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Research Article

Reflection crack resistance of geogrid reinforced bituminous concrete under simulated repeated loads

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Abstract

Reflection cracking is a notable factor in flexible pavements, which will compromise their real-life performance and durability. This study focuses on evaluating the performance of bituminous concrete mixes for the Bituminous Concrete layer prepared by conventional materials. Gradations of natural aggregates were prepared and tested for their mechanical properties using Marshall stability tests to determine the Optimum Bitumen Content. Beams of dimensions 500mm × 100mm × 100mm were casted with 2-dimensional geogrid reinforcement and tested under reflection crack simulator, integrating the cams with upliftment heights and gap of 5 mm, 10 mm & 15 mm combinations to mimic the condition of repeated wheel loads. The tests reveal that the performance of bituminous concrete beams, such that when they are subjected to lower upliftment heights and higher gaps shown better resistance to reflection cracking, while increased upliftment heights and lower gaps resulted in earlier failure. Further, the 2-dimensional geogrid insertion as reinforcement in beam has shown the better performance than beam without geogrid for all upliftment heights. The study highlights the innovative testing method to evaluate the durability of flexible pavements.

1. Introduction

Flexible pavements play a crucial role in modern transportation infrastructure by providing efficient & smooth movement of people & goods. However, their long-term performance and reliability are frequently undermined by various types of structural distresses. Among these, reflection cracking stands out as one of the most common and challenging problems encountered in flexible overlays. Reflection cracking generally originates from discontinuities in the underlying pavement layers, such as joints or existing cracks in a cement-treated base or old pavement, which propagate upward through the new bituminous layer due to repeated traffic-induced movements, temperature fluctuations, and moisture variations. Such cracks not only compromise the ride quality and aesthetics but also accelerate moisture infiltration and subgrade weakening, leading to premature pavement failure and frequent maintenance interventions.

Bituminous concrete is the main structural component in flexible pavement systems due to their strength, durability, and effective load distribution. Performance of these layers is heavily governed by characteristics of materials used, particularly the type and grading of aggregates, binder content, and degree of compaction achieved during construction. The behaviour of the aggregates under cyclic and dynamic loading is complex, as they undergo shear deformation and rutting over time,

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particularly under heavy traffic conditions. Hence, the accurate selection of mix components and proportioning is critical. Marshall method of mix design continues to serve as the most widely adopted standard to increase the mechanical characteristics of bituminous mixtures & to find the Optimum Binder Content (OBC), which ensures adequate strength, flexibility, and durability of the mix under field conditions[1]. While initial mix design through standard laboratory tests like Marshall Stability, flow value & indirect tensile strength (ITS) provides an essential baseline, these tests are generally insufficient to fully predict the long-term cracking behaviour of bituminous concrete[2-5]. This is especially true in the context of reflection cracking, which develops under a complex interplay of vertical and horizontal movements transmitted from the base layers to the surface course[6]. To address this challenge, researchers and pavement engineers have employed advanced testing methodologies and field evaluation tools, like falling weight deflectometer (FWD), overlay tester, grounds penetrating radar (GPR), and core extraction techniques, to analyse the structural integrity and response of pavements. However, even these methods have limitations in capturing the dynamic upliftment and displacement behaviour mimicking actual traffic loads, thereby limiting their applicability for crack resistance evaluation[7-10].

Crack formation is a phenomenon causes in asphalt pavements which is unpredictable. Its starting and propagation are directed by various factors which are interrelated to each other. Some of them are frequency of load, temperature stress, defects in material & unconditional exposure to adverse environment [11]. This twist creates difficulty to define a one reason or universally acceptable testing method to measure the resistance to reflection cracking. Accordingly, nowadays so many researchers are concentrating on preparing proper testing machines and simulation methods which can have ability to mimic real stress in pavement. Reflection Crack Simulator (RCS) is such a testing device which simulates upward movement repeatedly in the pavement layer like it will be caused by traffic loads by inducing vertical upliftment or deflections. This is the testing method which helps in the evaluation of resistance to crack in the surface mix subjected to realistic conditions. Also, the method offers a way for assessment of lifecycle and performance-oriented design [4,12-14].

A broad range of techniques were developed to mitigate the reflection crack formation in layers or overlays of flexible pavements from the past few years. The use of some of inter-layer systems like Stress Absorbing Membrane Interlayers (SAMIs), binders modified by polymers, bituminous mixes with fiber-reinforcement & recycled materials by rejuvenation were included in this. Stress Absorbing Membrane Interlayers (SAMIs) will mitigate the stress concentrations effectively and slow down the crack propagation. The modification by polymer will increases thermal susceptibility & elasticity of binder. Recently, geosynthetics like geogrids & geotextiles have acquire traction as reinforcement material for the layers of pavement. Geogrids have many advantages like resistance to chemical, improved tensile strength & stability in maintaining dimension by making them as ideal solution for employing them in crack control [15-18].

