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# Influence of Polyurethane Modification on the Mechanical and Frictional Properties of Cold Mix Asphalt

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ABSTRACT

*Cold Mix Asphalt (CMA) is not only appealing in low-energy and low-emission pavement work but it tends to have poor mechanical and surface performance. The research question is the investigation of the possibility of using low-dose polyurethane (PU) modifier to improve CMA without jeopardizing skid safety. PU (6% by aggregate mass) was mixed into CM-100 emulsion and tested by laboratory tensile and direct shear tests in polyol: isocyanate ratios (1:1, 2:1), curing time (1, 3, 7, 15 days), and environmental conditioning (dry, wet). The British Pendulum Tester (ASTM E303) was used to measure field skid resistance on six patched potholes on dry and wet surfaces at early age (4 hours) and after curing (7 days). The findings demonstrate that the 1:1 ratio gave the best ultimate tensile stress at 15 days, which is a densely cross-linked yet brittle matrix, and 2:1 gave a consistently higher ductility and strain capacity. Shear behaviours have different pattern, where 2:1 variant delivered the most balanced stress-strain response, while 1:1 generally have reduced shear strength. Both PU-CMA and control CMA had a higher skid resistance than the Transport and road Research laboratory (TRRL) threshold values at all ages and anticipated decreases on wet surfaces, PU-CMA was similar to CMA in dry and wet conditions. In general, low-dose PU can be implemented in CMA to enhance mechanical strength and toughness without compromising the necessary skid resistance, which is sustainable and quick in pavement maintenance (median-to-heavy traffic) conditions.*

*Keywords: Cold Mix Asphalt (CMA); Polyurethane (PU) modification; tensile and shear strength; skid resistance; sustainable pavement materials*

## INTRODUCTION

Cold Mix Asphalt (CMA) has been gaining popularity because of its less energy consumption in production and lower greenhouse gas emissions compared to the traditional Hot Mix Asphalt (HMA) (Jain & Singh 2021). Although these are positive environmental impacts, CMA has a wide limitation in terms of its use because of its poor mechanical and surface characteristics, such as regular deformation problems that are vital to the integrity of road structures (Shanbara et al. 2018).

The polyurethane (PU) has proven to become a potential asphalt modifier, showing outstanding elasticity, moisture resistance, and adhesion, thereby enhancing rutting, fatigue, and aging resistance, mainly in CMA scenarios (Xu et al. 2024). Additionally, the durability of cold-mix PU systems has been reported to be more water stable and dynamic in strength (Guolin et al. 2020).

Interfacial adhesion between the PU and the asphalt matrix is one of the most prominent aspects that have an influence on overall performance of the PU-modified asphalt. The splicing pavement stress analysis diagram is displayed in Figure 1 (Zhong et al. 2023). As transition zones are typically the weakest areas of any structure, this interface zone is crucial because it involves the joining of two distinct materials. An inadequate bond could cause the repair to fail prematurely. Zhong (2023) investigated interface bonding characteristics of PU and pavement materials. Interface roughness and PU density significantly enhanced shear and splitting tensile strengths. Splitting tensile strength increased with interface roughness and PU density, demonstrating a strong positive correlation. Practical engineering implications for effective pavement repairs though frictional behaviour was not addressed (Zhong et al. 2023).

Hence, it is vital to identify the most suitable dosage of PU because certain doses have demonstrated the best performance properties (Sun et al. 2023).

Sustainability improvement has also encouraged the need to use bio-based polyols in the manufacture of PU. As an example, palm oil-based polyols and other renewable raw materials have been tested with the possibility of creating environmentally friendly PU with competitive mechanic properties (Pawlik & Prociak 2012; Yeoh et al. 2020). These contents contribute to the creation of biodegradable PU systems that become more and more applicable in the field of application where a weighed compromise between mechanical properties and environmental sustainability is needed (Yeoh et al. 2020).

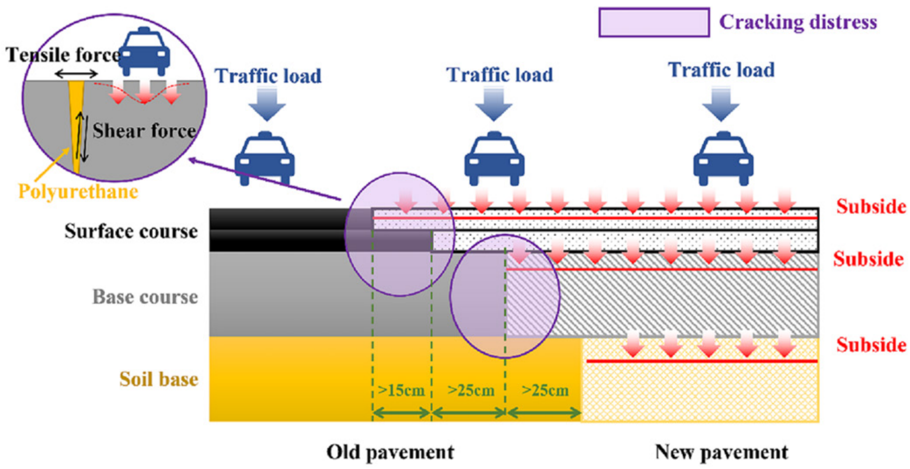



FIGURE 1. Stress Analysis Diagram of Splicing Pavement (Zhong et al. 2023).

