Open Graded Asphalt Concrete for Mitigation of Reflection Cracking on Asphalt Concrete Overlays

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ABSTRACT: Conventional pavement rehabilitation technique of laying asphalt concrete (AC) overlay over it has a major problem of reflection cracking. The existing cracking pattern on the old distressed rehabilitated pavement gets reflected on the newly laid AC overlay soon within first few months and starts its deterioration which results in drastic reduction in overlay life and the purpose with which it laid does not get fulfilled to the desired/designed extent. This paper presents the laboratory studies carried out on open graded asphalt concrete (OGAC) as a crack relief layer on indigenously developed Asphalt Concrete Slab Fatigue Testing Equipment under opening and mixed modes of displacement. The conventional dense bituminous macadam (DBM) and the OGAC overlays are investigated under cyclic simulated thermal and traffic loads with 5 mm differential deflection of zero load efficiency factor. Variation of tensile strength and strain in AC overlay with number of simulated thermal load cycles are observed and cumulative decay of parameters viz. tensile force, stiffness and shear modulus are computed. Overlay life, decay parameters and base isolation effectiveness factor (BIEF) are also evaluated. It is found that, the OGAC overlay works as a crack relief layer.

1 Introduction

In the last more than four decades the reflection cracking phenomena has been emerged out as a major challenge to the pavement designers. Figure 1 shows the typical reflection cracks.

![Reflection Cracks](image)

Figure 1. Reflection cracks on overlays with further deterioration in the form of secondary cracking.

It is observed that apart from the traffic loads, the thermal loads due to daily / seasonal thermal changes cause the existing crack to propagate in upward direction through newly laid overlay. Field trials using open graded asphalt concrete (OGAC) have shown some potential for the mitigation of crack propagation (Hensley, 1980 and Hani et al., 2003). However, most of the earlier study of OGAC has been in the form of field trials and no laboratory study with the aim of evaluating base isolation effectiveness factor has been addressed. The term open graded is used since the percentage of air voids in it, is more than 20%, which is much higher than that in the normal asphalt concrete mixes. The OGAC mix is used as a “Crack Relief Layer (CRL)”, to mitigate the reflection of cracks on the newly laid asphalt overlays. It is due to the large interconnecting voids obtained by gap grading an aggregate that relieve motion caused by the underlying pavement before it creates a stress on the upper layers of the overlay. This may give rise to highly compressible mix if aggregate skeleton with positive contact is not formed. Bailey Method of aggregate gradation (Vavrik et al., 2002) ensures good aggregate interlock that gives CRL layer which virtually incompressible in a confined state of stress. A CRL would therefore serve two purposes, both as a delay mechanism for crack growth as well as a structural layer. This paper presents the laboratory experimental results performed on the indigenously designed and developed “Asphalt...
Concrete Slab Fatigue Testing Equipment” (Bhosale and Mandal, 2007) to investigate crack retardation performance of the freshly laid OGAC overlays.

2 Asphalt Concrete Slab Fatigue Testing Equipment

This indigenously designed and fabricated equipment simulates not only daily thermal contraction and expansion phenomena of pavement but also traffic loads with differential deflection, maximum of 5 mm, with zero load efficiency factors. Figure 2 shows the overall view of the equipment. The equipment details can be had from Bhosale and Mandal (2007).

Figure 2. View of the equipment highlighting the special attachment of aluminum frame to the fabricated equipment for simulating top-down cracking.

3 Experimental Configuration

The experimental work is performed at a strain-controlled environment with an average room temperature of 29°C. A gap of 5 mm is maintained between two pavement plates, which represented the initial existing crack width in an old distressed pavement. Simulation of daily/seasonal thermal contraction and expansion cycle is achieved by cyclically opening and closing the initial existing crack by 1.83 mm at a strain rate of 4.547 mm/min. For the safety of electric motor and the assembly of gear system, a rest period of 5 sec is kept between pull and push cycle and vice versa. Thus, in purely opening mode of displacement the thermal loading cycle approximately shows resemblance to that with triangular waveform as shown in Figure 3.

Figure 3. Loading waveform in purely opening mode of displacement simulating thermal contraction and expansion.

