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The Effect of Mold Curing on the Mechanical Integrity of Cold Mix Asphalt: A Laboratory Study from Marshall Stability Perspective

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ABSTRACT

Cold Mix Asphalt (CMA) is increasingly recognized for its environmental and economic advantages, yet its mechanical performance is still heavily reliant on the curing condition, an aspect often ignored in laboratory evaluations. A lack of standardized curing procedures during sample preparation has led to inconsistencies in performance assessments, making it difficult to compare results across studies or optimize mix designs effectively. This study presents a laboratory investigation in order to examine the impact of curing conditions on the mechanical integrity of CMA, with a particular focus on the mold curing process. CMA specimens were cured both inside and outside the Marshall mold to evaluate differences in mechanical performance as measured by the Marshall Stability test. It is found that specimens which underwent curing inside the mold have higher Marshall Stability value with 7.480kN as compared to 3.415kN for specimens that were cured outside of the mold. The results show a significant greater stability and durability for the specimens cured inside the mold due to enhanced cohesive development and the preservation of compaction. While this curing approach may not replicate actual field conditions, the findings are vital for improving laboratory protocols and ensuring accurate, reproducible evaluations of CMA formulations.

Keywords: Cold mix asphalt; Laboratory curing; Marshall stability; Compaction.

Abbreviations

CMA	Cold mix asphalt
HMA	Hot mix asphalt

1.0 INTRODUCTION

Cold Mix Asphalt (CMA) has emerged as a popular substitute for Hot Mix Asphalt (HMA) especially for patching and maintenance tasks. It is perfect for emergency repairs and isolated areas because of its simplicity of storage, ambient temperature application, and less environmental impact. However, historically, its application has been limited to short repairs due to its mechanical limitations, which include lesser strength and a longer cure period. Enhancing CMA performance through fiber modification, optimum emulsion content, and curing techniques has garnered considerable attention in recent years.

According to [1], CMA applications are seeing a resurgence in Malaysia due to the growing need for safer, more affordable, and sustainable road rehabilitation solutions. CMA can be produced and applied at room temperature, in contrast to traditional HMA, which needs high temperatures for both production and laying. This offers distinct benefits, including lower carbon emissions, less energy consumption, increased worker safety, and improved workability in a variety of weather conditions.

The durability, cohesiveness, and structural integrity of CMA are all significantly influenced by the curing process. Unlike HMA that solidifies when cooled, CMA depends on bitumen setting and slow moisture evaporation to create strength. This trait increases the unpredictability of field performance and laboratory testing, particularly in cases when curing conditions are irregular.

The impact of curing on CMA properties has been emphasized in a number of research. In their study of curing procedures for loose CMA mixes, [2] found that regulated moisture loss by ambient air and oven curing improved the mechanical characteristics of the finished compacted specimens. Both the curing temperature and duration have a substantial impact on Marshall Stability and tensile strength, according to investigation by [3] on the curing of elevated temperatures using silica fume and hydrated lime fillers.

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In their investigation into the curing of compacted CMA specimens, [4] found that oven curing at 60 °C enhances the structural bonding and cohesiveness between the aggregates and binder. Similarly, [5] demonstrated that compacted CMA samples may attain lab-measured stiffness and strength equivalent to field-cured cores, supporting a combined ambient and elevated-temperature curing regime.

The curing environment right after compaction has received little attention despite these developments. In contrast to curing after demolding, the current study investigates whether curing CMA inside the mold—while maintaining its compressed form and pressure—improves its mechanical stability. This problem is especially pertinent to laboratory testing, since assessing CMA formulations requires accurate and repeatable data.

The Marshall Stability test, one of the most widely used techniques for evaluating asphalt mixture performance, was used in this study to determine how mold curing affects CMA. One set of compressed CMA specimens was demolded before curing, and the other set was cured inside the Marshall mold. The comparative research highlights the significance of curing conditions in asphalt material evaluation and provides insights into sample preparation procedures.

