Capability of chained interlocking plastic beads in enhancing properties of dense bituminous macadam

P W Liew, R Muniandy, F M Jakarni and S Hassim
Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
E-mail: jacqueline.liew@hotmail.com

Abstract. Typically, Dense Bituminous Macadam (DBM) layers on expressway flexible pavements tend to take up the flexural loading more than the top layers with binder and wearing courses. A lot of road failures associated with DBM are reflected as tensile cracks or typically known as Alligator cracks. In view of this mechanism of failure, a new thinking was foreseen in reinforcing the DBM layer with Chained Interlocking Plastic Beads (CIPB) to enhance the fatigue resistance of the layer. The CIPB in the DBM layer greatly reinforced and improved the interlocking mechanism within the pavement layer. The asphaltic binder with 60-70 penetration grade was used and the gradation for this DBM was selected in accordance with Lembaga Lebuhraya Malaysia (LLM) specification. CIPB of two diamond shaped beads are linked with 0.5 mm to 1.0 mm diameter strands. In this study, different percentages of CIPB were added into the bituminous mixture to determine the percentage of CIPB that would optimize the strength of DBM in terms of resilient modulus, stability, and density. Several appropriate tests were conducted to determine the volumetric properties and stiffness modulus of the designed mixtures to determine the Optimum Asphalt Content (OAC). Based on the test results obtained, the CIPB did produce better interlocking mechanism within the mixture and greatly improved the stiffness and stability of the mixture. From this study, it was observed that, with an adequate amount of CIPB, the performance of the DBM mixture improved the Marshall stability and resilient modulus. The study shows that the newly developed interlocking mechanism with CIPB has great potential to minimize tensile cracks that migrate to the top through the binder and wearing courses and thus extend the life of the pavement. Such long-lasting effect may certainly reduce the road rehabilitation costs. The objectives of this study was to determine the Optimum Chained Interlocking Plastic Beads content in Dense Bituminous Macadam and to evaluate the capability of Chained Interlocking Plastic Beads in enhancing properties of Dense Bituminous Macadam.

1. Introduction
Plastic is a cheap and versatile substance that can be recycled from wastes and transformed to CIPB for use in road construction. Therefore, the plastic made products such as water bottles and plastic bags are easily being dumped after single use and this leads to massive amounts of plastic wastes in Malaysia and worldwide. As of 2010, the recycling rate in Malaysian is at 5%. This rate is considered as low compared to other countries such as Singapore (11%), Thailand (14%), Japan (40%), China (13%) and Germany (52.8%). Therefore, numerous recycling campaigns have been conducted by Kementerian Kesejahteraan Bandar, Perumahan dan Kerajaan Tempatan (KPKT) towards achieving the recycling target of 22% by the year 2020 [1].
1.1. Utilization of reclaimed plastics for road construction

Although there are several uses for recycled plastic materials, reutilizing the plastic waste particles as bitumen modifier for flexible pavement construction seem to be very promising. The use of recycled waste plastics in asphalt pavements represents a valuable outlet for such materials. Literature review indicates that the use of modified bitumen with the addition of processed waste plastics of about 5 to 10% by weight of bitumen helped in improvement of the Marshall stability, strength, fatigue life and other desirable properties of bituminous concrete mixtures. Such improvements may result in the longevity and pavement performance with saving in bitumen usage [2]. Reclaimed polyethylene derived from low density polythene carry bags collected from domestic waste is also used as an additive in flexible pavement construction. When those polyethylene materials mixed with hot bitumen, they melt to form an oily coat over the aggregate and the mixture when laid on the road surface like a normal asphalt road. The durability of plastic waste modified road was much more as compared with roads of ordinary mix [3].

