achieve the desired air voids. Once compacted, the samples were placed in an oven at 60°C for 48 hours for curing.

HMA samples were an ArDOT 12.5mm ACHM mix. The HMA was split using Method B, “Quartering,” of ASTM C702-18 to sample sizes of 3500 grams. The HMA samples, molds, and funnels were heated to 265°F in an oven before compaction in a Pine gyratory compactor at 265°F, the specified compaction temperature of the mix used. The HMA samples were allowed to cool down to room temperature without curing in an oven.

For both CIR and HMA after compaction, the bulk specific gravity (G_{mb}) was determined for each sample by vacuum sealing the samples with an InstroTek CoreLok machine in accordance with AASHTO T 331-21. Additionally, the percent air voids was found for each sample by AASHTO T 269-14, and samples were then grouped into representative categories for 8% air voids, 12% air voids, and 17% air voids.

Rebound Testing Setup

To prepare for the Rebound Test, a level location was found by obtaining two level readings in perpendicular directions with a bubble level. This location was outlined with tape to ensure all samples were tested at the same location. Then, a tripod was setup 32” above the ground and 6’ away from the Stiffness Raveling Mechanism, facing its viewing window. A camera was placed on the tripod to record each trial so the rebound height could be read by reviewing a recording frame-by-frame. The setup used can be seen in **Figure 3**. The room temperature where the test was performed and where samples were stored between tests was kept at a temperature of 21°C for the duration of the experiment.

Figure 3. Stiffness Raveling Mechanism Setup

Rebound Testing Procedure

Two methods for the rebound testing procedure used for analysis. The first method is performed with a single operator and a video camera to obtain rebound heights from a frame-by-frame review of the video footage. The second method is performed with two operators; one operator performs the test as with a single operator and a second operator visually determines the rebound height in real-time.

To perform the rebound test with one operator, the compacted sample was first placed on the floor. Then, the Stiffness Raveling Mechanism (SRM) was placed directly on top of it, ensuring to face the viewing window towards the camera tripod. For future viewing, an index card noting the sample, test, and trial was placed in-frame of the camera. The recording of the trial was then started. Standing behind the SRM, the operator held a standard golf ball by pinching it between their thumb and index finger, then positioned the ball at the neck of the fitting at the top end of the SRM. Finally, the operator released the ball, allowing it to fall straight down inside the SRM and bounce several times. The recording of the trial was then ended. If the golf ball audibly struck the tube soon after the first bounce, the trial was discarded. To prepare for the next test, the SRM was lifted and replaced to retrieve the ball. When reviewing the video footage, the maximum height of the first bounce, to the nearest inch, is recorded as the Rebound Height.

To perform the rebound test in real-time with two operators, all steps from the single-operator method were performed as before, omitting video recording. In its place, the second operator squats or kneels approximately 6’ away from the SRM with their eye height slightly below the top of the SRM if possible. The visual observation of the maximum height of the first bounce, to the nearest inch, is recorded as the Rebound Height.

Experiment Procedure

All CIR samples were prepared and placed through all testing, then all HMA samples were prepared and placed through all tests. In the case of both mix types, all samples underwent the SRMT for the following six cumulative testing conditions. Test 1 was performed for all samples, then the same set of samples from Test 1 proceeded to Test 2. The same samples proceeded through each test sequentially until Test 6, after which the SRMT had been performed once with three replicates for each sample for each testing condition. Each replicate was recorded to obtain measurements from frame-by-frame analysis.

Test 1: The SRMT was performed at room temperature (21°C) with 3 replicates for each sample.

Test 2: After completing Test 1, the samples were moved to a 40°C oven. Immediately as each sample reached 40°C as determined by a digital temperature gun, they were removed from the oven and the SRMT was performed at 40°C with 3 replicates for each sample.

Test 3: After completing Test 2, the samples were allowed to cool down to room temperature (21°C) and the SRMT was performed with 3 replicates for each sample.

Test 4: After completing Test 3, the samples were placed in a 60°C oven. Immediately as each sample reached 60°C as determined by a digital temperature gun, they were removed from the oven and the SRMT was performed at 60°C with 3 replicates for each sample.

Test 5: After completing Test 4, the samples were allowed to cool down to room temperature (21°C) and the SRMT was performed with 3 replicates for each sample. Then moisture conditioning was performed on each sample before proceeding to Test 6.