2.0 METHODOLOGY

Materials such as aggregates and bitumen emulsion were prepared based on the standard recommendation to conduct pothole repair. No modifiers were added in the study. The testing method involved in this study is Marshall Stability test which was carried out according to [6].

2.1 Materials

Aggregates were acquired and graded based on the recommended gradation of Cold Mix Patching Mixture from [7]. Table 1 below shows the standard gradation of aggregate. Bitumen emulsion used was of type MS-1K which is the recommended type of emulsion as shown in Table 2.

Table 1: Recommended gradation of aggregate, [7]

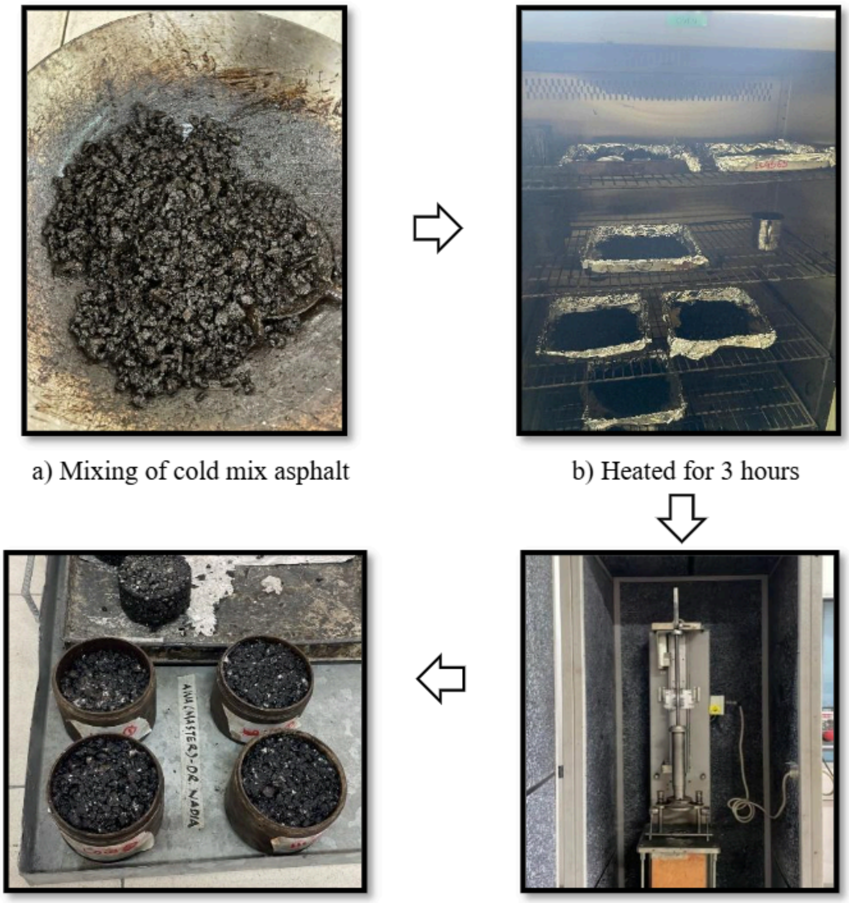
B.S. Sieve size (mm)	Percentage passing by weight (%)
14.0	100
10.0	75-100
5.0	20-70
3.35	10-60
1.18	5-40
0.15	2-15
0.075	0-8

Table 2: Grade of bitumen emulsion based on usage

Bitumen emulsion grade	Usage recommendation
RS-1K and RS-2K	Tack coating
RS-3K	Surface dressing
MS-1K and MS-2K	Cold patch and penetration macadam
SS-1K	Slurry seal and prime coating