1.2. The newly developed and designed Chained Interlocking Plastic Beads

Chained Interlocking Plastic Beads (CIPB) is an intellectual propriety of Universiti Putra Malaysia (UPM) that was designed and fabricated to be used as reinforcing structure in asphalt mixtures in general. Based on the previous study by UPM researchers, CIPB was able to reinforce the asphalt concrete through the interlocking mechanism between the aggregates in the mixture. Several tests were carried out such as Marshall stability and resilient modulus on the CIPB reinforced cylindrical sample in order to determine the performance of the CIPB in asphalt mixtures. CIPB is designed and fabricated with diamond shaped terminal beads linked by strands that is able to reinforce Hot Mix Asphalt (HMA), Stone Mastic Asphalt (SMA) and Fiber Mastic Asphalt (FMA). The researchers from Universiti Putra Malaysia looked into the shape, size, dimension and type of plastic materials from new and recyclable plastics that are suitable to be fabricate into CIPB. The newly designed CIPB expected to provide additional fatigue and rutting resistance in most of the asphalt mixtures. Due to the melting point characteristic of above 220°C, the thermoplastic Nylon 66 was found to be ideal in the fabrication of the CIPB. Based on the several shape analyses carried out, the diamond shaped beads turned out to be very effective in rendering increased interlocking between the aggregates in the asphalt mixtures. CIPB produced in small sized beads such as 4 and 6 mm gave better flexibility with the links compared to larger beads and link sizes that posed problems during compaction of asphalt mixtures. Since the beads are linked up with two different sizes of strings or strands of 0.5 mm and 1.0 mm in diameter with the beads spaced at 20 mm, further analysis were carried out to determine their effectiveness. Based on UPM, s research and analysis on the newly developed plastic beads, it shows that the overall performance of the SMA mixtures with the CIPB performed better than the control mix [4].

1.3 Flexible pavement reinforcement in previous study

There are also others methods or technologies used to improve flexible pavements. The application of carbon fiber in asphalt mixture increased the strength, durability and resistance towards creep, fatigue and rutting condition. The amount of fiber that added to the bituminous mix designs, which at the optimum fiber content are resulted an increase in pavement strength [5]. Application of fiber into bituminous mixture slightly increased the Optimum Asphalt Content but it also provided additional tensile strength and fracture energy. It is able to the volumetric properties of hot mix asphalt [6]. The reinforcement mesh is embedded at the bottom of asphalt concrete mixture for the binder course enforced the initiation and propagation of cracks to be bottom-up. This decreased the tensile strain at the bottom of asphaltic mix and increased the number of cycles to initiate the cracks. There is improvement in the number of cycles and deformation rate for reinforced slab samples over the
equivalent unreinforced slabs [7]. However, the implementation of CIPB takes the asphalt mixture performance to a different level by providing increased interlocking of aggregates in the mixture.

1.4 The Dense Bituminous Macadam

Bitumen macadam is composed of asphalt binder and three fractions of aggregate which were continuously graded. The three fractions of aggregate for bitumen macadam is consisted of coarse, larger fine and fine fractions of aggregate. Its strength is primarily achieved through friction and mechanical interlock of the coarse aggregates. Air void contents in typical Bituminous Macadam tend to be slightly higher than asphaltic concrete and it is thus relatively permeable to air and water, and consequently not as durable as asphaltic concrete. However, the higher level of air voids ensured the proportions of the mixture are not as critical as for asphaltic concrete, thus easier to produce [8].

Mixture volumetric properties are important to the long-term performance and durability of a pavement. If the required volumetric properties of the mixture are achieved, the minor deviations in gradation and asphalt binder content can be tolerated. The most important factor contributing to pavement performance is the in-place volumetric properties. Reduction of the in-place air voids below 8.0% significantly improved fatigue life, moisture resistance, and ravelling resistance [9].

1.5 Background of study

Generally, the structure of flexible pavement is formed by asphaltic layer, road base layer, sub-base layer and subgrade layer. When there is traffic loading on this pavement structure, each of the layers in the pavement system undergo the vertical compressive strain and also horizontal tensile strain. Figure 1 shows that the horizontal tensile strain and vertical compressive strain in pavement structure during traffic loading. The axle loads on the pavement cause the horizontal tensile strain to develop at the bottom of each layer in the structure, particularly the DBM layer. After certain number of load passes, this horizontal tensile strain could result in the cracking at the bottom of the DBM layer. In order to treat this kind of pavement failures, partial reconstruction may be required depending on its severity.

In order to minimize the severity of the crack propagation, a research was carried out in Universiti Putra Malaysia with a newly developed CIPB pavement reinforcing agent made from reclaimed plastic wastes. CIPB was found to be effective for use in DBM mixtures to improve the tensile strength properties and to provide reinforcement properties of DBM.