Several studies have mentioned the useful improvements in geogrid-reinforced pavements performance. Geogrids reinforcement has been proven the increased fatigue life and crack width reduction by delaying the formation of reflection cracks caused by cyclic loading. The reinforcement will effectively block the crack propagation path by redistributing the stress to area away from crack tip & also, increasing tensile strength of mix. Placement of geogrid can also reduce the interface differential movements between old pavement layer & overlay or layers of pavement by improving the bonding of interlayers to maintain structural integrity [19-22].

In this current investigation, bituminous concrete beams were casted of size 500mm × 100mm × 100mm by using the VG-30 grade binder and conventional aggregates. Then tested in custom-fabricated Reflection Crack Simulator. The simulator was incorporated with varying cams upliftment heights (5, 10 & 15 mm) and different horizontal gaps which will replicate the in-service wheel loading. The intension of this experiment is to study the impact of upliftment magnitude & geogrid reinforcement on crack resistance of bituminous concrete beams[23-24]. The presence of geogrid layer in bituminous beam improved the reflection cracking resistance significantly when compared to beams without geogrid. This highlights the important role of reinforcement in design of flexible pavements particularly for which are subjected to frequent & heavy wheel loading. The major research gap noticed is the lack of standardized laboratory test method that can precisely predict the crack resistance in bituminous concrete layers when subjected to realistic load conditions. Only few studies present which can explain the effects of reinforcement, upliftment height and gap variation combination in a single testing framework. By focusing on the interaction between geogrid reinforcement and varying upliftment levels, the study generates critical data that can inform future pavement design strategies and improve overlay durability.[25-27]

The uniqueness of this research is its development and use of a unique testing method that integrates upliftment simulation with geogrid reinforcement in a controlled laboratory setup. Unlike conventional tests, this approach closely mirrors real-world conditions and provides more meaningful insights into crack propagation behaviour. The outcomes of this work are expected to come out with the formulation of performance-based design practices and help in selecting reinforcement strategies for flexible pavement overlays subjected to repeated traffic loads. Ultimately, the findings will assist pavement engineers, researchers, and policymakers in developing cost-effective and sustainable pavement systems that reduce maintenance needs and environmental impact over the service life.

2. Materials and Methods

The materials employed and methodology adopted for this work is schematically represented in the chart as shown in Figure 1.

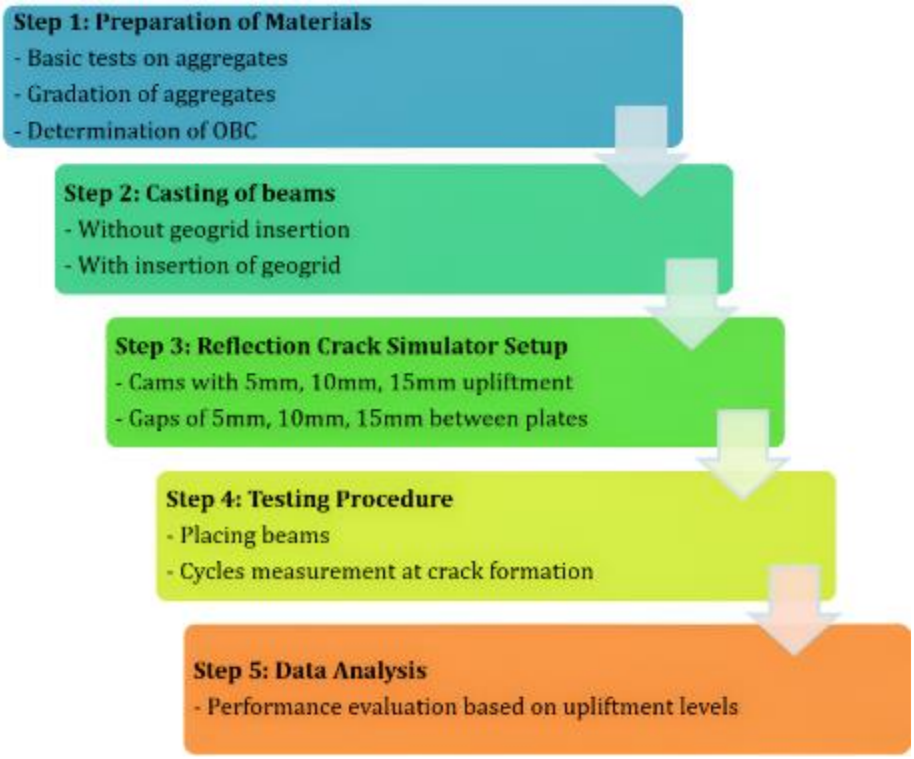

Fig. 1. Methodology of the study

2.1. Materials

The knowledge on properties of materials is very much essential in designing the bituminous concrete for providing longer service without failure. Hence, the materials used for this study were selected carefully by performing the quality tests on them to check whether they meet the requirements or not. Bitumen of VG-30, Natural aggregates and filler materials used to synthesize the BC mixture. In addition to that, the geogrid is inserted in the layer at middle position of beam specimens. The details of raw materials used, tests performed on them and results were discussed in this section.

2.2. Test on Materials

The characteristics of bituminous concrete materials will affect its performance and quality. The constituent materials such as bitumen, cement as filler, aggregates and geogrid were tested in laboratory with standard procedure to check the suitability within the mix.