2.2 Sample preparation and curing protocol

1,200g of aggregates were mixed thoroughly and uniformly with 8% bitumen emulsion by total aggregate weight. The well-coated mixture was then heated at 135ºC for three (3) hours. This is done to accelerate and stimulate field conditions before testing is done [7]. Then, the mixture was compacted with the Marshall compactor for 75 number of blows. The process was repeated to acquire two sets of cold mix asphalt which can be seen in Fig. 1. As shown in Table 3, Sample A was cured for 72 hours at room temperature within the Marshall mold while Sample B was demolded immediately after compaction and cured in room temperature for 72 hours. Fig. 2 shows the sample that has been compacted in two different conditions.



a) Mixing of cold mix asphalt

b) Heated for 3 hours

d) Compacted mix

c) Compaction of 75 blows

Figure 1. Process of mixing and compacting CMA

Table 3: Sample preparation

Sample	Curing method for 72 hours (at room temperature)
A	In the mold
B	Outside the mold

a) Sample A – In the mold

b) Sample B – Outside the mold

Figure 2. Sample cured under different conditions

2.3 Testing method

Marshall Stability test, as shown in Fig. 3, was conducted with [6] as the guideline. By using Marshall Stability Testing Machine, the compacted sample was tested. The asphalt mixture's mass viscosity, or the maximum load that the specimen could support, was measured using a compacted specimen and a loading rate of 50.8 mm/min. Test was conducted on specimens that had completed 72-hour curing processes as stated in Table 3. The stability value was then computed by noting the loading rate data.

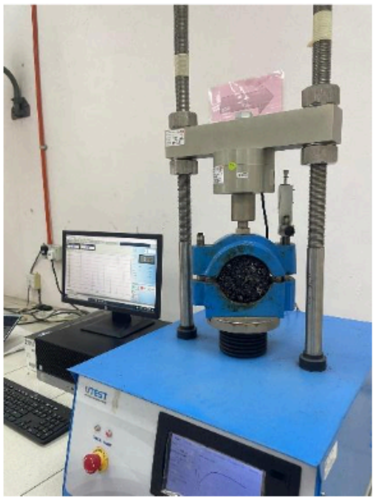


Figure 3. Marshall Stability Test

3.0 RESULTS AND DISCUSSION

This section presents the experimental results evaluating the effect of mold curing on Cold Mix Asphalt (CMA) performance. Key parameters examined include Marshall stability, air void content, and compaction characteristics. These results provide insight into the influence of curing conditions on mix integrity and the implications for laboratory standardization. Results acquired for the test are as follows.

Table 4: Marshall stability test result

Sample	Curing method	Minimum requirement (kN)	Marshall stability (kN)
A	In the mold	6	7.480
B	Outside the mold		3.415

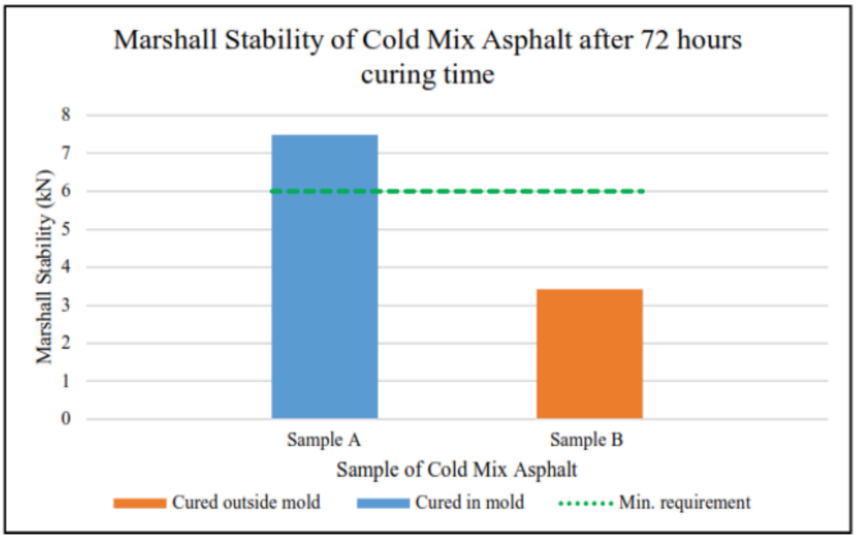


Figure 4. Graph of marshall stability of cold mix asphalt after 72 hours curing time