Polyurethane has been widely reported to enhance the mechanical strength, moisture resistance, and durability of asphalt materials. However, existing studies mainly focus on binder rheology, structural performance, thin overlays, or specialised wearing courses. Limited attention has been given to the effect of low-dosage PU modification on the skid resistance of conventional Cold Mix Asphalt (CMA), particularly under dry and wet conditions using the British Pendulum Test (BPT). This represents an important research gap because skid resistance is a critical safety and performance indicator for pavement surfaces (Fan et al. 2021; Guolin et al. 2020).Furthermore, the relationship between PU dosage, mechanical performance, and CMA surface friction remains insufficiently established. Although PU may improve bonding and durability, its influence on surface texture and frictional behaviour must be evaluated to ensure that mechanical enhancement does not compromise traffic safety. Therefore, this study addresses this gap by quantitatively assessing the mechanical properties of PU-modified CMA and examining their relationship with skid resistance under practical dry and wet testing conditions. This provides evidence-based insight into whether low-dosage PU can improve CMA performance while maintaining adequate pavement surface safety.

## METHODOLOGY

### SITE LOCATION

The skid resistance tests were conducted at a road which is the main road for heading to a quarry site, while the mechanical tests of PU were performed at the Highway and Pavement Engineering Laboratory, Universiti Teknologi MARA (UiTM), Malaysia. Figure 2 shows the road leading to quarry site where the location of skid resistance tests was conducted.


FIGURE 2. Location for skid resistance test (1.518786, 103.875754) from Google Maps

## MATERIAL

This study utilized materials specified under the Patch-Pro Cold Mix Asphalt system supplied by Probase Manufacturing Sdn. Bhd., which is commonly used for pavement patching and maintenance works. The materials include crushed aggregates, quarry dust, and CM-100 cold mix bitumen emulsion binder, all conforming to strict physical and mechanical requirements.

The requirements for aggregate as shown in Table 1 are to ensure that the aggregate contributes to adequate strength, durability, and surface texture necessary for both structural integrity and skid resistance performance.

Quarry dust serves as the fine filler in the mix. Its cleanliness and anionic properties enhance binder compatibility and improve the matrix cohesion. Table 2 shows the properties of the quarry dust used for this research.

The CM-100 binder is a cationic bitumen emulsion. Its thermal stability, flexibility, and adequate residue content as shown in Table 3 are essential to maintain bonding and cohesion in the cold mix system.

Mix design proportions for Patch-Pro CMA is shown in Table 4. This proportional formulation was used for both the control mix and PU-modified CMA, maintaining consistency to isolate the effect of polyurethane on skid resistance performance.

The polyurethane (PU) additive used in the modified mix was a commercially available, PU resin was added at 6% by weight of total aggregate into the CM-100 emulsion prior to mixing with the aggregates. 6% dosage of PU was selected for skid resistance test as it represents a balanced combination of bonding performance (Sheng et al. 2018). Lower PU contents may be insufficient to provide effective bonding and durability, while higher PU dosages can lead to excessive binder coverage of aggregate particles, which may unfavourably affect surface texture and friction.

TABLE 1. Aggregate requirements for CMA

| Property | Specification |
|---|---|
| Aggregate Type | Crushed hard rock, non-plastic, free from dust, clay, organic matter |
| Aggregate Size | 6–9 mm Diameter Chip Stone |
| Moisture Content | Not above 0.5% |
| Flakiness Index (MS 30) | ≤ 25% |
| Aggregate Crushing Value (MS 30) | ≤ 25% |
| Magnesium Sulfate Soundness Loss | ≤ 18% (5 cycles, ASSHTO T104) |
| Aggregate pH | Anionic or pH ≥ 8 |
| Cleanliness | Must be free from dust |

TABLE 2. Quarry Dust Specifications

| Property | Specification |
|---|---|
| Material Type | Screened crushed hard rock, non-plastic, dust- and clay-free |
| Moisture Content | Not above 0.5% |
| pH Condition | Must be anionic |

Table 3. CM-100 Cold Mix Binder Properties

| Parameter | Unit | Test Method | Requirement |
|---|---|---|---|
| Storage Stability (24 hours) | % diff | ASTM D244 | Max 0.3 |
| Particle Charge Test | – | ASTM D244 | Positive |
| Residue by Evaporation | % mass | ASTM D244 | Min 62% |
| Ring & Ball Softening Point | °C | ASTM D36 | Min 40 |
| Penetration @ 25°C, 100g, 5s | 0.1 mm | ASTM D5 | Min 80 |
| Ductility on Residue | cm | ASTM D113 | Min 60 |

TABLE 4. Mix Design Proportions for Patch-Pro CMA

| Material | Minimum % by Weight | Maximum % by Weight |
|---|---|---|
| CM-100 Binder | 9% | 10% |
| 6–9 mm Chip Stone | 75% | 81% |
| Quarry Dust | 10% | 15% |

## POLYURETHANE TENSILE STRENGTH AND SHEAR STRENGTH TEST

A key formulation parameter in polyurethane is the isocyanate-to-polyol stoichiometric balance, commonly expressed through the reactive –NCO:–OH ratio. The 1:1

ratio was selected because it represents the stoichiometric condition in which isocyanate and hydroxyl groups are balanced, allowing a more complete polymer network formation and higher crosslinking efficiency (Bagdi et al. 2010). In contrast, the 2:1 polyol-to-isocyanate ratio was selected to introduce higher polyol content, which increases the soft-segment contribution and may improve flexibility, elastic recovery, and deformation tolerance, although excessive polyol may reduce stiffness due to lower crosslink density (Huang & Zhang 2002).

The 1:2 isocyanate-rich ratio was excluded because excess isocyanate can react with moisture, producing $CO_2$ and forming additional pores within the polymer network (Havlík & Smith, 1964). This reaction is useful in foam production but may be detrimental for pavement bonding applications where compactness, adhesion, and mechanical integrity are required. Furthermore, isocyanate may react more rapidly with water than with polyol, increasing the risk of unwanted void formation in moisture-exposed systems (Rahman & Lee 2009). Therefore, this study focused only on the 1:1 and 2:1 ratios to compare a stoichiometrically balanced PU system with a more flexible polyol-rich PU system.