![Figure 1. Horizontal tensile and vertical compressive strains in pavement structure.](image)
2. Materials and Methods

2.1 The aggregate, asphalt binder and CIPB

The gradation requirement for DBM in this study was as stated in the Lembaga Lebuhraya Malaysia (LLM) specification: Series 800. The raw materials such as granite aggregates and asphalt binder with penetration grade 60-70 were provided by Kajang Rock quarry while the CIPB materials were supplied by UPM for the DBM study. Several tests were conducted to determine the physical and mechanical properties of the materials prior to formulating the appropriate mix designs. The raw materials that were used in mix design complied with the minimum requirement as stated in the Public Works Department (PWD) standard and specifications. A total of 80 samples with 60 compacted samples and 20 uncompacted loose samples were produced for the Marshall Mix design analysis in accordance with ASTM D1559. The materials properties of the aggregates, asphalt binder and CIPB used in this study are tested in accordance with ASTM and AASHTO standards. The LLM gradation for DBM is as shows in Table 1 and gradation plot is as shows in Figure 2.

Table 1. LLM Gradation Specification for DBM.

| Sieve size | % Passing | Median | % Retained |
|------------|-----------|--------|------------|
| 37.5 mm    | 100       | 100    | 0          |
| 25 mm      | 90 - 100  | 95     | 5          |
| 20 mm      | 71 - 95   | 83     | 12         |
| 12.5 mm    | 56 - 80   | 68     | 15         |
| 6.3 mm     | 44 - 60   | 52     | 16         |
| 3.15 mm    | 31 - 45   | 38     | 14         |
| 300 µm     | 7 - 21    | 14     | 24         |
| 75 µm      | 2 - 9     | 5.5    | 8.5        |
| Pan        |           |        | 5.5        |
| Total      |           |        | 100        |

Figure 2. Aggregate Gradation Envelop.
The tensile test on the CIPB was conducted in accordance with ASTM D638 to determine its tensile strength properties. The purpose of the test was to determine the tensile strength of the CIPB and also the effect of heating it at 160°C (mixing temperature) on the tensile strength of CIPB. Therefore, the CIPB that has undergone tensile test was categorized into two set which were the non-heat conditioned CIPB (original) and the 160°C conditioned CIPB. Figure 3 shows that the effect of heating on the CIPB. After one-hour heating in the oven at 160°C, the maximum load bearing capacity of CIPB was increased by 17.91% while the tensile stress at the maximum load was increased by 8.42%. This increased load bearing capacity and the tensile stress showed that the heating process of during mixing would not cause major any damage to the CIPB properties.

![Figure 3. Tensile Strength for Non-conditioned and 160°C Conditioned CIPB.](image)

Figure 4 (a) shows that the use of CIPB with a 2 bead and link system. As explained above, the CIPB has a great potential to stiffen at mixing temperatures. A preliminary assessment was carried out to determine whether the CIPB plastic beads with strand link would snap at terminal points upon compaction. The compacted samples were then loosened up to recover the CIPB through rotary extraction process using methylene chloride solvent. Figure 4(b) shows that the CIPB are still intact.

![Figure 4 (a)and (b). CIPB before and after compaction.](image)

2.2 The Marshall mix design analysis
There were four types of mix designs produced for the Marshall mix design analysis namely DBM-0, DBM-5, DBM-10 and DBM-15. DBM-0 was the controlled samples that did not contain any CIPB while DBM with 5 to 15 were the mixtures that contained 5.0 to 15 grams of CIPB for each Marshall specimen. The 5 grams weight of CIPB is also equivalent to 0.43% of CIPB by the weight of aggregate. Similarly, DBM-10 and DBM-15 were equivalent to 0.87% and 1.30% of CIPB by the weight of aggregate respectively.

A total of 20 specimens included 15 compacted specimens and 5 uncompact specimens were prepared for each mix design. Marshall Mix Design Analysis was then conducted on those specimens to determine their Volumetric Properties including VTM (Voids in Total Mix), VMA (Voids in
Mineral Aggregate), VFA (Voids Filled with Asphalt), Bulk Density, Marshall Flow, Marshall Stability and Resilient Modulus.

