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Influence of aromatic polyamide fibre on the early-age strength development of cold mix asphalt during curing

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ABSTRACT

Cold Mix Asphalt (CMA) is widely used for pavement maintenance because of its ease of application, low energy consumption, and ability to be produced at ambient temperatures. However, its relatively slow curing process delays strength development and limits the timely reopening of repaired pavement sections to traffic. This study investigates the influence of Aromatic Polyamide Fibre (APF) on the early-age strength development of CMA during curing. Laboratory evaluations were conducted on unmodified CMA and CMA modified with 0.05% APF using workability, volumetric properties, and Marshall Stability tests after curing periods of 24, 48, 72, and 96 hours. Exploratory linear regression was performed to examine the relationship between curing duration and Marshall Stability. The results show that the APF-modified mixture had a lower measured air-void content (7.08%) than the control mixture (8.42%). The APF-modified mixture exhibited approximately 35% and 18% higher mean Marshall Stability than the control at 24 and 48 hours, respectively, while both mixtures achieved the required Marshall Stability after 72 hours. Exploratory regression indicated an overall curing-time trend but was not statistically significant and therefore interpreted descriptively rather than as a predictive model. Overall, the findings indicate that APF can improve the early-age mechanical performance of CMA, particularly within the first 48 hours of curing, highlighting its potential as a fibre reinforcement for pavement maintenance applications.

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Abbreviations

APF	Aromatic polyamide fibre
CMA	Cold mix asphalt
HMA	Hot mix asphalt
MS	Medium setting

1. INTRODUCTION

Cold Mix Asphalt (CMA) has become an increasingly important pavement maintenance material owing to its ability to be produced, transported, and applied at ambient temperatures without the need for heating [1-2]. Compared with conventional Hot Mix Asphalt (HMA), CMA requires considerably lower production energy and can be manufactured without aggregate heating, thereby reducing fuel consumption and greenhouse gas emissions [1,3,4]. In addition, the ambient production process improves construction safety by eliminating high-temperature handling and allows the mixture to be stockpiled for emergency maintenance operations [5-6]. Owing to these practical advantages, CMA has been widely adopted for pothole repair, utility trench reinstatement, and routine pavement maintenance, particularly where rapid intervention and cost-effective construction are required [6-8]. Recent reviews have further identified CMA as a sustainable pavement technology because of its lower carbon footprint and compatibility with recycled materials and environmentally friendly modifiers [1,3,4,5].

Traffic lane closures associated with pothole repairs contribute to traffic congestion, increased road user delay, and additional maintenance costs, particularly on high-volume roads where maintenance activities directly affect traffic flow [9]. Besides reducing riding comfort, potholes present significant safety hazards to motorists, increase vehicle operating costs, and accelerate pavement deterioration if not repaired promptly [7-8]. Maintenance agencies therefore require repair materials that not only provide adequate durability but also restore pavement serviceability within the shortest possible time, consistent with pavement preservation strategies recommended by highway agencies [6,9]. Consequently, repair materials capable of developing sufficient engineering strength shortly after placement are increasingly desirable for modern pavement maintenance practices [8,10].

Despite these advantages, the engineering performance of CMA remains constrained by its relatively slow curing process and delayed strength development. Unlike HMA which rapidly develops strength after cooling, CMA depends on the gradual evaporation of water from the bitumen emulsion, emulsion breaking, binder coalescence, and the progressive formation of adhesive bonds between the bitumen and aggregate particles before sufficient mechanical strength can be achieved [2,11,12,13]. Consequently, newly repaired pavement sections remain susceptible to traffic-induced deformation, aggregate loss, and premature failure during the early curing period. Recent studies have consistently identified slow curing, high air-void content, moisture susceptibility, and insufficient early-age strength as the principal limitations preventing the wider adoption of CMA for permanent pavement repair applications [1,3,11,14]. Therefore, accelerating the rate of strength development during curing has become an important research objective for improving pavement durability, maintenance efficiency, and reducing traffic disruption.