To evaluate the mechanical behaviour of polyurethane (PU) as a binder additive, both tensile and direct shear tests were conducted under varying formulation and environmental conditions. The PU was prepared by mixing polyol and isocyanate in two different weight ratios: 1:1 and 2:1. After homogenization for approximately 60 seconds, the mixtures were poured into silicone moulds and allowed to cure under ambient laboratory conditions (25°C) for 1, 3, 7, or 15 days. To assess moisture-induced degradation, a subset of samples from each curing period was submerged in water for 24 hours prior to testing, resulting in two environmental conditions: dry and wet. This setup yielded a total of 16 unique test conditions, combining two PU ratios, four curing durations, and two moisture states. The 16 unique variant is listed under the Table 5 to ease reader to understand.

TABLE 5. Variants of Samples According to test Conditions

| Sample ID | Curing Period (Days) | Ratio | Condition |
|---|---|---|---|
| P0111D | 1 | 1:1 | Dry |
| P0121D | 1 | 2:1 | Dry |
| P0111W | 1 | 1:1 | Wet |
| P0121W | 1 | 2:1 | Wet |
| P0311D | 3 | 1:1 | Dry |
| P0321D | 3 | 2:1 | Dry |
| P0311W | 3 | 1:1 | Wet |
| P0321W | 3 | 2:1 | Wet |
| P0711D | 7 | 1:1 | Dry |
| P0721D | 7 | 2:1 | Dry |
| P0711W | 7 | 1:1 | Wet |
| P0721W | 7 | 2:1 | Wet |
| P1511D | 15 | 1:1 | Dry |
| P1521D | 15 | 2:1 | Dry |
| P1511W | 15 | 1:1 | Wet |
| P1521W | 15 | 2:1 | Wet |

Tensile specimens were cast in rectangular moulds with the size of 100x20x10mm. Steel plates were embedded at both ends of each specimen to prevent slippage and minimize grip failure during testing as shown in Figure 3. The effective gauge length for strain calculations was limited to the central 60 mm of the specimen, which was free of steel reinforcement.

Tensile tests were carried out using a Universal Testing Machine (UTM) at a loading rate of 5 mm/min. The machine recorded only applied force and stroke (displacement), from which tensile stress and strain were calculated manually using the cross-sectional area (200 mm²) and effective gauge length (60 mm). These data were used to construct stress–strain curves and determine tensile strength, elongation, and failure characteristics. Experimental setup is shown in Figure 4.

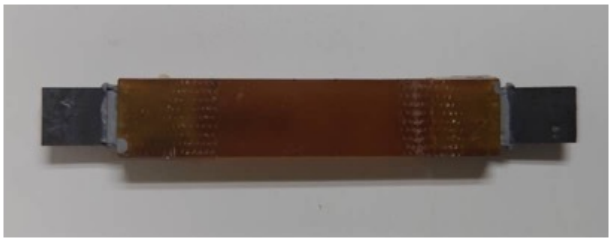


FIGURE 3. Sample of PU with Embedded Steel Plate at Both Ends

FIGURE 4. Tensile Strength Test Experimental Settings

For shear testing, PU specimens were prepared in cuboid sized 20x20x100mm to fit a custom-fabricated direct shear jig mounted on the UTM. A horizontal load was applied at a constant rate of 5 mm/min until failure occurred. Similar to the tensile test, only force and stroke data were recorded. Shear sample and experimental setup using customized jig is shown in Figure 5 and Figure 6 respectively. Figure 7 display the schematic detailed drawings for the customized jig used for shear strength test.

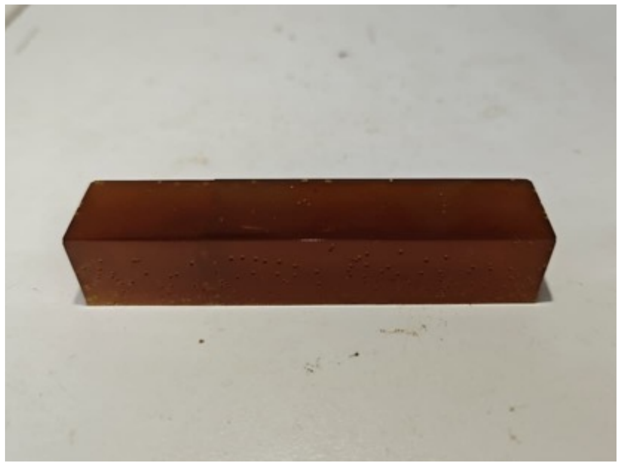


Figure 5. Shear sample specimen

Shear stress was then calculated by dividing the peak load by the sheared area of the sample. This test simulated the in-plane shear forces that a binder would encounter within an asphalt matrix, thereby reflecting its capacity to maintain cohesion and resist lateral deformation.