In mixed mode of displacement, vertical compressive load, generating contact pressure of 478.7 kPa for a standard axle load of 80 kN is applied using pneumatic jack through 15 mm thick pressure plate which simulated the on highway truck dual tire assembly. The vertical load with a load pulse of 1 sec and a rest period of 4 sec, simulating vehicle speed of 1 mile/h (1.6 km/h), is applied simultaneously with simulated thermal load cycles of opening mode of displacement. Differential deflection with zero load efficiency factors, maximum up to 5 mm magnitude, caused due to the applied vertical load, is considered for the present investigation.

4 Material Characterization

The aggregates of fresh compact basalt rock having the maximum particle size passing 25.4 mm, and retained on 20 mm, and the minimum particle size passing 0.075 mm are used. Paving grade bitumen of 60/70 penetration (Pen 60/70) is selected on the basis of “Guidelines on selection of the grade of bitumen” (MORT&H, 2001). The physical and engineering properties of aggregate and the bitumen are found to satisfy the specified values in the respective Indian standards (Bhosale, 2006).
5 Asphalt Concrete Mix Design

The optimum bitumen content of asphalt concrete mixes, namely DBM, BC, and OGAC, are obtained using Marshall Stability Method (ASTM D 1559). The aggregate gradation for DBM and Bituminous Concrete (BC) mixes as specified by MORT&H (2001) are adopted. Though DBM and BC mixes have shown higher flow value and voids in mineral aggregates their respective stability were found to be 80% and 74% more than the MORT&H specified value. Due to lack of the MORT&H specifications for the OGAC with 25 mm nominal maximum particle size, the “Bailey Method for Gradation Selection” for ensured aggregate packing for resistance to permanent deformation is followed and aggregate gradation of OGAC is finalized with an aim to meet the special requirements of crack relief layer of more air voids and voids in mineral aggregate (Bhosale, 2006). In Figure 4, the gradation adopted by Nagato et al.,(1996) and Natraj and van der Meer (2000) and the gradation of bituminous macadam (BM), a porous AC mix, as specified by the MORT&H, are also shown for comparison along with the designed gradation curve of OGAC.

![Figure 4. Designed aggregate gradation for open graded asphalt concrete.](image)

Table 1 shows the Marshall Stability test results for the designed OGAC mix with 75 numbers of blows on each of the two faces of the specimen.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Author's Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen Content by mass of total mix (%)</td>
<td>3.85 (4 % of the total dry mix)</td>
</tr>
<tr>
<td>Stability at 60 °C (kN)</td>
<td>2.452</td>
</tr>
<tr>
<td>Flow (mm)</td>
<td>4.77</td>
</tr>
<tr>
<td>Air Voids (%)</td>
<td>25.76</td>
</tr>
<tr>
<td>Voids in mineral aggregate (VMA) (%)</td>
<td>33.18</td>
</tr>
<tr>
<td>Voids filled up with bitumen (VFB) (%)</td>
<td>22.36</td>
</tr>
<tr>
<td>Bulk Density ( kN/m³)</td>
<td>19.283</td>
</tr>
</tbody>
</table>

Since no standard specifications are available for the OGAC mix, the Marshall Stability test results are compared with the results of DBM and BC, and it is observed that; (a) The optimum bitumen content for OGAC mix is the least. (b) Stability for OGAC mix is almost one eighth. This may be attributed to the porosity of the specimen, which allowed the 60°C hot water to easily enter into it and soften the bitumen coating around an aggregate. Therefore, aggregate skeleton of such a hot specimen, when placed on its periphery during stability testing without lateral confinement, might have been disturbed that resulted in low stability value. In the field condition, this base course of OGAC will have lateral confinement as well as will be covered by the surface course. Hence, the field value will definitely be much higher than the laboratory result. (c) Flow value lies within those for DBM and BC. In addition to the above, a little crushing of the aggregates at their contact surfaces during dynamic compaction of Marshall Specimens confirmed strong aggregate skeleton as assured by the Bailey Method.