According to this study, samples cured in the mold recorded an average Marshall Stability of 7.480kN, whereas samples cured outside of the mold only recorded 3.415kN. Based on the result, it can be seen that mold confinement plays a crucial function in the early curing period of Cold Mix Asphalt (CMA), as seen by this huge contrast which is more than double the strength. For CMA to be deemed feasible for light duty pavement applications or permanent pothole repairs, only mold-cured specimens satisfy the structural requirements based on the minimum Marshall Stability criterion of 6.0 kN [7] while early demolding shows seriously impaired strength growth, as evidenced by the open-cured samples' failure to fulfill the requirement. As for the mold-cured sample, preservation of compaction pressure plays a big role in enhancing its performance. During moisture evaporation, the mold keeps the material under pressure, preserving bitumen contact and aggregate interlock since early-age CMA is vulnerable to warping or cracking because of uneven moisture loss and shrinkage in the absence of confinement. Lastly, it can be said that enclosed curing improves binder setting by promoting consistent temperature and humidity, which enables the emulsion to set more gradually and efficiently. These findings agree with [5], who highlighted that constrained curing environments improve early mechanical properties by allowing gradual binder cohesion and moisture escape.

3.1 Air Void content and compaction analysis

In order to further evaluate the mechanical performance through Marshall Stability, this study also examined the compactness and internal air structure of Cold Mix Asphalt (CMA) samples using bulk specific gravity (Gmb), maximum theoretical specific gravity (Gmm), compaction percentage, and air void content (Va) according to [8]. These factors are important predictors of long-term field performance, durability, workability, and mix integrity. Table 5 shows the result of the analysis while Table 6 shows the requirement for both compaction and air void.

Table 5: Compaction and air void analysis

Sample	Gmb	Gmm	Compaction (%)	Air void, Va (%)
A	2.231	2.322	96.1	3.9
B	2.221	2.322	95.7	4.3

Table 6: Requirement for compaction and air void for cold mix asphalt, [7], [9]

Item	Requirement
Compaction (%)	90-100
Air void, Va (%)	3-8

The results acquired for compaction and air void of both samples are compatible with their Marshall Stability. The samples cured in the mold showed improved compaction and less air voids alongside their enhanced mechanical performance. This association is consistent with the results of [10], who observed that cohesion and binder-aggregate contact are improved by higher density and reduced void content, hence increasing strength and deformation resistance.

Curing in the mold seems to prevent early relaxation or shrinkage and preserve internal structure. Early removal from the mold in cold mix applications, where strength builds gradually as a result of moisture evaporation and binder setting, may introduce uncontrolled moisture loss at the surface, geometric deformation especially along the edges and minor internal void expansions due to thermal or moisture gradients.

Besides that, curing in the mold helps in maintaining the compaction pressure produced throughout the Marshall process, stabilizing air voids and minimizing early loss of mix integrity, as indicated by [5]. The significance of confinement and curing temperature in attaining dimensional stability and uniform binder dispersion in cold asphalt mixtures was also underlined by [4].

As for the air void contents, the findings (3.9% and 4.3%) were within the ideal range, indicating that both curing techniques yield satisfactory lab requirement. The mold-cured materials' slight advantage, however, might result in more reliable and consistent performance in tests linked to fatigue, moisture susceptibility, and ITS.

Variability in curing could confuse performance interpretations, hence this uniformity is crucial when assessing or optimizing new CMA formulations. The AAPA IG2 standards provide similar recommendations, and research like [2] showed that curing in controlled conditions greatly stabilizes both density and void content before mechanical testing.