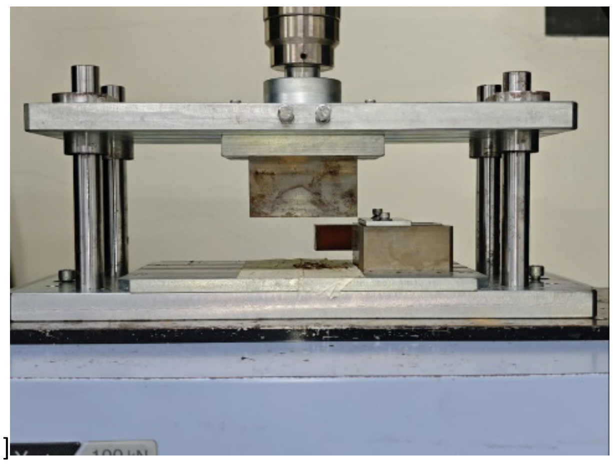
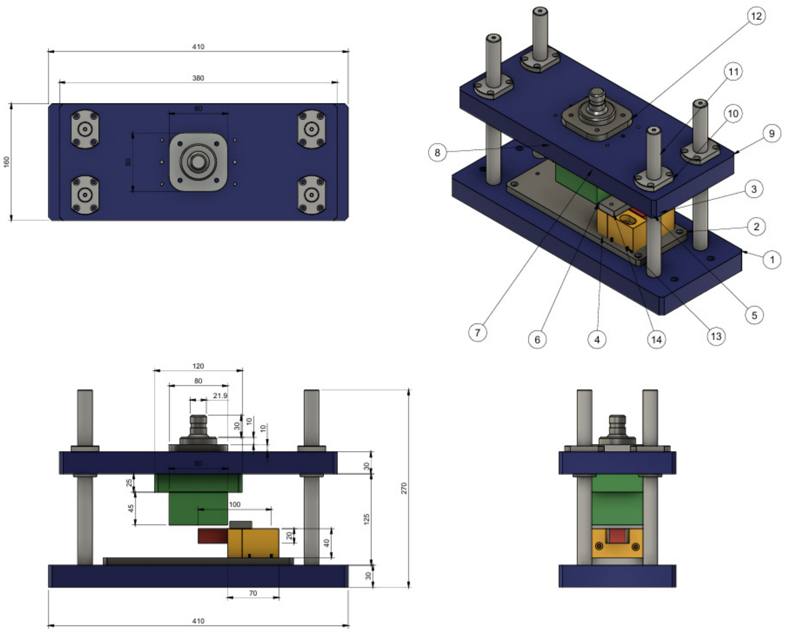


Figure 6. Custom-fabricated direct shear jig experimental settings



| Parts List | | |
|---|---|---|
| Item | Qty | Part Number |
| 1 | 1 | BASE |
| 2 | 1 | MIDDLE BASE |
| 3 | 1 | PRODUCT HOLDER |
| 4 | 1 | BOTTOM CUTTER |
| 5 | 1 | PRODUCT TEST |
| 6 | 1 | CUTTER TOP |
| 7 | 4 | E-SFJW15-40-M5-N5 |
| 8 | 1 | TOP MIDDLE PRESS |
| 9 | 1 | TOP PRESS |
| 10 | 4 | E-LBH20UU |
| 11 | 4 | E-SFJW20-250-M5-N5 |
| 12 | 1 | COLLER |
| 13 | 4 | DOWELL PIN D-3 |
| 14 | 1 | STAND BAR |

FIGURE 7. Customized Jig for Shear Strength Test

Each of the 16 test conditions was replicated three times for both tensile and shear configurations, resulting in a total of 48 tensile and 48 shear tests. The averaged results were analysed to assess the influence of PU formulation ratio, curing time, and moisture exposure on mechanical performance. This experimental design provided a comprehensive understanding of the behaviour of PU under realistic service conditions relevant to its application in cold mix asphalt modification.

## SKID RESISTANCE

Skid resistance testing was conducted to evaluate the surface friction performance of both the control CMA and the PU-modified CMA under real-world conditions. The CMA was manually mixed and patched into an actual pothole on-site, and compacted using a 3kg hand compactor hand compactor as shown in Figure 8. Six potholes were patched and labelled as spot A, B, C, for patching using PU-CMA composite, as shown in Figure 9 while spot D, E and F for patching that use only CMA, as shown in Figure 10. 1:1 polyol-to-isocyanate ratio was selected because it provides a stoichiometrically balanced PU formulation. Furthermore, the 1:1 ratio is commonly adopted as a baseline formulation in PU studies, making it suitable for comparison. The performance assessment was carried out using a British Pendulum Tester (BPT) in accordance with ASTM E303 as in Figure 11.

FIGURE 8. Hand compactor for manual compaction

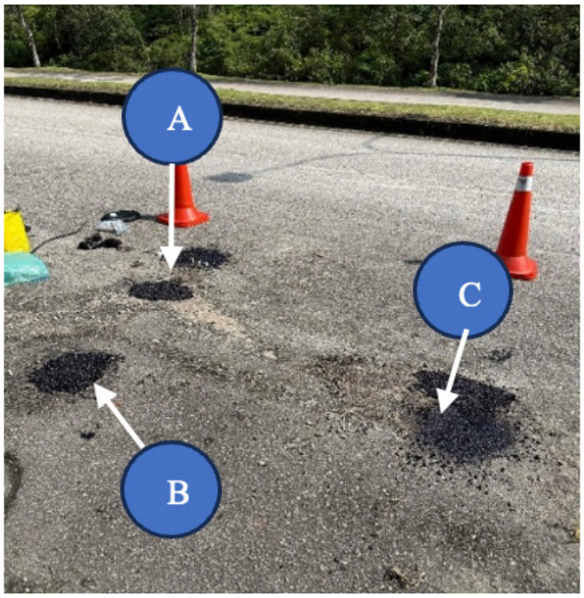



FIGURE 9. PU-CMA patches

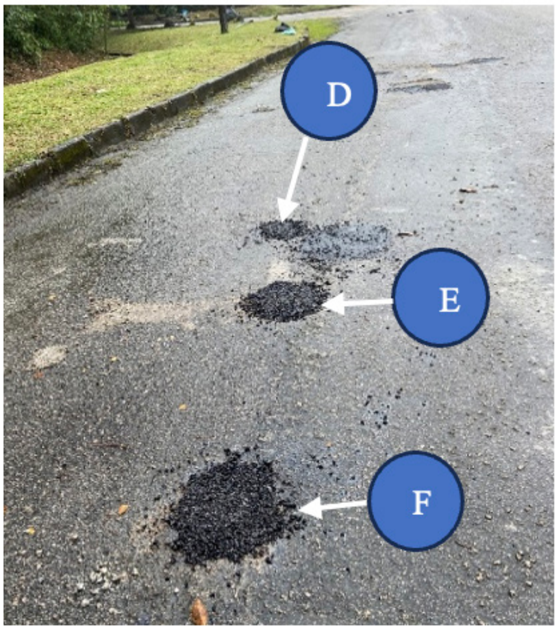



FIGURE 10. Conventional CMA patches

To capture both early-age and time-dependent behaviour, skid resistance was measured at two different curing intervals. First test was done 4 hours after patching to represent initial or early traffic opening conditions and 7 days after curing to reflect medium-term field performance as the binder further sets and moisture dissipates.