6 Test Procedure

The overlay test slab of 500 mm length, 400 mm width, and 75 mm thickness is casted using practical/field AC mixes as per MORT&H, (2001) guidelines. Each AC overlay test slab consists of 50 mm thick base course of DBM or OGAC and 25 mm thick surface course of BC as shown in Figure 5.
The present investigation uses four numbers of springs for the flexible base with maximum allowable differential deflection of 5 mm, which simulated modulus of subgrade reaction of 93.16 MPa/m (9.5 kg/cm²/cm). Gauge length of 80 mm is used for all the potentiometers to record the deformation in the AC overlay. The failure criteria for both opening and mixed modes of displacement tests is decided as (1) till the existing crack propagates and appears on the top surface of overlay test slab or (2) till no further decrease in the tensile load is observed for the large number of load cycles. Data logger is set to scan and log the data for every one-second. The performance of each overlay test slab is independently investigated in opening (O) mode as well as mixed (M) mode of displacement. The overlays of DBM and OGAC are designated as DBM and OG respectively. In purely opening mode of displacement, the overlay test slab is subjected to cyclic horizontal pull (tension) and push (compression) operation simulating purely opening mode of displacement due to daily/seasonal thermal contraction and expansion. Thus, it is subjected to simulated thermal load cycle. In mixed mode of displacement, the freshly casted similar type of overlay test slab is subjected to mixed displacement mode, simulating field pavement loading conditions of thermal load cycles due to thermal contraction and expansion and the traffic loads. The traffic load is simulated by applying cyclic vertical load, which introduced the differential deflection at the existing crack level with a load efficiency factor equal to zero.

7 Method of Analysis and Performance Indicators

Variation in tensile strength during the testing of overlay test slab is carefully recorded, based on which other engineering parameters viz. stiffness modulus and shear modulus are computed. Decay of each of these engineering parameters with the number of simulated thermal cycle is investigated. The concept of cumulative decay is utilized and the parameter that shows the least number of simulated thermal load cycles for 100 % cumulative decay is selected as critical engineering parameter. The number of simulated thermal load cycles corresponding to 100 % cumulative decay of a critical parameter, hereinafter termed as overlay life, is also evaluated. Using computed overlay life; base isolation effectiveness factor (BIEF) accounting for crack relief ness of the OGAC is evaluated. Overlay life in terms of the number of simulated thermal load cycles and BIEF, are considered as performance indices. Regression coefficients of trend line equations fitted in power series for the cumulative decay are considered as decay parameters of the overlay material. The basic equation obtained is in terms of “N”, i.e., the number of simulated thermal load cycle, and may be rearranged in terms of “D”, i.e., cumulative decay, which is a more useful form similar to that of the fatigue law describing crack initiation process. Hence, the equation of cumulative decay as shown in the following form may be used to describe combined phases of crack initiation and propagation:

\[ N = aD^b \]  

where, \( N \) = number of simulated thermal load cycles; \( D \) = cumulative decay of either tensile force, stiffness modulus, or shear modulus; \( a \) and \( b \) = regression coefficients representing decay parameters for the asphalt concrete overlay. Regression coefficient “a” represents overlay life in terms of number of simulated thermal load cycles for 100 % cumulative decay. Regression coefficient “b” is the index of durability of an overlay. The regression coefficients of equation of cumulative decay of critical engineering parameter are proposed as decay parameters of the overlay.

8 Results and Discussion

Figure 6 shows a variation of cumulative decay of tensile force with the number of simulated thermal load cycle for opening (O) and mixed (M) modes of displacement. From Figure 6 it is observed that (1) the rate of cumulative decay of tensile force under mixed mode of displacement is much higher than under opening mode. (2) Due to differential deflection with zero load efficiency factors, in mixed mode of displacement, the bending stiffness of the asphalt concrete mix near the existing crack plays a vital role and affects the rate of reduction of tensile force in mixed mode. (3) Unlike the overlay of porous OGAC mix, conventional overlay of DBM shows less cumulative decay in tensile force at the beginning for mixed mode than for opening mode. This may be attributed to the higher initial bending stiffness of DBM overlay as compared to OGAC overlay. In case of DBM overlay, the point of intersection of two curves marks the number of cycles beyond which the bending stiffness does not contribute to the tensile strength. (4) The OGAC being porous has almost zero bending stiffness. (5) In case of OGAC overlay, though at the beginning the cumulative decay of tensile force for both the modes are equal, it increases at a much faster rate with the number of simulated thermal as well as traffic loading cycles for the mixed mode of displacement.
The stiffness modulus based on absorbed tensile strain, which hereinafter will be termed as simply stiffness modulus, is the tensile stress per unit tensile strain absorbed by the AC overlay. Figure 7 shows the variation of cumulative decay of stiffness modulus with the number of simulated thermal load cycle for opening (O) and mixed (M) modes of displacement.