Moisture Conditioning: After Test 5, moisture conditioning was performed in accordance with AASHTO 283-21 with exceptions. Samples were saturated under a vacuum of 100 mmHg between 90 seconds and 5 minutes for CIR and between 2 and 7 minutes for HMA. Contrary to the standard, samples were not discarded if their degree of saturation was above 80, and these samples continued with conditioning. Directly after saturation, the samples were wrapped in cling film and placed in a plastic bag containing 10±0.1 grams of water. Then, each sample in its plastic bag was placed in a freezer at -18°C for 16 hours. After 16 hours, the samples were removed from the plastic bag and cling film and placed in a 60°C water bath for 24 hours. Then, the samples were placed in a water bath at 25°C for two more hours. The samples were finally removed and allowed to cool to room temperature (21°C) before performing Test 6.

Test 6: After completing Test 5 and undergoing moisture conditioning, the samples were allowed to cool down to room temperature (21°C) and the SRMT was performed on the damp samples with 3 replicates for each sample. Performing the SRMT on Test 6 concludes testing.

Results and Discussion

All results were obtained using the first method of the rebound test, using a frame-by-frame analysis to determine rebound height. To compare possible differences between the two methods, the same video footage was also reviewed in real-time to simulate the second method of using two operators.

The rebound heights of the CIR samples are shown in **Figure 4** for each test. It was anticipated that samples with higher air voids would have lower stiffness and exhibit lower average rebound heights as a result, a behavior which was observed to generally be the case. Additionally, the temperature of the sample had a significant effect on the rebound heights. The reductions in rebound heights during the two tests above room temperature, Test 2 and Test 4, show that large differences in temperature have a much greater effect on stiffness than the percent air voids. Returning the samples to room temperature restored their stiffness as seen in Test 3 and Test 5. Finally, the process of moisture conditioning was observed to lower the stiffness of the samples in Test 6, though not as greatly as temperature lowered the stiffness.