The test was performed on the surface of the patched area under both dry and wet conditions. For wet testing, the surface was thoroughly wetted with distilled water immediately before measurement to simulate rainfall or splash events. For each condition and time point, five BPN (British Pendulum Number) readings were taken from different spots on the patched surface, and the average value was reported to ensure measurement consistency.

FIGURE 11. Skid Resistance Test Using British Pendulum Tester

This dual-stage testing approach provides insights into how polyurethane modification influences the skid resistance of CMA during both early use and after partial curing, which is critical for evaluating the safety and performance of field-applied cold patch materials.

## RESULTS AND DISCUSSION

### POLYURETHANE TENSILE STRENGTH

The strength of PU at an early stage is demonstrated in Figure 12, where all samples show relatively low stress values, indicating weak internal bonding and inadequate curing. Out of the four conditions, the P0121W sample exhibits the highest peak stress and the maximum strain capacity which are 4.730 MPa at 75.7% strain. This implies that excessive polyol and moisture exposure may slow down cross-linking and hardening, resulting in increased ductility and flexibility. In contrast, the P0111D and P0121D samples exhibit lower stress and limited strain, 1.099 MPa at 26.5% strain and 1.594 MPa at 62.0% strain, respectively. This result indicates a rigid yet undeveloped matrix as a result of inadequate curing time.

Figure 13 shows the improvement in mechanical properties for all samples. The P0321W sample exhibits a more developed but still ductile structure and maintains the highest strength for 7.246 MPa at 20.5% strain values. Although the P0321D sample fails at a lower strain, 4.486 MPa at 49.4% strain, it also exhibits greater stress resistance, suggesting a stiffer and more brittle behaviour. Due to its limited toughness and early-stage brittleness, the P0311D formulation continues to be the weakest, 3.791 MPa at 6.6% strain, showing early failure and poor deformation capability.

Figure 14 shows that significant behavioural changes occur after seven days of curing. Both P0721W (8.233 MPa) and P0721D (5.853 MPa) samples perform significantly better in terms of stress resistance. A better and balanced mechanical profile is indicated by P0721D sample's modest ductility and clearly defined stress peak. On the other hand, the P0711D sample exhibits an abrupt failure after a sharp increase in stress, indicating that even if its stiffness has increased, it is still brittle. Although its strength increases, the P0721W sample still performs better in terms of strain, indicating that exposure to moisture might increase deformability.

The strength of PU after fifteen days of curing is displayed in Figure 15. The P1511D sample has the highest peak stress, 12.345 MPa, indicating that a highly cross-linked and strong matrix may be achieved with an ideal PU molar ratio of 1:1 and enough curing time. However, the curve drops down sharply after the peak stress, suggesting brittle fracture. The P1521D sample shows better ductility and moderate stress values 6.763 MPa at 29.8% strain, suggesting a more flexible matrix with increased toughness.

When compared to their dry counterparts, the wet-conditioned samples of 1:1 and 2:1 polyol-to-isocyanate ratio exhibit reduced stress levels. This implies that moisture exposure has a negative impact on the ultimate strength development of PU, even if it only occurs on the last day of curing. However, their stress-strain curves show longer deformation and more gradual slopes, suggesting greater ductility and elasticity.

The 1:1 polyol-to-isocyanate ratio have the best quality in terms of tensile strength, while higher polyol content in 2:1 polyol-to-isocyanate ratio gives more flexibility to the material, this pattern is compatible with results from Mohamed (2021)