From Figure 7 it is noted that, (1) the rate of cumulative decay of stiffness modulus under mixed mode (M) of displacement is much higher than that under opening mode (O) of displacement. This may be attributed to the large tensile strain caused due to the differential deflection in mixed mode of displacement and, hence, a large cumulative decay of stiffness modulus. These results confirm the testing sensitivity of the developed experimental system. (2) The differential deflection causes more damage to the DBM overlay than to the OGAC overlay (OG). At the 70th simulated thermal load cycle, DBM-M shows 100 % while OG-M shows only 78 % cumulative decay of stiffness modulus. This is due to more air voids in OGAC than in DBM, which acts as a cushion layer. The open structure of OGAC may not be allowing energy at the crack tip to accumulate and, hence, it shows more durability (Hensley, 1980; Nagato et al., 1996 and Hani et al., 2003).

Figure 8 shows the variation of cumulative decay of shear modulus (defined as the shear stress per unit shear strain) with a number of simulated thermal load cycle for opening (O) and mixed (M) modes of displacement.
From Figure 8, it is evident that (1) Mixed mode of displacement has shown larger cumulative decay of shear modulus than during opening mode of displacement. (2) At the end of the first simulated thermal load cycle, conventional overlay of DBM in mixed mode of displacement has shown 40% more cumulative decay of shear modulus than in opening mode of displacement. This indicates that shearing action near the existing crack due to the differential deflection has more predominant effect in reducing durability of an overlay. (3) Unlike conventional overlay of DBM, OGAC overlay under mixed mode of displacement (OG-M) initially shows 29.5% less cumulative decay of shear modulus. This may be attributed to the porosity of OGAC, which initially absorbs induced shear strain but, within the first 20 cycles, it becomes equal to that of OG-O. This may be due to 50 mm thickness of the base course of OGAC, which may be insufficient under the differential deflection of 5 mm with zero load efficiency factors. (4) The testing results of conventional overlay of DBM and OGAC overlays have confirmed the sensitivity of the developed experimental system.

Using the trend line equations of cumulative decay as shown in Figures 6-8, the overlay lives in terms of simulated thermal load cycles based on 100% cumulative decay for opening and mixed modes of displacement are computed and shown in Figures 9 and 10, respectively.

From Figures 9 and 10, it is confirmed that differential deflection under mixed mode of displacement causes overall reduction in the overlay life of all the overlays. The OGAC being porous mix has less tensile strength and, therefore, OGAC overlay (OG) in mixed mode of displacement has shown the least overlay life of 10 with the greatest reduction of 99.7%. However, when tensile strain absorbed by an overlay is taken into account through parameter “stiffness modulus,” it shows overlay life of 176 with reduction of only 73.2%. Similar observations are also noted for the parameter “shear modulus.” This indicates that consideration of merely tensile strength for investigation of crack retardation performance of overlays may not be the correct approach, particularly for the porous asphalt concrete mix like OGAC. Hence, considering stiffness modulus, OGAC overlay (OG-M) has shown 138% more overlay life than the conventional overlay of DBM (DBM-M) and proved its utility as the crack relief layer. This result has shown that open structure of OGAC mix, though, reduces stiffness modulus of the overlay system, yet, at the same time, it provides a cushioning effect which is advantageous for rehabilitation of old distressed pavement, where differential deflections with zero load efficiency factors are suspected. Since the OGAC overlay (OG) shows the maximum decrease of 99.7% in overlay life due to differential deflection of 5 mm, it may be concluded that 50 mm thickness of base course of OGAC is insufficient, where differential deflection of...
5 mm or more is suspected. Large percentage reduction in overlay lives in mixed displacement mode indicates that shearing of overlay due to the differential deflection with zero load efficiency factor is the most fatal kind of action in crack propagation and every possible effort for the reduction of it must be made to ensure more durability of the newly laid overlay.