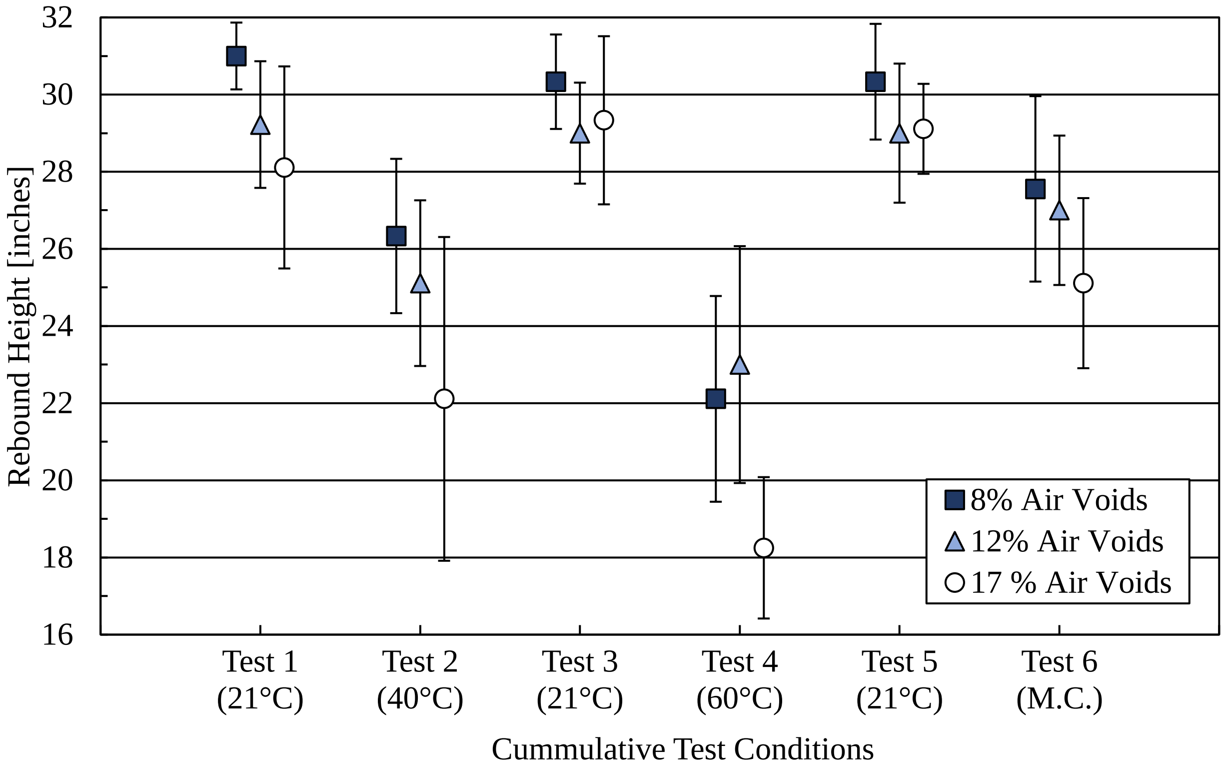

Figure 4. Cold In-Place Recycled Rebound Heights by Test

Similarly, the rebound heights of the HMA mixes are shown in **Figure 5**. It is once again observed that higher percent air voids samples typically exhibited lower rebound heights. High temperatures lowered the rebound heights of the HMA samples less so than observed in CIR. The moisture conditioning also showed smaller reductions from Test 5 to Test 6 than seen in CIR. Because of these lower reductions, over the course of all testing, the HMA samples rebounded higher than the CIR samples. The ratio of CIR to HMA rebound height is shown in **Figure 6** alongside an identity line. It can be concluded from **Figure 6** that the HMA mix better retained its stiffness throughout testing than CIR.