2.2.1 Aggregates

In bituminous concrete mix, aggregates act as load bearing skeleton and will cover the major portion of it. So, to maintain the proper strength and durability of the mix, the properties of aggregates must meet the standard requirements. The aggregate properties like specific gravity, abrasion resistance, particle size distribution, impact value and water absorption were tested. The naturally originated aggregates were collected from local quarry to use in this study. The tests were performed on them as mentioned in IS codes guidelines and results are summarized in Table 1.

Table 1. Tests on Natural aggregates

Sl. No.	Tests	Results	MoRTH Specifications	IS Code
1	Specific Gravity			IS:2386 [28]
	40mm	2.65	2.6 to 3.6	
	20mm	2.64		
	12.5mm	2.67		
	4.75mm	2.68		
2	Water Absorption	1.20%	< 2%	
3	Impact test	26.20%	< 30%	
4	Crushing test	27.30%	< 30%	
5	Abrasion test	28.90%	< 30%	
6	Combined FI & EI	26.08%	< 35%	

2.2.2 Bitumen

Bitumen acts as a binding agent in the bituminous concrete mix and plays a main role in ensuring cohesion and flexibility. The performance of the mix is influenced by the penetration grade, softening point, ductility, and specific gravity of bitumen [29]. A VG-30 grade bitumen was selected for this investigation, as it is commonly used for road construction under moderate climate conditions. The test results for bitumen properties are provided in Table 2.

Table 2. Tests on bitumen

No.	Test	Result	Code	IS:73-2003 Limits
1	Soften Point	48°C	IS:1205	>45°C
2	Penetration Value	64 mm	IS: 1203	>45 mm
3	Ductility	78 cm	IS: 1208	>40 cm
4	Specific Gravity	1.02	IS: 1202	0.96 – 1.02
5	Fire Point	295°C	IS:1209	>225°C
6	Flash Point	285°C	IS:1209	>220°C

2.2.3 Filler

In this study, cement was adopted as the filler. Cement serves not only to fill voids in the mineral aggregate matrix but also enhances the stiffness, durability, and moisture resistance of the bituminous mix[30], [31]. The fine particles of cement help improve interparticle contact and reduce air voids, contributing to better load distribution and crack resistance. Details of test results for cement (filler) are summarized in the table 3.

Table 3. Tests on filler

No.	Property	Results	Code	IS: 12269 (1987) Specified limits[32]
1	Sp. Gravity	3.02	IS:4031	—
2	Normal Consistency	33%		25% to 35%
3	Fineness Test	3%		< 10%
4	Initial Setting Time	50 min		> 30 minutes

2.2.4 Properties of Geogrid

Geogrids are synthetic materials used to reinforce pavements by distributing loads and minimizing deformation, especially under repeated loading conditions. In this study, a two-dimensional geogrid was incorporated as reinforcement within the bituminous beams. These geogrids are known for their high tensile strength, chemical resistance and minimal elongation, which makes them particularly suitable for mitigating reflection cracking. The geogrid used in this study is shown in figure 2.

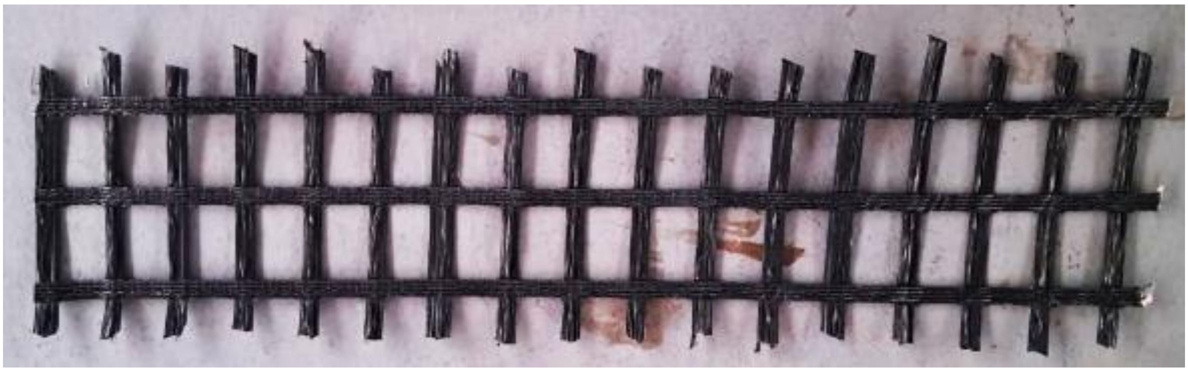

Fig. 2. Geogrid

The geogrid used in this study had a biaxial structure, allowing it to provide reinforcement in both transverse and longitudinal directions. Apertures of the grid allow proper interlocking with the bituminous matrix, enhancing the composite action of the material. The geogrid used in this study had a tensile strength of over 50 kN/m, low elongation (<5%), and good compatibility with bituminous materials. These characteristics contribute to the enhanced fatigue life and resistance to reflection cracking in reinforced bituminous concrete.