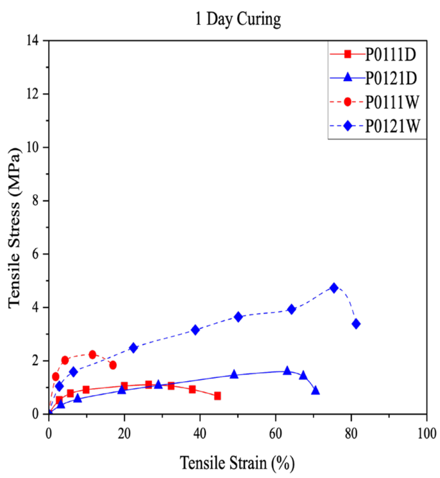



FIGURE 12. Stress-Strain Tensile Curve for 1 Days Curing

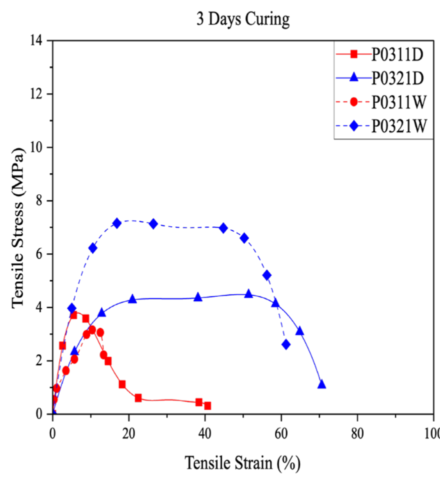



FIGURE 13. Stress-Strain Tensile Curve for 3 Days Curing

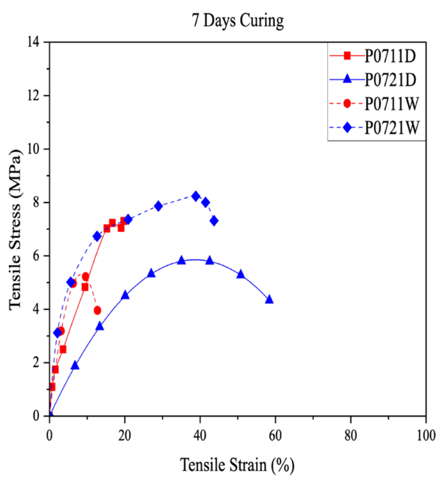



FIGURE 14. Stress-Strain Tensile Curve for 7 Days Curing

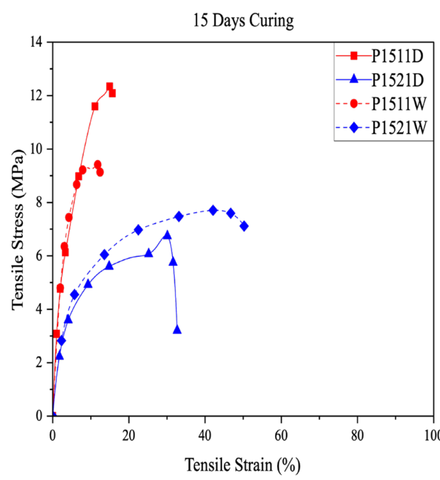



FIGURE 15. Stress-Strain Tensile Curve for 15 Days Curing

The trend of maximum stress in polyurethane (PU) samples under various material ratios and exposure conditions is displayed in Figure 16 for curing times of 1, 3, 7, and 15 days. At all curing times, the 2:1 wet sample continuously exhibits the greatest stress values, suggesting improved mechanical performance over time. While this ratio represents an excess of polyol compared to isocyanate, it acts as a proof that the improved strength is not necessarily due to increased cross-linking (Mohd Fauzi et al. 2024). Rather, it implies that the increased polyol content helps the PU matrix become more flexible and durable, which enables the material to withstand applied stress without failing prematurely. The 1:1 Wet samples, on the other hand, show the lowest strength over all curing times, highlighting the negative effects of moisture exposure, particularly when the formulation already has a low level of toughness.

Although all samples demonstrate a general increase in strength with curing time, indicating continuous material development, the wet-conditioned samples consistently underperform. This is likely due to water absorption affecting the integrity of the PU structure, even after surface drying. Overall, the results suggest that longer curing durations might enhance PU strength. However, the combination of higher polyol content and dry curing yields the most favourable mechanical properties possibly due to a more flexible and tough polymer network rather than a more cross-linked one. This result is consistent with study by Pawlik & Prociak (2012)

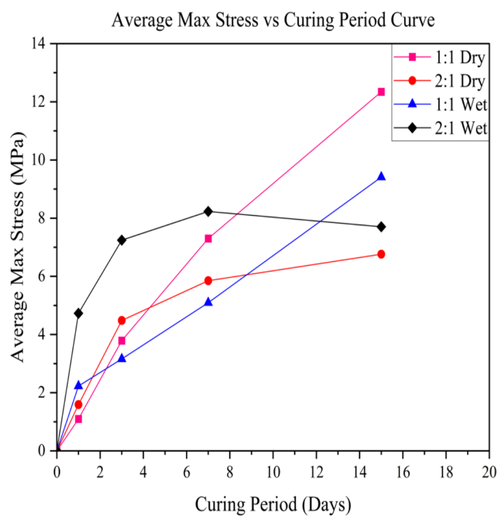



FIGURE 16. Average Max Tensile Stress vs Curing Period Curve

## POLYURETHANE SHEAR STRENGTH

Tensile strength measures a material's resistance to forces that pull it apart, whereas shear strength measures its resistance to forces that cause it to slide apart. The main difference is the direction of the force. Tensile forces stretch the material perpendicular to its surface, while shear forces cause layers to slide parallel to the material's surface.

Figure 17 to Figure 20 show the shear stress-strain behaviour of PU cured for 1, 3, 7, and 15 days under different polyol-to-isocyanate ratios and environmental conditions. Overall, the shear response followed a trend similar to the tensile behaviour, with the 2:1 formulation consistently demonstrating higher resistance to sliding deformation.

At Day 1, P0121D and P0121W recorded shear stresses of 7.750 MPa and 7.691 MPa, respectively, which were higher than P0111D and P0111W at 1.982 MPa and 2.141 MPa. This indicates that the 2:1 formulation developed stronger early shear resistance, while the 1:1 wet sample showed greater deformability but lower shear strength.

After 3 days, shear strength increased across the samples, indicating progressive crosslink development. P0321D reached 8.930 MPa, and the 2:1 samples continued to show higher stress resistance with lower strain at peak stress, suggesting improved stiffness and sliding resistance. In contrast, the 1:1 samples showed only moderate strength development.

At 7 days, the superior performance of the 2:1 formulation became more evident. P0721W achieved the highest shear stress of 10.211 MPa, followed by P0721D at 9.042 MPa. The 1:1 samples showed gradual improvement but remained lower in shear capacity, indicating a less stable matrix under shear loading.

By 15 days, the 2:1 formulation maintained its superior shear performance, with P1521D and P1521W recording 10.361 MPa and 10.223 MPa, respectively. In comparison, P1511D and P1511W reached only 4.606 MPa and 4.361 MPa. These results suggest that the 2:1 formulation provided better shear resistance throughout curing, likely due to a more ductile matrix capable of redistributing stress along the shear plane.