The curing behaviour of Cold Mix Asphalt (CMA) is governed by several interacting factors, including mixture composition, aggregate gradation, emulsion characteristics, and environmental conditions [11,15]. Variations in temperature, humidity, wind speed, and moisture evaporation influence

the rate of emulsion breaking and binder coalescence, thereby controlling the development of engineering strength during curing [12,16]. Recent review studies have highlighted that reinforcing fibres improve the mechanical behaviour of asphalt mixtures by enhancing aggregate interlocking, stress transfer, and internal cohesion [17-18]. Recent state-of-the-art reviews have reported that synthetic fibres generally provide greater improvements in rutting resistance, fatigue performance, cracking resistance, and mixture stability than natural fibres owing to their superior tensile strength, durability, and compatibility with asphalt binders [17,19]. Since the reopening of repaired pavement sections is governed primarily by the development of sufficient load-bearing capacity rather than the ultimate strength achieved after complete curing, understanding the progression of strength during the curing period is essential for practical pavement maintenance applications. Accordingly, Marshall Stability remains one of the most widely adopted engineering indicators for evaluating asphalt mixtures because it reflects the load-bearing capacity and structural integrity of compacted asphalt under loading. For Cold Mix Asphalt, monitoring Marshall Stability throughout the curing period provides a practical means of evaluating the progression of engineering strength and identifying the earliest stage at which repaired pavement sections may be safely reopened to traffic.

Numerous modification techniques have been proposed to improve the engineering performance of Cold Mix Asphalt (CMA), including cementitious materials, polymer modifiers, reclaimed asphalt pavement, chemical additives, and reinforcing fibres [3,4,8]. While cement and polymers primarily enhance curing characteristics and moisture resistance, reinforcing fibres have emerged as one of the most promising modification approaches because they improve the internal mechanical behaviour of asphalt mixtures without substantially altering conventional production procedures [20-21]. Fibre reinforcement enhances aggregate interlocking and internal cohesion within asphalt mixtures, thereby improving stress transfer between aggregate particles [20,22]. The resulting reinforcement mechanisms increase resistance to rutting, fatigue damage, and crack propagation under repeated loading [21,23]. Experimental studies have further demonstrated that these benefits can also be achieved in Cold Mix Asphalt mixtures, leading to improved mechanical stability during curing [24]. Recent state-of-the-art reviews have reported that synthetic fibres generally provide greater improvements in rutting resistance, fatigue performance, cracking resistance, and mixture stability than natural fibres owing to their superior tensile strength, durability, and compatibility with asphalt binders [20-22]. These improvements can often be achieved without substantial modification to conventional asphalt production and construction practices.

Among synthetic fibres, aramid-based fibres have attracted increasing attention because they combine high tensile strength with excellent fatigue resistance while maintaining low density and good chemical stability [21,25,26]. Aromatic Polyamide Fibre (APF), a type of aramid fibre, possesses high tensile strength, excellent thermal stability, low density, and superior fatigue resistance, making it a promising reinforcing material for asphalt mixtures [22-23]. Previous experimental studies have shown that fibre incorporation enhances the stability, cohesion, and mechanical performance of Cold Mix Asphalt mixtures [24-25]. Nevertheless, the influence of APF on the progression of early-age strength development during curing has received comparatively limited attention [26]. Previous studies have demonstrated that synthetic fibres improve the structural integrity of asphalt mixtures by enhancing stress transfer between aggregate particles and delaying crack initiation under repeated loading [23,27]. Aramid-based fibres, in particular, have attracted considerable attention because of their high tensile strength, excellent fatigue resistance, and effective crack-bridging capability [25-26]. Experimental investigations on fibre-reinforced Cold Mix Asphalt have further reported improvements in mixture stability, durability, and mechanical performance,

although research focusing specifically on early-age strength development during curing remains limited [24,28,29]. However, most published studies focused on Hot Mix Asphalt or evaluated the ultimate mechanical properties of asphalt mixtures after complete curing. Comparatively limited attention has been given to the influence of APF on the rate of early-age strength development of emulsion-based Cold Mix Asphalt mixtures [24,30,31,32].