2.4. Gradation of Aggregates

Aggregates grading is an important factor when constructing pavements and preparing bituminous mixtures for pavement construction. It involves modification of aggregate shape and gradation to obtain optimum packing and maximum rationally achievable density in the aggregate. This provides stability, durability and strength necessary for pavement to be familiarly loaded without collapsing. There are three classes of aggregates namely, coarse aggregate, fine aggregate and filler materials whose proportions should meet the stipulated proportions in related specifications sources like IS, ASTM, /AASHTO MoRTH. The graduation curve for BC and DBM layer Represented in the figure 3 and 4.

2.5. Optimum Binder Content (OBC)

The parameter of OBC is the most sensitive component in the case of bituminous mixes. It is the proportion of the binder or bitumen for a given mix to meet the set performance criteria such as stability, durability, deformation and cracking. The determination of OBC requires a lot of testing, and this is often done in the laboratory, and the Marshall Mix Design method was used[33].

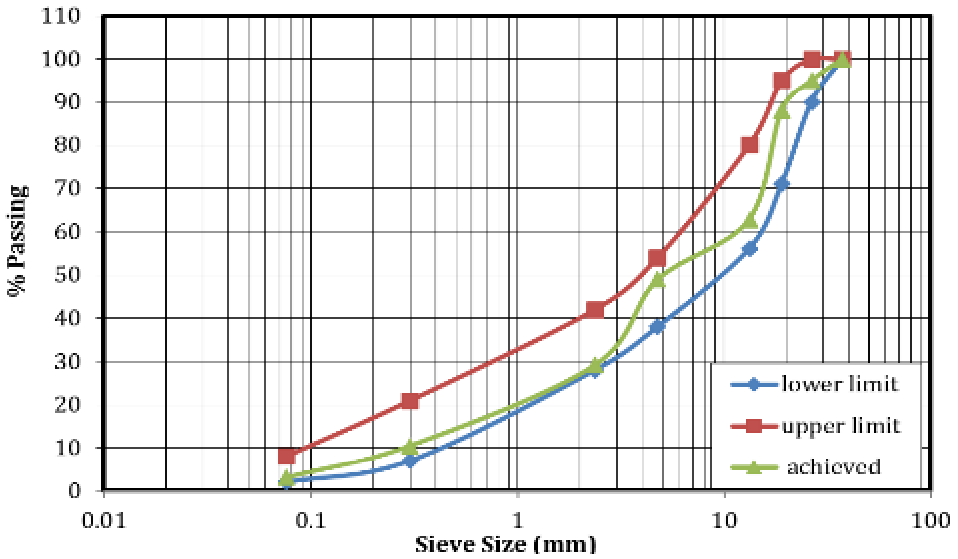

Fig. 3. Grading curve-DBM

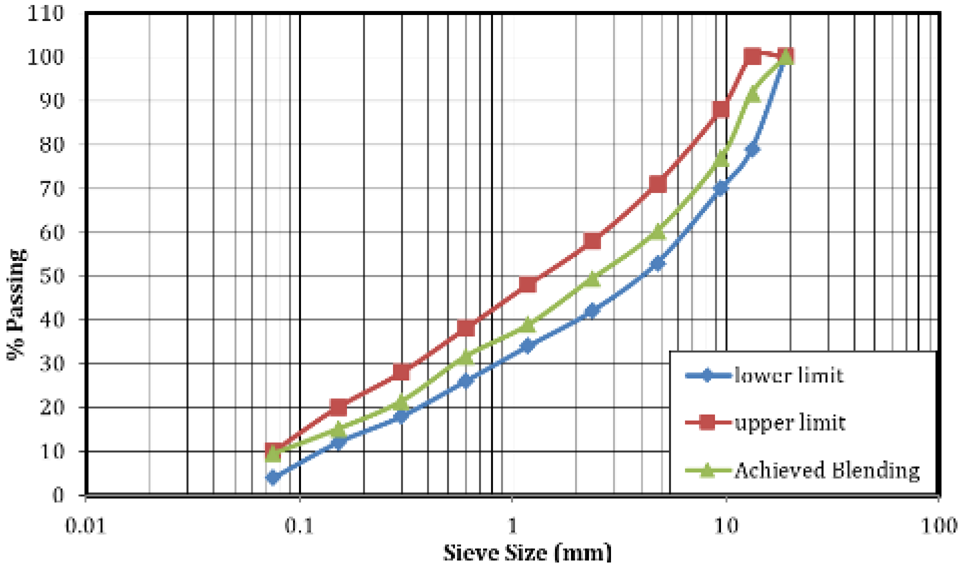

Fig. 4. Grading curve-BC

Fig. 5. Preparation of Marshall specimens

The Marshall specimens were casted and tested to find out the OBC. Fifteen moulds were casted for each bituminous concrete mix as shown in figure 5 & 6. The Marshall properties were calculated and plotted in the graphs using the results obtained as shown in figure 6. The final OBC was obtained by according to MoRTH's specifications and the bituminous concrete beam specimens were casted as per these obtained OBC[34,35].