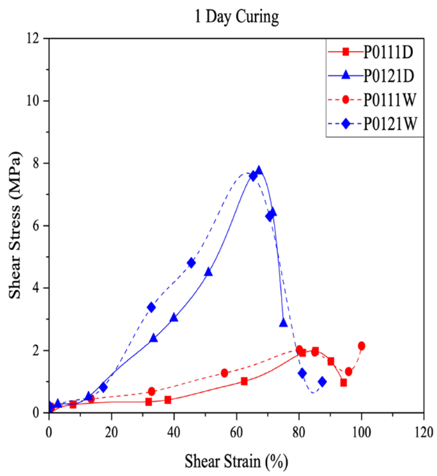



FIGURE 17. Stress-Strain Shear Curve for 1 Day Curing

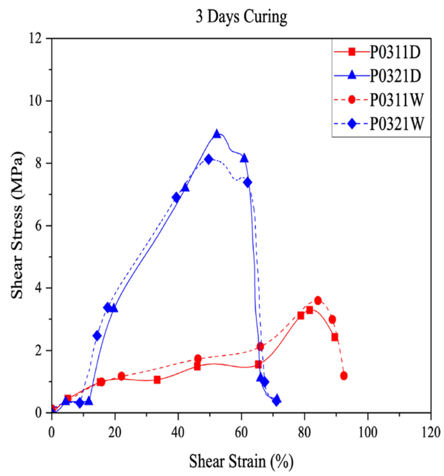



FIGURE 18. Stress-Strain Shear Curve for 3 Days Curing

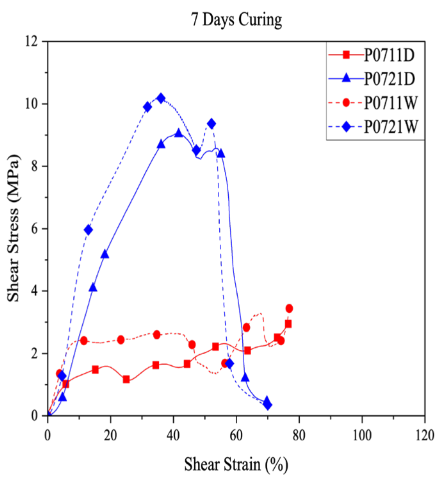



FIGURE 19. Stress-Strain Shear Curve for 7 Days Curing

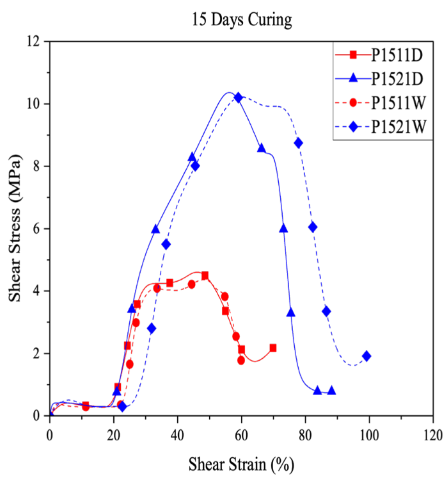



FIGURE 20. Stress-Strain Shear Curve for 15 Days Curing

Figure 21 shows the trend of maximum shear stress in polyurethane (PU) samples for curing durations of 1, 3, 7, and 15 days under different material ratios and exposure conditions. The 2:1 dry sample consistently shows the highest stress values almost at all curing intervals, indicating gradually better mechanical performance. This ratio serves also as evidence that the enhanced strength is not always the result of more cross-linking, even while it shows an excess of polyol relative to isocyanate (Fauzi et al. 2024), this case is also applied to tensile strength in the earlier discussion. This suggests that the higher polyol content makes the PU matrix more resilient and flexible, allowing the material to sustain applied stress without breaking down too soon. Water absorption by the wet-condition may help the PU gets its flexible properties in the early stage. However, compared to wet-conditioned variant, the dry counterparts break at slightly lower stress value, but in the 15 days of curing it exceeded the maximum stress resistance of the wet-condition variant. This indicate that the dry-condition variant might surpass the stress level of wet-condition variant if the curing period takes longer time.

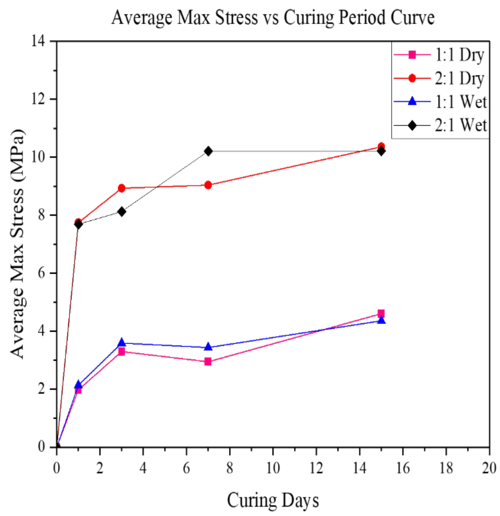



FIGURE 21. Average Max Shear Stress vs Curing Period Curve

## SKID RESISTANCE

Minimum skid resistance suggested by Transport and Road Research Laboratory (TRRL) is as in Figure 22.

Figure 22 shows the dry skid resistance measured 4 hours after patching. The average British Pendulum Values (BPV) for Spot A, B, C, D, E, and F were 58.0, 63.75, 64.25, 58.5, 63.5, and 67.75, respectively. The comparable BPV between Spot A, B and C and Spot D, E and F indicates that PU modification did not significantly reduce initial surface friction. All mixtures satisfied the recommended skid resistance for Categories B and C, while only Spot F satisfied Category A.

Under wet conditions after 4 hours, as shown in Figure 23, the BPV decreased slightly due to the lubricating effect of water on the patching surface, consistent with Fwa (2017). The BPV for Spot A, B, C, D, E, and F were 58.0, 60.25, 59.75, 57.0, 63.5, and 62.25, respectively. Although lower than the dry condition, the values remained relatively stable, suggesting that water did not severely compromise the skid resistance of PU-modified CMA. This indicates acceptable moisture resistance, in agreement with Kazemi et al. (2024). All spots also satisfied the recommended values for Categories B and C.