From the perspective of pavement maintenance, the ability of a repair material to achieve sufficient engineering strength within the shortest possible curing period is often more important than attaining the highest ultimate strength. Earlier development of Marshall Stability may support earlier traffic reopening if the required load-bearing threshold is reached sooner, thereby potentially reducing traffic disruption, user delay, and maintenance downtime. Although considerable progress has been made in developing fibre-reinforced asphalt mixtures, comparatively few studies have investigated the progression of Marshall Stability throughout the curing period, particularly for APF-modified Cold Mix Asphalt. Addressing this knowledge gap is important for developing Cold Mix Asphalt repair materials with improved early-age engineering performance while maintaining satisfactory long-term pavement serviceability.

Accordingly, this study investigates the influence of Aromatic Polyamide Fibre (APF) on the early-age strength development of Cold Mix Asphalt during curing. The effects of APF incorporation on workability, volumetric properties, and Marshall Stability were evaluated at curing durations of 24, 48, 72, and 96 hours. Linear regression was used only as an exploratory description of the relationship between curing duration and Marshall Stability; it was not intended as a predictive curing model. Unlike previous studies that primarily emphasised ultimate mechanical performance, this study focuses on the progression of Marshall Stability during curing as a practical indicator of early-age strength development. It was hypothesised that APF would enhance early-age strength by improving internal reinforcement within the mixture. The study therefore evaluates whether APF-modified CMA exhibits improved early-age engineering performance while acknowledging that the selected curing intervals cannot establish the exact traffic-opening time [4,31,32].

2. MATERIALS AND METHODOLOGY

This study experimentally evaluated the influence of Aromatic Polyamide Fibre (APF) on the early-age strength development of Cold Mix Asphalt (CMA). Two mixtures were prepared: an unmodified control mixture and a CMA mixture containing 0.05% APF by aggregate weight. Laboratory evaluations included workability, volumetric properties, and Marshall Stability at curing durations of 24, 48, 72, and 96 hours. Descriptive statistics and exploratory pairwise comparisons were used to quantify variability between replicate specimens. Linear regression was retained only as an exploratory trend analysis because the dataset contained four curing ages per mixture.

2.1 Aggregates

Crushed coarse and fine aggregates were used in preparing the Cold Mix Asphalt (CMA). The aggregate gradation was designed in accordance with the *Guidelines on Cold Mix Asphalt for Permanent Pothole Patching* published by the Road Engineering Association of Malaysia (REAM) [6]. The selected gradation satisfied the recommended grading envelope to ensure adequate aggregate interlocking and workability for pothole repair applications. The target aggregate composition is presented in Table 1, while the resulting gradation curve is illustrated in Figure 1.

Table 1. Aggregate gradation by REAM standard

B.S sieve size (mm)	Percentage passing by weight (%)	Percentage passing (%)	Percentage retained (%)	Aggregate content (g)
14.0	100	100	0	0
10.0	75-100	85	15	180
5.0	20-70	35	50	600
3.25	10-60	25	10	120
1.18	5-40	10	15	180
0.15	2-15	5	5	60
0.075	0-8	3	2	24
Pan	0	0	3	36
Total			100	1200