Fig. 6. Casting and testing of marshall specimens

2.6. Reflection Crack Simulator Setup

The Reflection Crack Simulator is a specialized testing apparatus designed to replicate the conditions that cause reflection cracking in flexible pavements. The testing set up consist of the crack simulator integrated with cams of different upliftment heights and base plate gaps (5, 10 & 15mm) in order to create the stresses which will imitate the stresses of repetition loads of traffic. The same testing arrangement is picturised in figure 8. [18,36,38]

The simulator machine is priorly calibrated to create and apply vertical direction displacements in a cyclic manner on the bituminous concrete beams placed for testing. The cams are designed and installed in such a way that can vary the upliftment heights by creating the differential movements, it simulates the displacement in upward direction caused by repeated loading. Three cams were used in this study with specific upliftment levels. Cams of 5mm represents minimum upliftment or mild stress, 10mm represents moderate stress & 15mm represents severe stress condition simulations. [19, 37]

The beams were placed on the platform of simulator and firmly fixed by using clamps and bolts to avoid the misalignment or premature displacement when subjected to repeated cyclic loads. The loads are applied on beam in repeated cyclic manner through the simulating device to assess the behaviour of bituminous concrete beams under varying levels of stress. Number of cycles per minute will be 260 [19].

2.6.1. Casting of Bituminous Concrete Beams

To assess the ability of the developed bituminous concrete against reflection cracking, beam coupons in the size of 500mm - length, 100 mm - height & 100 mm thick are used. The process starts with choosing aggregates, filler, binder (bitumen), and the amount of each of these materials is estimated according to the gradation and OBC established. The selected materials including aggregates, filler, and bitumen, which are proportioned based on the determined gradation and Optimum Binder Content (OBC). The aggregates and bitumen are pre-heated to the temperatures of 150°C to 165°C and 90°C respectively, then mixed thoroughly to ensure a uniform coating of the aggregates[39-41]. The hot DBM mix was filled to form compacted 60mm height layer and geogrid placed above this layer, then the hot BC mix was filled above and compacted to form 40mm layer. Totally, the compacted height of beam was 100mm when finished. The insertion of geogrid in a bituminous concrete beam is schematically represented in the figure 7.

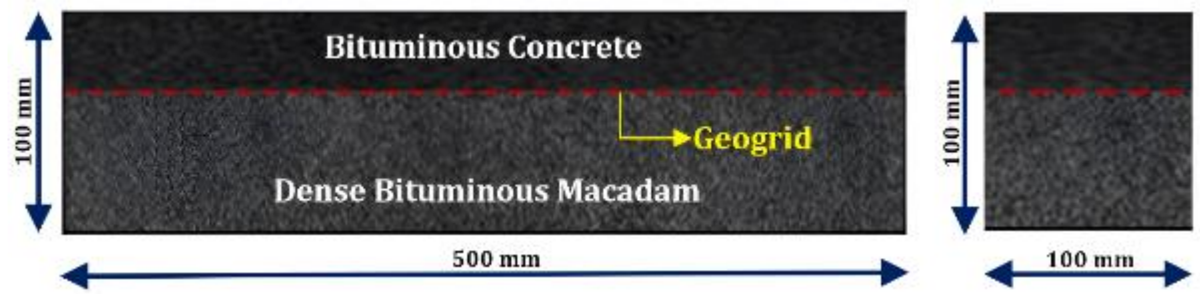

Fig. 7. Bituminous concrete beam with geogrid

The Clean metal moulds of the specified dimensions are prepared and oiled lightly to prevent the mix from sticking while demoulding. The hot bituminous concrete mix is transferred into the moulds and is compacted to remove air voids and achieve the required density. After compaction, the moulds are allowed to cool and cure for 24 hours at room temperature. Then, the beams are carefully demoulded and tested. The moulding of beams is represented in figure 6.