Figure 24 and Figure 25 present the dry and wet skid resistance after 7 days. Compared with the 4-hour results, both conditions showed improved skid resistance, indicating that curing contributed to better surface friction. Under dry conditions, the BPV for Spot A, B, C, D, E, and F were 66.25, 61.00, 59.25, 66.25, 65.25, and 61.00, respectively. Spot A, D, and E satisfied Category A, while Spot B, C, and F satisfied Categories B and C. The variation between spots was likely caused by uneven compaction, which affected the micro-texture and macro-texture of the patching surface.

For the wet surface after 7 days, the BPV for Spot A, B, C, D, E, and F were 55.50, 54.50, 51.50, 59.50, 59.75, and 56.00, respectively. These values were lower than the corresponding dry values, confirming the effect of moisture in reducing surface friction, as reported by Kazemi et al. (2024) and consistent with typical pavement behaviour (Fwa, 2017). Spot A, D, E, and F satisfied Category A, while Spot B and C satisfied Categories B and C.

- **Suggested minimum values of skid resistance (measured with the pendulum tester)**

| | Type of site | Minimum skid resistance (surface wet) |
|---|---|---|
| A | Difficult sites such as:<br>1. Roundabouts<br>2. Bends with radius less than 150 m on unrestricted roads<br>3. Gradients 1 in 20 or steeper of lengths greater than 100 m<br>4. Approaches to traffic lights on unrestricted roads | 65 |
| B | Heavy traffic roads in urban areas (carrying more than 2000 vehicles per day) | 55 |
| C | All other sites | 45 |

Figure 21. Suggested minimum values of skid resistance (TRRL 1969)

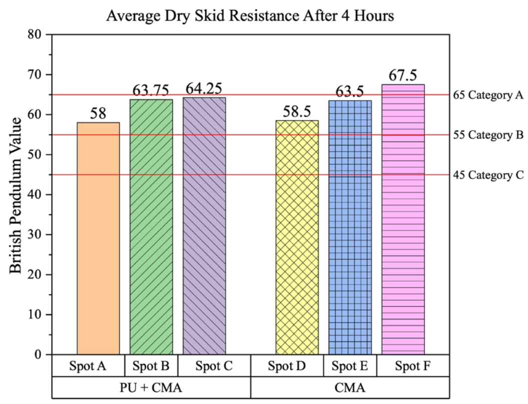



Figure 22. Average Dry Skid Resistance 4 Hours After Patching

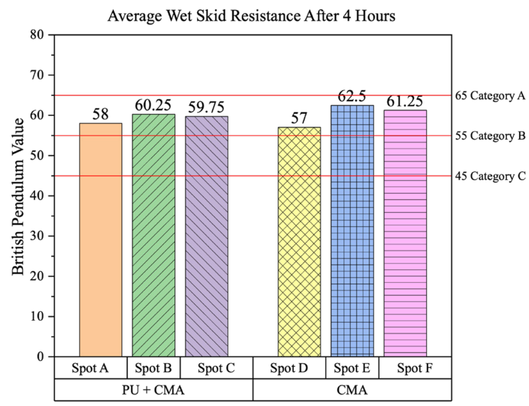



Figure 23. Average Wet Skid Resistance 4 Hours After Patching

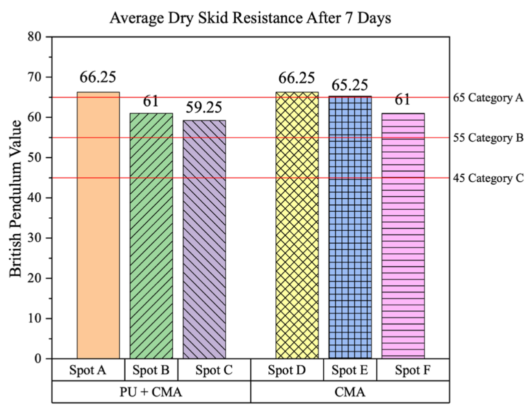



Figure 24. Average Dry Skid Resistance 7 Days After Patching

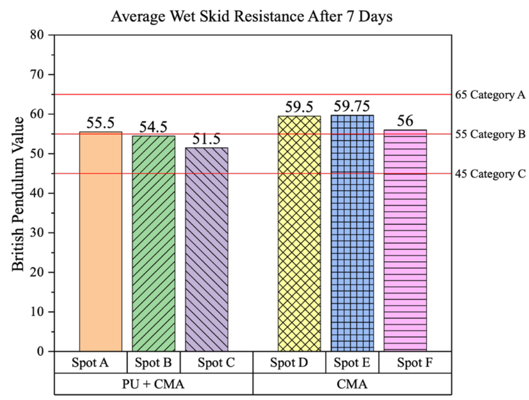



Figure 25. Average Dry Skid Resistance 7 Days After Patching

## CONCLUSION

The results of this research indicate the mechanical and functional performance of polyurethane (PU) at different curing periods, polyol to isocyanate ratios and under different environmental conditions. Tensile strength analysis showed that the 1:1 ratio had the highest ultimate stress following enough curing (15 days) indicating the development of a robust, highly cross-linked structure. This formulation was however prone to brittle failure. Conversely, the 2:1 ratio always exhibited better ductility and strain capacity, which implies a more flexible and tougher matrix although it has the lowest peak stress at longer curing periods. Likewise, shear strength development showed that the most balanced mechanical response was 2:1 dry variant, which exhibited progressive stress resistance and strain tolerance, and 1:1 samples were brittle and had uneven curing behaviour. The exposure to moisture tended to reduce the strength development but increase deformability indicating a trade-off between durability and flexibility.

Skid resistance tests also established that PU-modified cold mix asphalt (CMA) can be used to satisfy the recommended standards, and its performance is similar to the conventional CMA in both dry and wet conditions. Although the wet skid resistance values were less, all the mixtures were within the Transport and Road Research laboratory (TRRL) range. All in all, PU modification has high potential to be a feasible material in road maintenance applications especially in high traffic places.

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## DECLARATION OF COMPETING INTEREST

None.

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