The targeted air void was selected as the ideal void content of 4% based on research and past performance shown that the value was ideal for asphalt mixtures. Therefore, OAC was determined based on 4% of design VTM. Volumetric Properties Ranking system was carried out to determine the optimum CIPB content. Table 2 shows the OAC for CIPB reinforced DBM Mix Designs. For the determination of Optimum CIPB Content, the mix design with the Optimum CIPB Content was the mix design with the highest Volumetric Properties Ranking.

| Mix Design | Optimum Asphalt Content |
|------------|-------------------------|
| DBM-0      | 5.45%                   |
| DBM-5      | 5.48%                   |
| DBM-10     | 6.45%                   |
| DBM-15     | 6.68%                   |

3. Results and Discussion

Graphs below were plotted based on the data obtained from the Marshall Mix Design Analysis. The specific gravity of CIPB was 1.06 which was much lower than the specific gravity of aggregate. Therefore, introduce the CIPB into mixture reduced the bulk density of the total mixture. Higher percentage of CIPB added into mixture resulted in lower bulk density. Based on Figure 5 plot of Bulk Density against AC, it showed that DBM-15 had the lowest bulk density among the mixes due to DBM-15 contained the highest percentage of CIPB.

Based on Figure 6 plot of Marshall Stability against AC, it showed that mix design with the adequate amount of CIPB, DBM-5, did effectively improved the Marshall Stability of the mix design. By comparing between the controlled sample and DBM-5 (0.43% of CIPB by the weight of aggregate), it was able to improve the stability properties of DBM up to 6.53%. However, from the graph, it was observed that the mix design with increased amount of CIPB resulted in low Marshall Stability due to the higher amount of CIPB in the mixture that resulted in greater influence in the matrix of aggregate in the mix design and may cause segregation. The matrix of aggregate in the mixture seemed to be disturbed by the exceeding amount of CIPB causing the aggregates not slipped into the perfect position during the compaction stage to enable the interlocking mechanism among the aggregate.

From Figure 7 below a plot of Resilient Modulus against AC showed that with introduction of adequate amount of CIPB, it can effectively improve the Resilient Modulus properties of the mix design. But increased amount of CIPB tend to lower the Marshall Stability and also resulted in low Resilient modulus of the asphalt mixtures. Comparing between the controlled sample and DBM-5, by introducing 0.43% of CIPB by the weight of aggregate, it was able to improve the stiffness modulus properties of DBM up to 13.32%.
Figure 5. Plot of Bulk Density against Asphalt Content.

Figure 6. Plot of Marshall Stability against Asphalt Content.
Table 3 shows that the summarized results of the Volumetric Properties and Resilient Modulus properties for DBM-0, DBM-5, DBM-10 and DBM-15. The results were obtained from Volumetric Properties graphs that plotted based on the Marshall Mix Design Analysis. Table 4 shows that the Volumetric Properties Ranking among the mix designs. Comparisons were made among DBM-0, DBM-5, DBM-10 and DBM-15 to find out the highest ranking mix design and to determine the Optimum CIPB Content. Comparison of Volumetric Properties among the mix design based on results from Table 3 were converted to the Volumetric Properties Ranking table as in Table 4. The ranking was from 1 to 4 (best → least), Therefore, mix design with the smallest number will have higher ranking.

![Figure 7. Plot of Resilient Modulus against Asphalt Content.](image)

**Figure 7.** Plot of Resilient Modulus against Asphalt Content.

Table 3. Volumetric properties of all the mix design at their OAC.

| Mixtures | Resilient Modulus (MPa) | Stability (kN) | VTM (%) | Bulk Density | VMA (%) |
|----------|--------------------------|----------------|---------|--------------|---------|
| DBM-0    | 3401.7                   | 9.80           | 4.00    | 2.388        | 16.41   |
| DBM-5    | 3854.9                   | 10.44          | 4.00    | 2.374        | 16.98   |
| DBM-10   | 2208.9                   | 8.67           | 4.00    | 2.235        | 20.20   |
| DBM-15   | 1651.3                   | 6.86           | 4.00    | 2.170        | 21.22   |

Table 4. Volumetric Properties Ranking.

| Mixtures | Resilient Modulus (MPa) | Stability (kN) | Bulk Density | VMA | Ranking |
|----------|--------------------------|----------------|--------------|-----|---------|
| DBM-0    | 2                        | 2              | 1            | 2   | 7       |
| DBM-5    | 1                        | 1              | 2            | 1   | 5       |
| DBM-10   | 3                        | 3              | 3            | 3   | 12      |
| DBM-15   | 4                        | 4              | 4            | 4   | 16      |
Based on the above results the mix designs with CIPB, DBM-5, DBM-10 and DBM-15, it was observed that DBM with 5 grams of CIPB had the highest ranking between them. Based on the data obtained, the OAC of the DBM-5 mixture was 5.48% and the Optimum CIPB Content was 0.43% by the weight of aggregate. If compared the mix design properties between the DBM-0 and DBM-5, DBM mixture with 5 grams or 0.43% CIPB effectively enhanced the DBM mixtures by improving the properties of stability and stiffness modulus. However, with compare among the mixes with CIPB, DBM-10 and DBM-15 have low stability and stiffness modulus. It was also observed that high percentage of CIPB may cause the mixture homogeneity issue that resulted in greater influence in the matrix of aggregate and may cause segregation. The matrix of aggregate in the mixture been disturbed by the exceeding amount of CIPB caused the aggregate not slipped into the perfect position during the compaction stage to enable the interlocking mechanism among the aggregate.