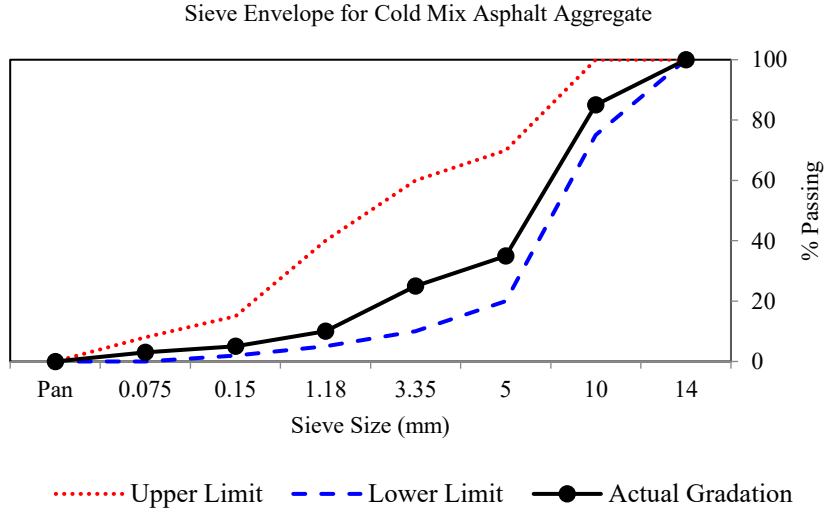


Fig. 1. Sieve envelope for CMA aggregate

2.2 Bitumen emulsion

A cationic medium-setting bitumen emulsion (MS-1K) was used as the binder. Preliminary coating assessments were conducted using emulsion contents from 7.0% to 9.0% by aggregate weight at 0.5% increments. An emulsion content of 8.0% was selected based on satisfactory aggregate coating and mixture workability, corresponding to 96 g of bitumen emulsion for the 1,200 g aggregate batch used in specimen preparation. This selected content is consistent with previous studies on cold mix asphalt mixtures [11,33].

Table 2. Classification of bitumen emulsion grade

Bitumen emulsion grade	Usage recommendation
MS-1K	Cold patch and penetration macadam

2.3 Aromatic polyamide fibre (APF)

APF was incorporated as the reinforcing material in the modified CMA. The fibre possesses high tensile strength, excellent thermal stability, and low density, making it suitable for asphalt reinforcement applications. The physical properties of APF are summarised in Table 3.

The APF dosage was selected based on the fibre proportion adopted in prior industrial practice and proportionally scaled for laboratory preparation. A dosage of 0.05% by aggregate weight corresponds to approximately 496.3 g per tonne of aggregate, or 0.6 g for the 1,200 g laboratory aggregate batch. This low dosage was selected to facilitate uniform fibre dispersion without adversely affecting mixture workability. The fibre was blended uniformly with the aggregate before the bitumen emulsion was added. Because only one APF dosage was evaluated, the present investigation is a comparative performance study rather than a fibre-content optimisation study.

Table 3. Properties of aromatic polyamide fibre (APF)

Properties	Characteristics
Tensile strength	2,758 MPa
Specific gravity	1.44
Operating temperature	-73 ºC to 427 ºC

2.4 Experimental design

The experimental design was developed to evaluate the influence of APF on the early-age strength development of CMA during curing. Two mixtures were prepared: an unmodified control mixture and a mixture containing 0.05% APF by aggregate weight. Standard Marshall cylindrical specimens (nominally 101.6 mm in diameter and 63.5 mm in height) were compacted using 75 blows on each face. For each mixture, two replicate specimens (n = 2) were prepared for each curing period of 24, 48, 72, and 96 h, giving eight specimens per mixture and 16 specimens in total for the curing-time investigation. Specimens were stored and cured under ambient laboratory conditions at approximately 25 °C; relative humidity was not continuously monitored during the original experimental programme. Before Marshall testing, specimens were conditioned at the laboratory test temperature of approximately 25 °C. Marshall Stability

and flow were determined using a loading rate of 50.8 mm/min. The four curing ages were selected to monitor early strength development and threshold attainment. Because only four curing-age observations were available, linear regression was used only as an exploratory description of the overall trend and not as a predictive curing model. The overall experimental design is presented in Figure 2.

For statistical reporting, Marshall Stability results are presented as mean ± standard deviation. Exploratory Welch's independent-samples t-tests were used to compare the control and APF-modified mixtures at each curing age. Because only two replicate specimens were available per mixture at each age, these pairwise tests have low statistical power and are interpreted cautiously. A significance level of $p < 0.05$ was used.