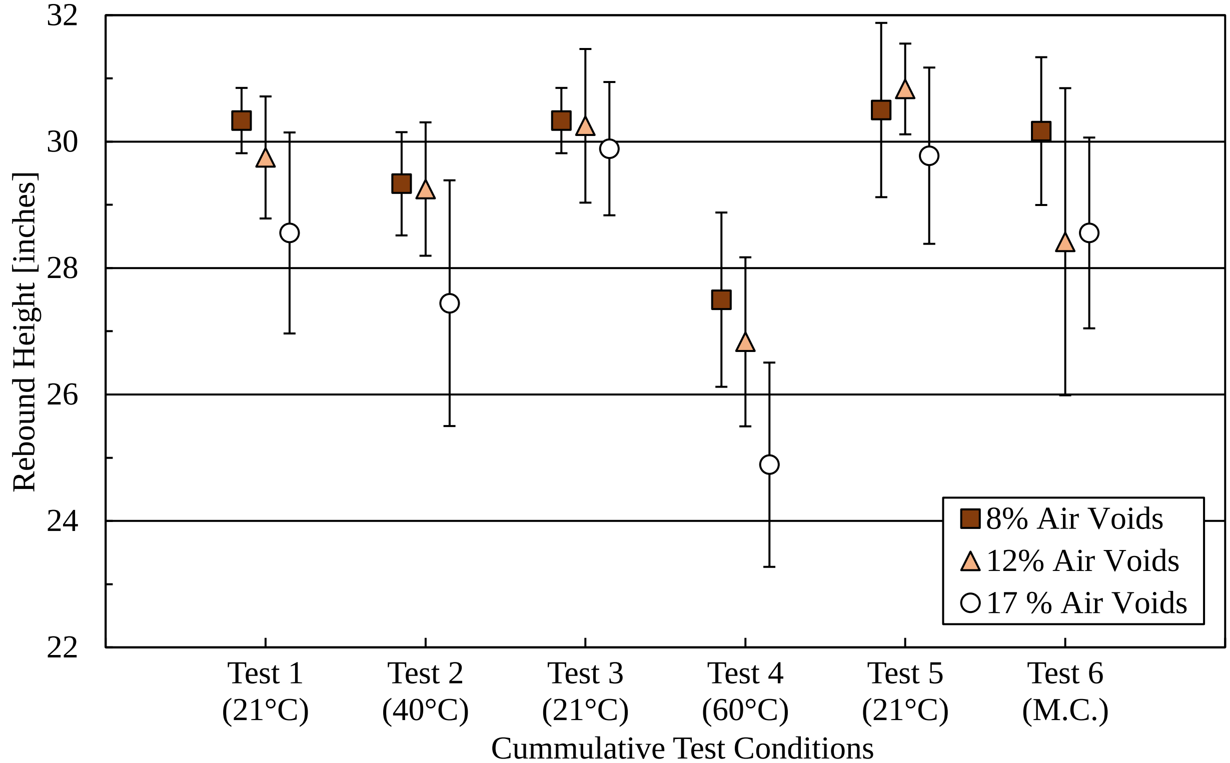

Figure 5. Hot Mix Rebound Heights by Test

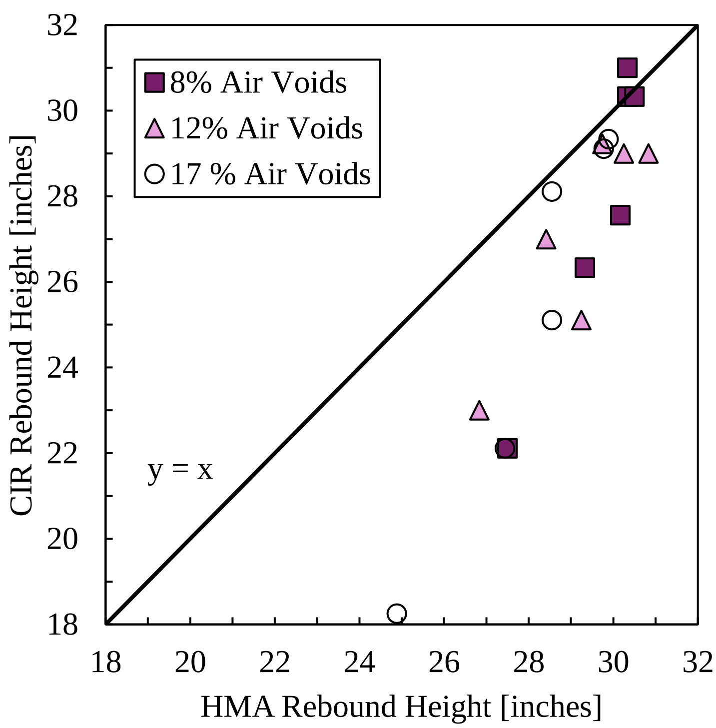

Figure 6. CIR vs HMA Rebound Height

The rebound height reductions observed due to temperature and moisture conditioning are also seen in **Figure 7**, which compares the performance of each mix to their initial conditions following compaction. For each asphalt type as a whole, reduction in rebound heights due to moisture conditioning was less than the reduction due to the 40°C temperature which was less than the reduction due to the 60°C temperature. CIR was more greatly affected by moisture conditioning and temperature than HMA was, evident most notably by CIR retaining 72% of its initial rebound height compared to HMA retaining 89% of its initial rebound height at 60°C in Test 4. It can also be seen that the HMA samples not only regained stiffness but exhibited slightly increased average stiffness after being heated and cooled compared to the initial SRTM following compaction. As such, despite the reduction caused by moisture conditioning, the HMA samples' final rebound height was nearly identical to their initial rebound height.