As explained in the section "Method of Analysis and Performance Indicators," for further analysis results of critical parameters showing the least overlay life in the respective modes of displacements only are considered. Based on the concept of base isolation, a new factor, namely, Base Isolation Effectiveness Factor (BIEF), is introduced to quantify the effect of base isolation. The BIEF of an overlay is the ratio of overlay life of an overlay under consideration to the overlay life of conventional overlay of DBM. Figure 11 shows the BIEF of an overlay for opening and mixed modes of displacement.

From Figure 11 it is evident that, in mixed mode, OGAC overlay (OG) has shown increment of 24 % in BIEF, which confirmed that base course of OGAC has performed as a crack relief layer. It is further proved that Bailey method of aggregate gradation selection is a useful tool in designing porous OGAC mix. Table 2 shows critical equations of cumulative decay with regression coefficients as proposed decay parameters for the overlay and overlay life in terms of simulated thermal load cycles for opening (O) and mixed (M) modes of displacement.

<table>
<thead>
<tr>
<th>Overlay Test Slab Designation</th>
<th>Critical Equation of Cumulative Decay</th>
<th>Overlay Life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Opening (O) Mode</td>
<td>Mixed (M) Mode</td>
</tr>
<tr>
<td>DBM</td>
<td>N = 363.316 D&lt;sub&gt;0&lt;/sub&gt;</td>
<td>9777</td>
</tr>
<tr>
<td>OG</td>
<td>N = 657 665 D&lt;sub&gt;0&lt;/sub&gt;</td>
<td>3954</td>
</tr>
</tbody>
</table>

Note: N = Number of simulated thermal load cycles, DG = Cumulative decay in shear modulus, DS = Cumulative decay in stiffness modulus

Results presented in Table 2 shows that (1) the value of decay parameter "b" for OGAC overlay in opening and mixed modes of displacement are 3.577 and 3.954, respectively, which are around 4 as found by Majidzadeh et al. (1971) and, hence, it may be considered as a material property. Both these values are less than 4 and approximately match. Hence decay parameter "b" is definitely the material property of the material, which is independent of the mode of displacement. These results match well with the findings of Majidzadeh and Ramsamooy (1973). (2) The value of material constant "b" for OGAC overlay is less than that for conventional overlay of DBM which indicates that OGAC overlay is more durable than conventional overlay of DBM.
9 Conclusions

The following conclusions are drawn from the experimental investigation described in this paper. (i) Better aggregate gradation of porous asphalt concrete mix like OGAC has been obtained using Bailey Method for aggregate gradation selection. (ii) The conventional overlay of DBM shows faster rate of decay with number of simulated thermal load cycle than OGAC overlay and, therefore, it may be concluded that it does not arrest the crack propagation. (iii) Since OGAC overlay shows BIEF of 1.810 and 2.253 in opening and mixed modes of displacement, respectively, it is confirmed that it serves the purpose of crack relief layer. (iv) The value of decay parameter “b” for OGAC overlay (OG-M) is 3.954. Due to the introduction of differential deflection with zero load efficiency factors, least increment of 10.54% in material constant “b” is observed. This point confirms the efficacy of OGAC as the crack relief layer. (v) The value of decay parameter “b” for OGAC overlay under opening and mixed modes of displacement are 3.577 and 3.954, which are around 4 and matching well with the material constant found by Majidzadeh et al. (1971) and hence, may be considered as the material property. Similarly, since both the values approximately match, decay parameter “b” can be considered as the fracture property of the material, which is independent of the mode of displacement (Majidzadeh and Ramsamooj, 1973).

10 References


MORT&H (Ministry of Road Transport & Highways), 2001, Specifications for Road and Bridge Works, Fourth Revision, Indian Roads Congress, New Delhi.