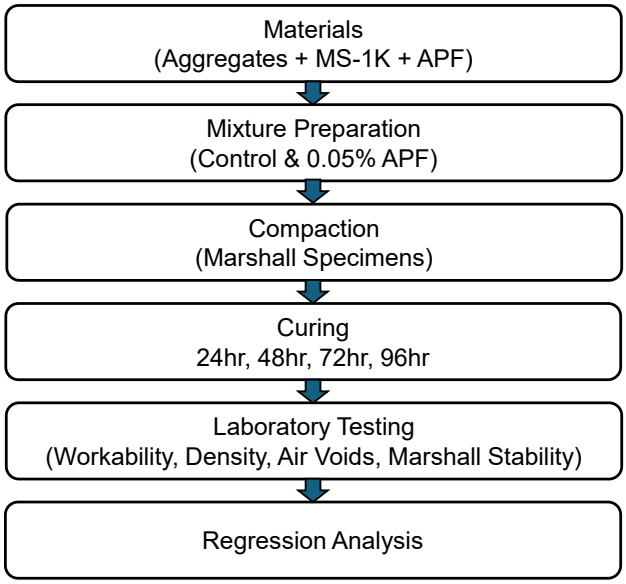


Fig. 2. Experimental design adopted for evaluating the early-age strength development of APF-modified Cold Mix Asphalt

3. RESULTS AND DISCUSSION

3.1 Workability test

Based on visual observation, both the unmodified and APF-modified mixtures flowed without obstruction during the workability assessment, indicating satisfactory handling characteristics. Figure 3 shows the mixtures during the workability test. Good workability is important for adequate compaction and complete filling of potholes during maintenance operations. The incorporation of 0.05% APF did not visibly compromise mixture handling under the laboratory conditions used.



a) Cold mix asphalt without APF



b) Cold mix asphalt with APF

Fig. 3. Workability test

3.2 Volumetric properties

Table 4 summarises the volumetric properties of the unmodified and APF-modified Cold Mix Asphalt mixtures after 72 hours of curing. The APF-modified mixture recorded a Gmm of 2.387 and a Gmb of 2.218, compared with 2.436 and 2.231, respectively, for the control mixture. The resulting air-void contents were 7.08% for the APF-modified mixture and 8.42% for the control. Thus, the APF-modified mixture satisfied the recommended 3–8% air-void range, whereas the control was slightly above the upper limit. The present measurements do not establish the physical mechanism responsible for the lower Gmm of the APF-modified mixture. In particular, lower Gmm should not by itself be interpreted as evidence of improved aggregate packing. The volumetric results are therefore reported as measured characteristics of the two mixtures, while the influence of APF on early-age mechanical performance is evaluated using the Marshall Stability results in the following section.

Table 4. Density and air void analysis of cold mix asphalt

Unmodified mix			**APF modified mix**			**Requirement for air void (Va)**
Gmm	Gmb	Va (%)	Gmm	Gmb	Va (%)	3-8 %
2.436	2.231	8.415	2.387	2.218	7.080	

3.3 Early-age strength development

Marshall Stability testing was conducted to evaluate the development of load-bearing capacity of the unmodified and APF-modified Cold Mix Asphalt mixtures during curing. The test was performed after curing periods of 24, 48, 72, and 96 hours to assess the influence of APF on the rate of early-age strength development. The corresponding Marshall Stability results are presented in Table 5.