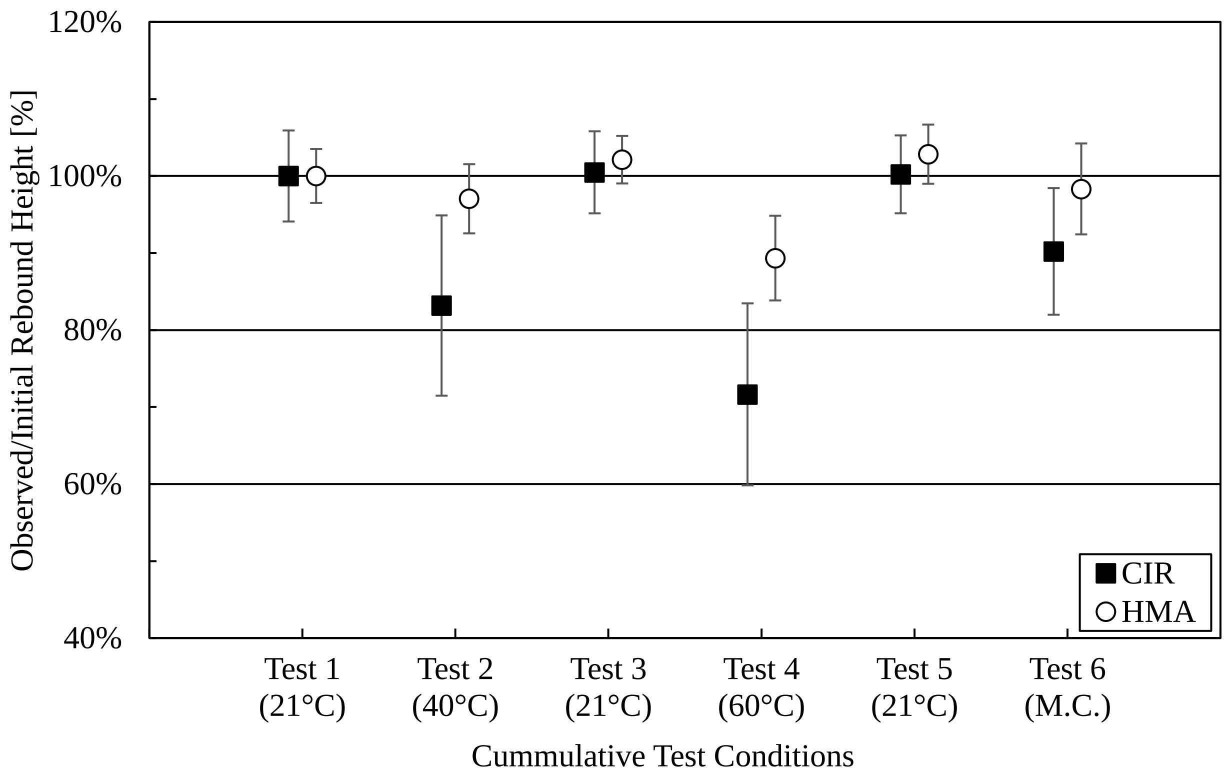

Figure 7. Rebound Heights as Percent of Initial Condition by Test

Due to the observed rebound height decrease at higher temperatures in **Figure 7**, it could be beneficial to define a standard testing temperature or define a temperature correction factor. While previous applications of the SRMT involving timing of return to traffic (Hill & Braham, 2016) may benefit from assessing the stiffness considering temperature in the hours and days after placement, other applications could benefit from accounting for temperature differences. If an agency wants to compare the stiffness of two different roadways in the same local region to better anticipate which will require maintenance first, for example, then correcting for the effect of temperature on asphalt stiffness would allow the performance of each roadway to be compared to each other or modeled over time when the ambient temperature is not identical between measurements.

Since the temperature cannot be controlled in the field, the use of a temperature correction factor for existing roadways would be more feasible than a standard testing temperature, which could be applicable in a lab setting. Due to the different percentage of initial rebound heights observed for the CIR and HMA mixes in **Figure 7**, there is no temperature correction factor which would be appropriate for all asphalt pavements. The factors which affect this behavior could potentially be determined with future testing of several more asphalt materials than one CIR source and one HMA source. A broader analysis may yield correction factors based on compaction temperature, gradation, binder content, or some other aspect of a given pavement's mix design.

The standard deviations of each percent air void group for each test condition was typically within 3" for CIR and 2" for HMA as shown in **Figure 8**. The standard deviations for each mix were typically slightly higher for conditions other than room temperature as a whole, though this behavior is not present for all percent air voids groups. Since the Rebound Test is