3.2 Laboratory Implications

Although curing in the mold is not representative of field application methods, it serves an essential role in standardizing laboratory evaluations. If specimens are demolded too early in the lab, their measured stability may underestimate the actual mix performance, especially in early-age testing scenarios. Thus, for CMA materials, mold curing should be recommended in laboratory testing protocols to ensure repeatable and comparative results. This is because it helps simulate a more uniform curing condition compared to uncontrolled air exposure. On top of that, it prevents misclassification of potentially good CMA mixes due to premature degradation in sample handling.

When specimens are demolded prematurely and left to cure in open air, differential drying may occur, particularly along the exposed edges. This leads to non-uniform curing profiles, increased air voids near the surface, and a higher likelihood of microcracking, all of which reduce the measured Marshall stability. As a result, early demolding may underestimate the true performance potential of the mix, especially for formulations that are slow-setting or dependent on curing time for strength gain. In this laboratory study, mold-cured samples result in a significantly higher mechanical integrity compared to the outside-cured. This study demonstrates that mold confinement during early curing stages enhances cohesion, stability, and dimensional uniformity. For reliable CMA evaluation, it is encouraged to standardize curing protocols in order to achieve a well uniformed result.

By contrast, mold curing ensures uniform boundary conditions and reduces curing-related variability between samples. This is particularly important in research and quality control contexts, where consistent and comparable results are needed to evaluate mix performance, optimize formulations, and validate material specifications. In this study, samples cured in the mold exhibited significantly higher Marshall stability values, lower air voids, and improved compaction retention, indicating that mold curing supports better binder-aggregate bonding and matrix integrity during the critical early phase of strength development.

Therefore, while mold curing may not reflect in-situ behaviour, it is strongly recommended as a standardized procedure in laboratory protocols for CMA evaluation [6], [11]. It minimizes result variability, prevents premature misclassification of viable mix designs, and provides a more controlled baseline for assessing the influence of other variables such as additives, emulsions, or curing duration. Incorporating mold curing as a standard practice can ultimately support more accurate performance prediction and informed decision-making in CMA mix development.

4.0 CONCLUSION

Although mold curing does not replicate actual field conditions where Cold Mix Asphalt (CMA) is typically exposed to ambient air curing after placement, it plays a critical role in enhancing the reliability and repeatability of laboratory evaluations. During the initial setting process, confinement is maintained by curing CMA specimens inside the Marshall mold. This reduces moisture loss, maintains compaction, and encourages uniform binder distribution. Particularly in early-age testing, these elements support more reliable coherent development and mechanical integrity.

This study aimed to evaluate the influence of mold curing on the mechanical performance of Cold Mix Asphalt (CMA) using the Marshall Stability test. Two curing conditions were compared: specimens cured inside the Marshall mold and those demolded prior to curing. The results clearly demonstrate that mold curing significantly improves the mechanical integrity of CMA mixtures. Mold-cured specimens exhibited higher Marshall stability, lower air void content, and better compaction retention, indicating enhanced cohesion and structural uniformity during early-age curing.

By limiting moisture loss and maintaining the compacted structure, the mold's confinement during curing produces mechanical qualities that are more dependable and predictable. Although mold curing does not mimic field conditions, it offers a controlled environment that minimizes variability in laboratory testing. These findings underscore the importance of standardized curing protocols in the laboratory to ensure consistent, comparative, and accurate evaluation of CMA performance. Adopting mold curing as a standard laboratory practice can help prevent underestimation of mix quality and support better decision-making in CMA formulation and quality control.

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AUTHORS CONTRIBUTION

The authors confirm their contribution to the paper as follows:
Nur'aina Syamimi Nazri: study conception and design, data collection, analysis and interpretation of results, Writing – Original Draft;
Norfarah Nadia Ismail: supervision, study conception and design, Writing - Review & Editing, Validation;
Ekarizan Shaffie: Supervision, Writing - Review & Editing, Validation;
Wan Nur Aifa Wan Azahar: Supervision, Writing - Review & Editing, Validation
All authors reviewed the results and approved the final version of the manuscript.

DECLARATION OF COMPETING OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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