Table 5. Marshall stability of cold mix asphalt

Sample	Curing duration (hours)	Marshall stability, mean ± SD (kN)	Requirement for marshall stability (kN)
Unmodified mix	24	3.167 ± 0.168	Minimum 6kN
	48	4.525 ± 0.049	
	72	7.480 ± 0.039	
	96	6.329 ± 0.155	
APF-modified mix	24	4.287 ± 0.023	
	48	5.344 ± 0.224	
	72	7.674 ± 0.625	
	96	6.090 ± 0.117	

The Marshall Stability results show that the APF-modified mixture had higher mean stability than the control during the first 24 and 48 h of curing. As presented in Table 5 and Figure 4, mean stability increased from 24 to 72 h for both mixtures and then decreased at 96 h. At 24 h, the APF-modified mixture recorded 4.287 kN compared with 3.167 kN for the control; at 48 h, the corresponding values were 5.344 and 4.525 kN. These represent increases in mean stability of approximately 35% and 18%, respectively. Because the pairwise comparisons are based on only two replicate specimens per group, the statistical results are interpreted cautiously.

Both mixtures first satisfied the minimum Marshall Stability requirement of 6 kN at the 72 h measurement, recording 7.480 kN for the control and 7.674 kN for the APF-modified mixture. At 48 h, neither mixture met the requirement. Therefore, the present experimental intervals demonstrate higher mean early-age stability for the APF-modified mixture but do not establish an earlier traffic-opening time. Additional testing at shorter intervals between 48 and 72 h would be required to determine whether APF enables earlier attainment of the 6 kN thresholds.

The observed early-age differences are consistent with the reinforcing role reported for synthetic fibres in asphalt mixtures, where fibres can contribute to stress transfer, crack bridging, and restriction of local particle movement [23,27]. However, the present study did not directly measure fibre–aggregate interaction during curing; these mechanisms are therefore considered plausible explanations rather than directly verified causes of the measured Marshall Stability differences.

From a practical perspective, the higher mean Marshall Stability observed for the APF-modified mixture at 24 and 48 h is relevant to pavement maintenance because early load-bearing capacity is important during curing. Nevertheless, the present data should be interpreted as evidence of enhanced early-age strength development rather than proof of earlier reopening, since both mixtures first exceeded 6 kN at the 72 h test interval.

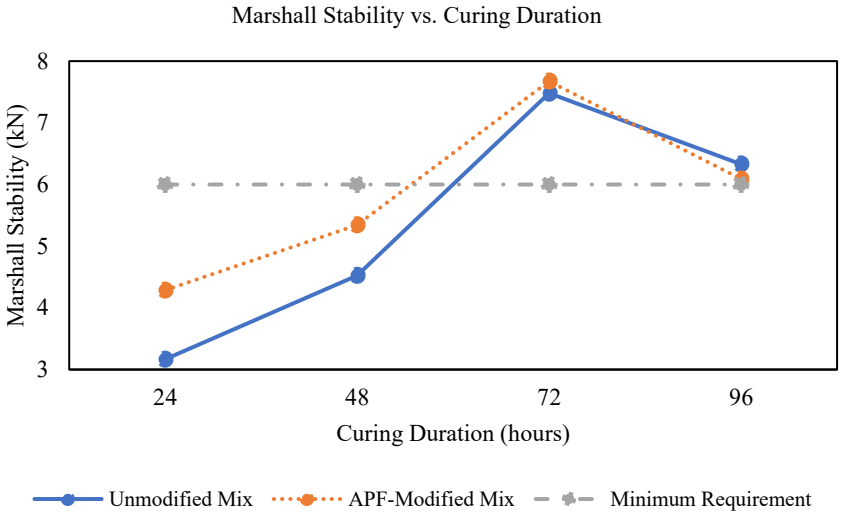


Fig. 4. Marshall stability of CMA with and without APF at different curing durations

Both mixtures reached their highest measured Marshall Stability at 72 h, followed by a reduction at 96 h. The control decreased from 7.480 to 6.329 kN (about 15.4%), while the APF-modified mixture decreased from 7.674 to 6.090 kN (about 20.6%). Because the decline occurred in both mixtures, it cannot be attributed solely to APF. CMA strength development involves moisture loss, emulsion breaking, and binder coalescence, and continued curing may be accompanied by changes in the mechanical condition of the mixture. Specimen-to-specimen variability may also contribute to the observed post-72-h response. Because moisture evolution and corresponding material changes were not independently monitored between 72 and 96 h, the precise mechanism cannot be established from the present results. Both mixtures nevertheless remained above the minimum 6 kN requirement at 96 h.