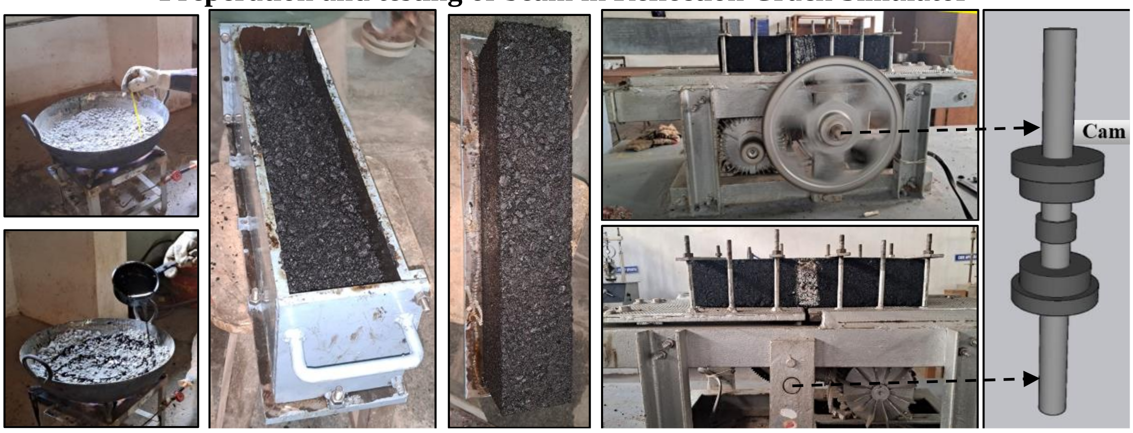

Fig. 8. Beam casting and reflection crack simulator setup

2.6.2. Testing Procedure

The testing procedure involves evaluating the performance of bituminous concrete beams under simulated conditions of repeated loading. The prepared beams are carefully placed in the testing frame of the Reflection Crack Simulator. Once the beams are securely positioned, repeated loads are applied using the simulator. The cyclic loading, controlled by cams with varying upliftment heights (5 mm, 10 mm & 15 mm), induces vertical displacements that simulate the stresses causing reflection cracking in pavements. The applied loads mimic the continuous movement experienced in real-world conditions, testing the cracking resistance of the bituminous concrete beams. During the process, time taken for the formation of cracks is noted in terms of minutes and seconds. Then converted into the cycles [42]. This test provides important data on the behaviour of bituminous concrete mix under different upliftment levels, which helps to evaluate its durability, performance and ability to sustain under repeated loads without causing structural failure [21,43].

3. Results and Discussions

3.1. Marshall Volumetric Properties of DBM

The DBM mix Grade-II is prepared confirming MoRTH specifications with bitumen content 3.5% to 5.5% of total weight of mix. Three moulds were casted for each bitumen content (%) & average results of Marshall properties were potted in graph as represented in the figure 8. The OBC of 4.8% is obtained by considering the average bitumen content (%) at maximum stability & bulk density and bitumen content corresponding to 4% air voids.

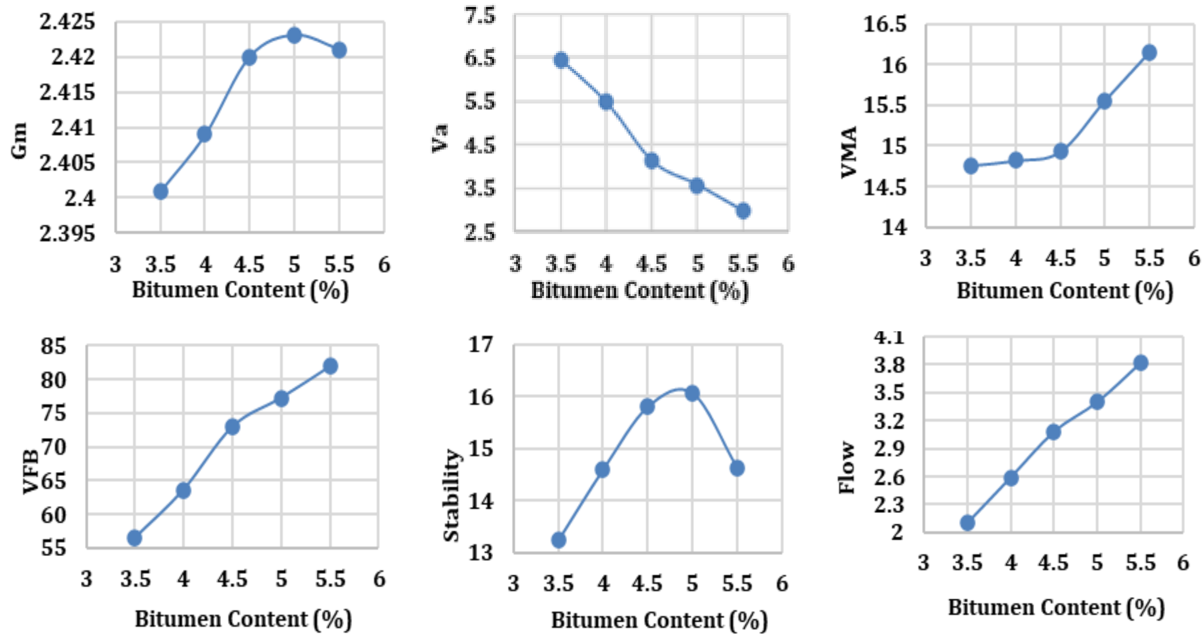

Fig. 8. Marshall volumetric properties of DBM

3.2. Marshall Volumetric Properties of BC

The BC mix Grade-II is prepared confirming MoRTH specifications with bitumen content 4.5% to 6.5% of total weight of mix. Three moulds were casted with respect to bitumen percentage & average results of Marshall properties were potted in graph as represented in the figure 9. The OBC of 5.3% is obtained by considering the average bitumen percentage at maximum stability & bulk density and bitumen content corresponding to 4% air voids.