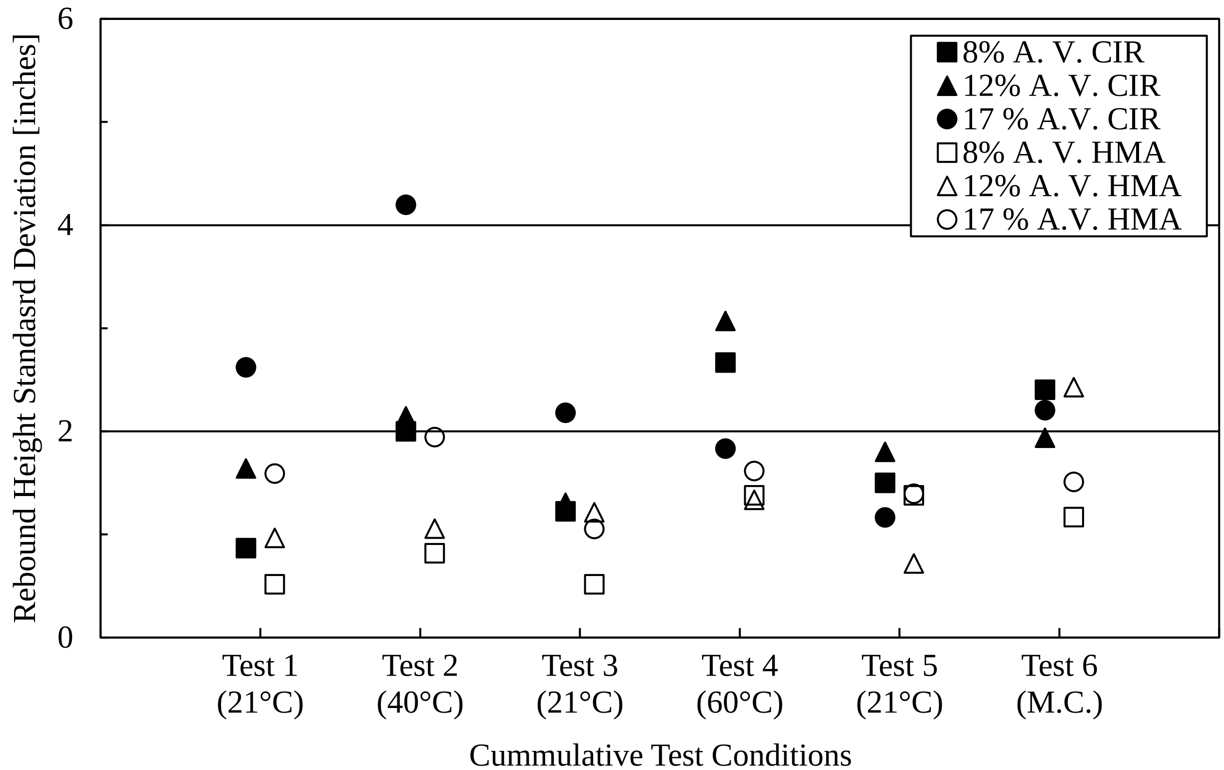

Figure 8. Standard Deviations by Test

performed by an operator dropping a ball held in-hand, the development of a mechanical release method may be able to lower standard deviations. When an operator releases the ball, it tends to occasionally graze the wall of the SRM between release and reaching the height of the first rebound. A release mechanism may improve the ability to drop the ball with less horizontal motion, and therefore decrease the likelihood of such an event occurring. Due to the inexpensive and simple construction of the SRM, the added cost and complexity of such a mechanical release may not be preferred unless there is a large improvement in the consistency of Rebound Heights.

While all results were found using frame-by-frame determinations of Rebound Heights, all recordings were later viewed in real-time to simulate the two-operator method of performing the SRMT. **Figure 9** shows the difference between the real-time observation measurements compared to the frame-by-frame observation measurements. The greater number of points with a difference over zero show that there was a slight tendency to overreport rebound heights when