As shows in Table 4, among the mix designs with CIPB, DBM-5, DBM-10 and DBM-15, DBM-5 had the highest ranking among them. Therefore, DBM with a 0.43% or 5 grams by the weight of aggregate seemed to be the optimum for the selected DBM aggregate gradation. It was also observed that the properties between the controlled sample (DBM-0) and the mix design with Optimum CIPB content (DBM-5), DBM-5 had a higher Resilient Modulus of 3854.9 MPa and a Marshall Stability of 10.44 kN. As such, it can be assured that CIPB did improve the properties of DBM mixture in term of Stiffness Modulus and Stability.

4. Conclusion

Based on the results and analysis above, the following conclusion can be made:

i. From the Volumetric Properties Ranking, DBM-5 had the highest ranking among others. The OAC for DBM-5 was 5.48% while the Optimum CIPB content was 0.43% by the weight of aggregate. The result showed that the Marshall Stability and Resilient Modulus of DBM-5 gave were the highest. It meant that the degree of stiffness of the mixture was higher and that CIPB effectively enhance the DBM mix performance through its interlocking mechanism.

ii. The Volumetric Properties of DBM-5 at its OAC and Optimum CIPB Content: VTM = 4%, Bulk density = 2.374, Marshall Stability = 10.44kN, Resilient Modulus = 3854.9 MPa, and VMA = 17% which fulfilled all the specification requirements. Adequate amount of CIPB did improve the properties of the mixture in term of Resilient Modulus and Stability, but it will reduce the bulk density of the mixes as the percentage of added CIPB increases.

iii. Based on the tests results, adequate amount of CIPB can effectively improve the Marshall stability and Resilient Modulus of the mixture.

iv. With the appropriate amount of CIPB, DBM layers on the expressways can be reinforced to resist fatigue cracking. This can minimize cracks migrating to the top of the flexible pavement and prolong rehabilitation intervention measures by the road authorities. Such improvements to DBM layers could save cost on maintenance of roads.

5. References

[1] National Solid Waste Management Department 2011 *A study on plastic management in Peninsular Malaysia*

[2] Ahmad N, Muniandy R, Hassim S and Aburkaba E 2013 Development of interlocking chained plasti-beadsfor use in stone mastic asphalt *Australian Journal of Basic and Applied Sciences* 7(4) 466–74

[3] Amit G, Zamarea G, Rengea V C, Saurabh T and Bharsakale G 2012 An overview on waste plastic utilization in asphalting of roads *Journal of Engineering Research and Studies* (E-ISSN0976-7916)

[4] Donald L C 2013 Roads building fundamentals: Volumetric properties of asphalt mixes *Arizona Pavements and Materials Conference*
[5] Malik S A 2014 Low density polyethylene modified dense graded bituminous macadam *International Journal of Engineering Trends and Technology* **16** 8

[6] Kumar B K, Kumar V R and Rao M K 2016 Experimental behaviour of carbon fiber in dense bituminous macadam *International Journal for Technological Research in Engineering* **3** 6

[7] Kaloush K E 2014 Fiber Reinforced Asphalt Pavements 54th Annual Idaho Asphalt Conference Idaho

[8] Radzi H M, Harun M H and Hanafi WRW 2010 *Asphalt concrete on roads in Malaysia: Is quality under control?* (Kuala Lumpur: Public Work Department)

[9] Donald L C 2013 Roads building fundamentals: Volumetric properties of asphalt mixes *Arizona Pavements and Materials Conference*

**Acknowledgement**

The authors would like to thank the Ministry of Higher Education for providing the research grant and Universiti Putra Malaysia for providing the required facilities and support for this study and all those directly or indirectly assisted in the research project.