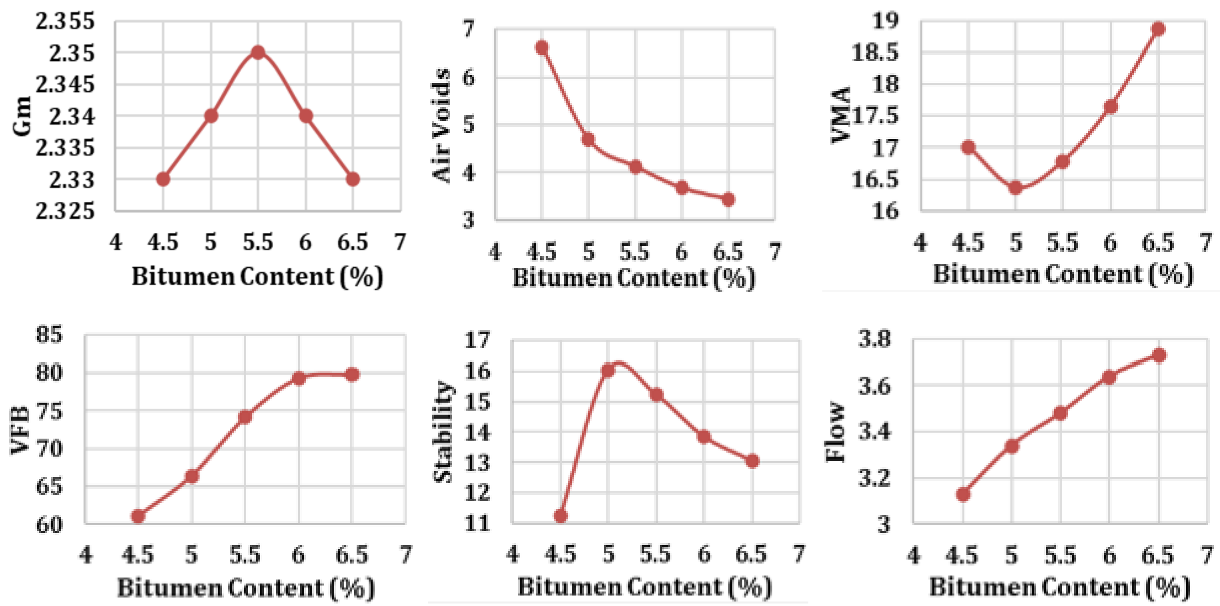

Fig. 9. Marshall volumetric properties of BC

3.3. Reflection Crack Test Results

The bituminous concrete beams were casted with OBC of 4.8% and 5.3% for DBM & BC Respectively, and subjected to testing in Reflection crack simulator. Here the specimens were tested under reflection crack simulator, integrating the cams with upliftment heights and gap of 5 mm, 10 mm & 15 mm combinations to mimic the condition of repeated wheel loads. The test results were tabulated in table 4 and graphically represented in figure 10 as shown below:

Table 4. Reflection crack simulation testing results

Type of mix	Cam	Gap	Time taken to failure (Minutes: Seconds)	Average Number of cycles
BC + DBM without geogrid	5mm	5mm	21:52	5685
		10mm	23:39	6149
		15mm	25:18	6578
	10mm	5mm	16:53	4390
		10mm	19:01	4944
		15mm	20:46	5399
	15mm	5mm	12:55	3358
		10mm	15:05	3921
		15mm	16:27	4277
BC + DBM with geogrid	5mm	5mm	30:45	7995
		10mm	32:34	8467
		15mm	34:15	8905
	10mm	5mm	25:51	6721
		10mm	27:40	7193
		15mm	29:13	7596
	15mm	5mm	21:54	5694
		10mm	23:43	6166
		15mm	25:22	6595

The reflection crack simulation test was conducted on bituminous concrete (BC) beams layered over dense bituminous macadam (DBM) with and without geogrid reinforcement, under varying cam upliftment's (5mm, 10mm, 15mm) and gap widths (5mm, 10mm, 15mm). The results provide crucial insights into how the variation in mechanical setup and structural reinforcement affects the beam's resistance to reflection cracking.