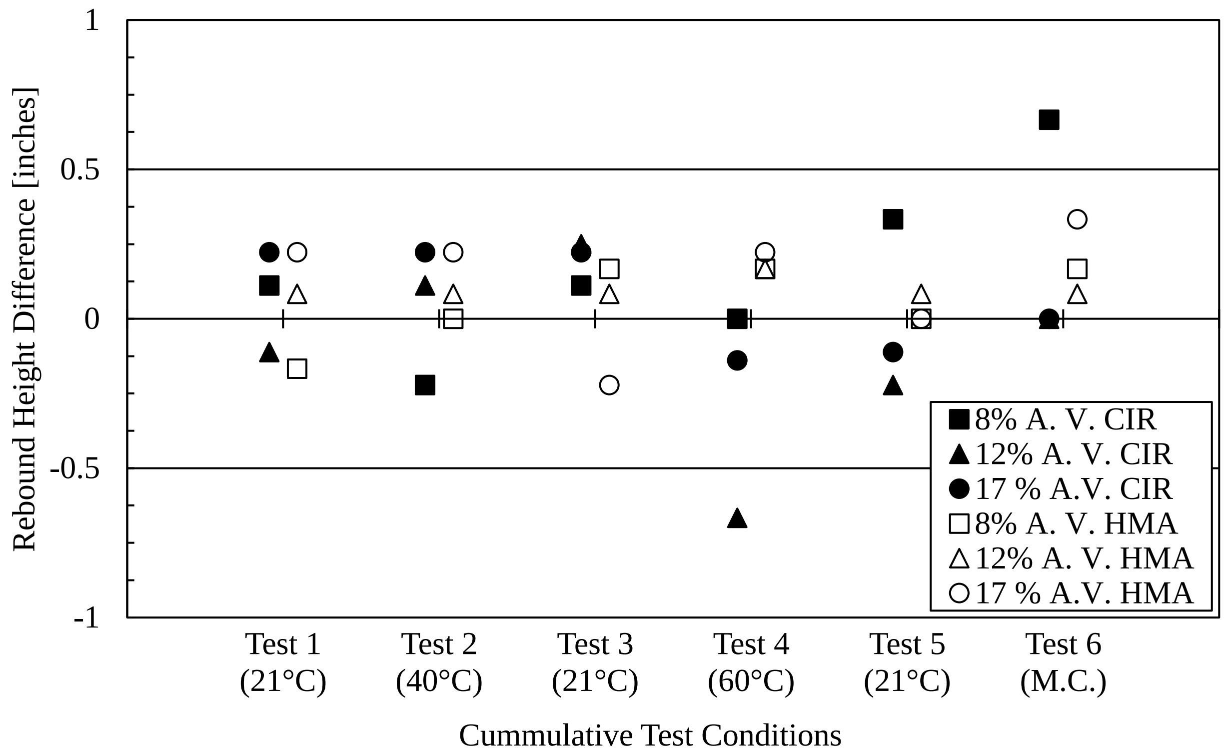

Figure 9. Real-time Observation Difference by Test

observed in real-time compared to the frame-by-frame method. Each replicate for every sample for every test was observed in real-time to be within one inch of the corresponding replicate as determined through frame-by-frame video analysis. The average differences for each sample group were typically within 0.4 inches and always within 0.7 inches. This is much smaller than the standard deviations between replicates which were typically 3 inches or less. As such, the use of the two-operator method yields results very similar to the frame-by-frame analysis. This is beneficial for all potential uses of the SRMT, as a measurement can be taken by two operators with no equipment other than the SRM itself to obtain an immediate result. The accuracy of real-time observation benefits the use case of timing return to traffic, as inspectors can quickly determine on-site when a roadway has met sufficient stiffness for reopening to traffic without the need to record and review footage.

Conclusions

The SRMT was originally developed as an indirect measure of pavement stiffness used to determine a pavement's tendency to ravel. Applied to roads rehabilitated by FDR, concerns of the SRMT's field repeatability was expressed (Hill & Braham, 2016).

An analysis of lab-compacted samples demonstrated that both CIR and HMA behaved similarly to the effects of percent air voids, temperature, and moisture conditioning. It was observed that higher air voids, higher temperatures, and moisture conditioning all lowered rebound heights. HMA maintained greater rebound heights than CIR throughout testing. Standard deviations were observed to be smaller for HMA than for CIR. Standard deviations were also higher for both CIR and HMA in tests at elevated temperatures and the test following moisture conditioning at room temperature. The SRMT may be more reproducible for asphalts with certain characteristics as evident by the different degrees to which the CIR and HMA samples were affected.

Since only one CIR and one HMA set of samples was tested, future research may be required to assess the behaviors of several different mixes and determine which properties most greatly affect standard deviations. Since only one set of CIR samples and one set of HMA samples were tested, it cannot be concluded that these differences were due to the compaction temperature. Improvements to the SRMT, such as a mechanical release, may also prove effective in reducing variations seen due to human error if developed, which could improve the SRMT for all applications.

Real-time observation of the SRMT did not substantially increase the test's variability or decrease its accuracy compared to frame-by-frame observation. This improves the SRMT's attractiveness as a rapid method of measuring stiffness. Coupled with its low cost and small size, the SRMT also serves as an inexpensive, accessible measurement of stiffness for lower precision applications.

The trends observed in measurements obtained with the SRMT were reproduced with CIR and HMA, and real-time visual measurements did not greatly harm the readings. These aspects of the findings are encouraging for the continued use of the SRMT. Standard deviations were observed to be higher for CIR than HMA, which might make application of the SRMT to CIR projects less attractive. To better understand what aspects of an asphalt mix influence the standard deviations, testing of several more CIR and HMA mixes should be undertaken. To determine if standard deviations can be improved for all asphalt materials, exploration of improvements to the SRMT's design should also be considered.

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