3.4 Regression analysis of strength development

Exploratory linear regression was performed to describe the overall association between curing duration and mean Marshall Stability over the investigated 24–96 h period. Because only four curing ages were available and both mixtures showed a post-72-h decline, the regressions are not treated as predictive curing models. The regression statistics are summarised in Table 6.

For the control mixture, the fitted relationship was $MS = 0.0518t + 2.2648$ ($R^2 = 0.707$, $p = 0.159$). For the APF-modified mixture, the relationship was $MS = 0.0323t + 3.9135$ ($R^2 = 0.492$, $p = 0.298$), where MS is Marshall Stability (kN) and t is curing duration (h). Neither slope was statistically significant at the 5% level.

The R^2 values indicate only how much of the variation in these four mean observations is represented by a straight-line fit; they should not be interpreted as evidence of superior or inferior mechanical performance. The lower R^2 for the APF-modified mixture does not establish a different curing mechanism. Instead, the measured response is non-monotonic, with both mixtures increasing to 72 h and decreasing at 96 h.

Given the limited number of curing ages and the non-monotonic response, fitting a more complex nonlinear model would risk overfitting and did not provide a validated representation of the curing process. Accordingly, the linear regressions are retained only as descriptive trend indicators. Additional, more closely spaced curing observations would be required to establish and validate an appropriate time-dependent strength model.

Table 6. Linear regression statistics for Marshall Stability development during curing

Unmodified mix	Regression statistics	APF-modified mix
0.841	Multiple R	0.702
0.707	R square	0.492
0.561	Adjusted R square	0.238
1.265	Standard error	1.243
4	Observations	4
MS = 0.0518t + 2.2648	Regression equation	MS = 0.0323t + 3.9135
0.159	Slope p-value	0.298

4. CONCLUSION

This study evaluated the influence of Aromatic Polyamide Fibre (APF) on the early-age strength development of Cold Mix Asphalt (CMA) during curing. The 0.05% APF-modified mixture maintained satisfactory workability and recorded a lower measured air-void content (7.08%) than the control mixture (8.42%). The physical cause of the accompanying Gmm difference was not independently established and is therefore not attributed to a specific APF-induced mechanism.

The APF-modified mixture exhibited higher mean Marshall Stability at 24 and 48 h, by approximately 35% and 18%, respectively. Exploratory pairwise tests did not indicate statistically significant differences at the 5% level, and the small number of replicates (n = 2 per condition) limits inferential strength. Both mixtures first exceeded the minimum 6 kN requirement at the 72 h measurement; therefore, the present data demonstrate enhanced early-age mean stability but do not establish an earlier traffic-opening time for the APF-modified mixture.

The exploratory linear regressions were not statistically significant and did not adequately represent the complete non-monotonic curing response. They are therefore interpreted only as descriptive trend indicators rather than predictive models. The reduction in stability between 72 and 96 h occurred in both mixtures and cannot be assigned to a specific mechanism because moisture evolution and related material changes were not independently monitored.

Future studies should use a larger number of replicate specimens, additional curing points which is particularly between 48 and 72, and multiple APF dosages. Monitoring moisture evolution alongside mechanical testing would also help clarify the post-72-h response and support development of a validated traffic-readiness model.

Overall, the results indicate that 0.05% APF can enhance the early-age mechanical response of CMA, particularly within the first 48 h of curing. Further testing with denser curing intervals is required before any claim of earlier traffic reopening can be established.

5. ACKNOWLEDGEMENTS/FUNDING

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6. CONFLICT OF INTEREST STATEMENT

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.

7. AUTHORS' CONTRIBUTIONS

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.

8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to improve the readability, language quality, and clarity of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi Mara (UiTM).

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