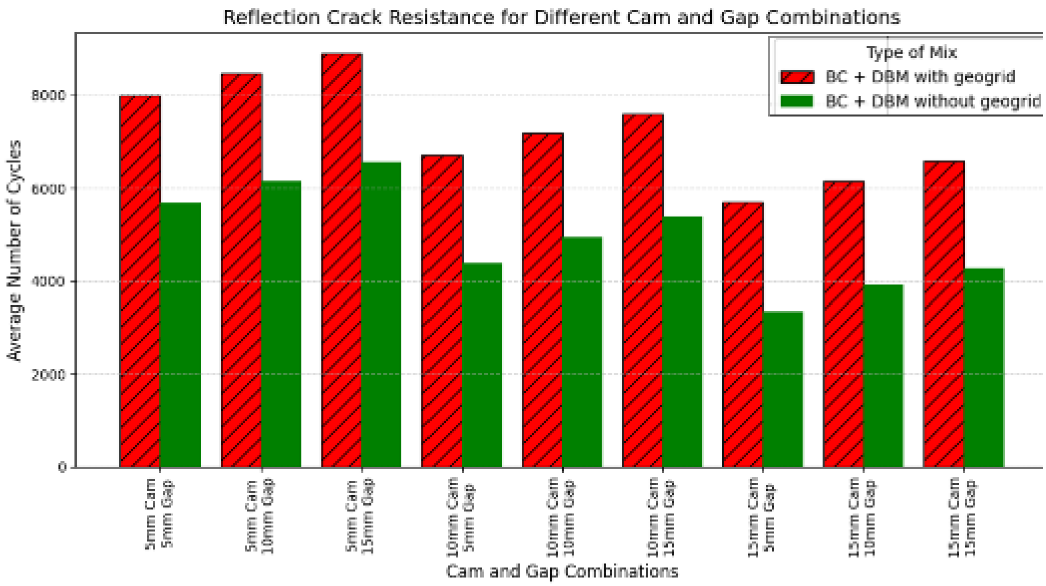

Fig. 10. Comparison of reflection crack simulation testing results

For unreinforced specimens (BC + DBM without geogrid), it was observed that the increase in gap width significantly enhanced the reflection crack resistance. At a 5 mm upliftment, the time to failure increased from 21:52 minutes at 5mm gap to 25:18 minutes at 15 mm gap, with the corresponding number of cycles rising from 5685 to 6578. This trend indicates that a wider gap allows the beam to distribute stresses more evenly, thereby delaying crack initiation and propagation. The same pattern was evident under 10 mm and 15 mm upliftment's, although the overall resistance decreased with higher cam displacement. At 15 mm upliftment and 5 mm gap, failure occurred at 12:55 minutes, while at a 15 mm gap, the beam withstood 16:27 minutes and 4277 cycles, indicating marginal but notable improvement. Among all the combinations of repeated loading, the highest resistance to crack value obtained for BC + DBM without geogrid at the combination of 5 mm cam upliftment and 15 mm gap was 6578 cycles at failure.

When geogrid reinforcement was introduced between the BC and DBM layers, a substantial enhancement in crack resistance was evident across all configurations. At the lowest upliftment (5 mm) and smallest gap (5mm), the geogrid-reinforced beams resisted failure up to 30:45 minutes, with 7995 cycles—a 40% increase in performance compared to unreinforced beams. This effect amplified with increasing gap widths; at 15 mm gap, failure occurred after 34:15 minutes and 8905 cycles. This demonstrates that geogrid reinforcement effectively restricts crack propagation by enhancing interlayer tensile strength and distributing stresses more uniformly across the interface[44], [45], [46]. Among all the combinations of repeated loading, the highest resistance to crack value obtained for BC + DBM with geogrid at the combination of 5 mm cam upliftment and 15 mm gap was 8905 cycles at failure. The 26.13% improvement in crack resistance was observed, when the geogrid implemented in beam.

A similar trend was maintained for 10 mm and 15 mm upliftment's. With a 10 mm cam and 15 mm gap, the geogrid-reinforced beams reached up to 29:13 minutes and 7596 cycles, which was significantly better than the 20:46 minutes and 5399 cycles of the unreinforced counterpart. Even under the harshest loading condition of 15 mm upliftment and minimal gap (5 mm), the geogrid-enhanced beam lasted 21:54 minutes—nearly equivalent to the best-performing unreinforced beam at 5 mm upliftment.

4. Conclusions

This study concentrated on evaluating the resistance of bituminous concrete layers to reflection cracking when reinforced with geogrids and subjected to simulated repeated loading. Laboratory prepared BC & DBM mixes were optimized for stability and durability, with beam specimens cast in both reinforced and unreinforced forms. The reflection crack simulator reproduced field-like conditions through varying upliftment heights and gap widths, enabling a controlled assessment of crack initiation and propagation. Test observations indicated that lower upliftment heights and wider gaps reduced stress concentrations, thereby improving crack resistance, while geogrid reinforcement further enhanced tensile strength and delayed crack formation under all test conditions. The combined influence of optimal structural parameters and reinforcement resulted in significantly better performance compared to unreinforced sections. These findings reinforce the importance of integrating geogrid reinforcement and suitable geometric configurations to improve the service life and durability of flexible pavements in the presence of underlying structural discontinuities.

The test results clearly indicate that both gap width and geogrid reinforcement play a critical role in enhancing reflection crack resistance of bituminous concrete layered over DBM. As upliftment height increases, crack resistance reduces, but this effect is considerably mitigated by increasing gap and by introducing geogrid. The following conclusions were stipulated based on the study made;

- The OBC for DBM and BC grade-II was found to be 4.8% and 5.3% respectively. Optimizing mix gradation and binder content improves durability and performance.
- The resistance of beam to Reflection cracking is higher at 5mm upliftment level and lower at 15mm upliftment level.
- The highest resistance to crack value obtained for BC + DBM without geogrid at the combination of 5 mm cam upliftment and 15 mm gap was 6578 cycles at failure.
- The highest resistance to crack value obtained for BC + DBM with geogrid at the combination of 5 mm cam upliftment and 15 mm gap was 8905 cycles at failure. The 26.13% improvement in crack resistance was observed, when the geogrid implemented in beam.
- Larger cam upliftment induces more severe stress concentrations, accelerating crack formation and propagation.

- Wider gaps (15 mm) improve stress distribution, delaying crack initiation and prolonging failure time.
- Geogrid reinforcement significantly enhances the mechanical interlock and tensile strength, leading to higher resistance across all upliftment levels and gaps.

4.1 Scope for The Further Studies

In future, the researchers can concentrate on studies using the reflection crack simulator to incorporate temperature variation cycles and real-time traffic load studies to replicate field performance in actuals. Studies on alternative reinforcement materials with different geogrids or geo-composites and modified binders may support the optimization of crack resistance in broader range.

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