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# IMPACT OF RECYCLED ASPHALT PAVEMENT ON PROPERTIES OF FOAMED BITUMINOUS MIXTURES

Siksha Swaroopa KAR[1], Aravind Krishna SWAMY[2*], Devesh TIWARI[3], Pramod Kumar JAIN[4]

*[1, 3, 4]Central Road Research Institute, Mathura Road, New Delhi 110025, India*
*[2]Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India*

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**Abstract.** In recent years, the use of foamed bitumen technology along with Reclaimed Asphalt Pavement is gaining popularity across the world. The mechanical response of foamed bitumen mixtures containing reclaimed asphalt pavement is significantly influenced by constituent material properties and aggregate gradation. This article presents results from a study where foamed bitumen mixtures conforming to Indian specifications were evaluated. For this purpose, foamed bitumen mixtures using a different percentage of reclaimed asphalt pavement and bitumens were prepared. Initially, the foaming characteristics of virgin bitumens were evaluated to optimize for optimum water content and foaming temperature. In the second stage, mixture design was conducted to optimize for foamed bitumen content in foamed bitumen mixtures containing a different percentage of reclaimed asphalt pavement. Finally, these foamed bitumen mixtures were evaluated for their mechanical properties. The results from this laboratory study indicated properties of foamed bitumen and foamed mixtures are significantly influenced by properties of bitumen, the quantity of bitumen, and reclaimed asphalt pavement. Among the different mixtures, a mixture containing 50% reclaimed asphalt pavement exhibited best results in resilient modulus and resistance to moisture damage tests. A mixture containing 80% reclaimed asphalt pavement also shows acceptable strength and resistance to water susceptibility. Thus, it is possible to design high-quality bituminous mixes using higher reclaimed asphalt pavement percentages, which meet the required volumetric and desired performance criteria.

**Keywords:** foamed bitumen mixtures, indirect tensile strength, mixture design, reclaimed asphalt pavement, resilient modulus, tensile strength ratio.

## Introduction

Depletion of raw materials in many parts of the world has necessitated the adoption of various technologies in pavement design and construction. Among them, the use of Reclaimed Asphalt Pavement (RAP) materials in asphaltic mixtures is a popular construction practice across the world. Out of the all processes of recycling, Cold In-Place Recycling (CIR) is promising due to the environmentally friendly process and the maximal use of RAP material (Praticò, Vaiana, & Giunta, 2013). Cold In-Place Recycling essentially consists of milling the existing distressed pavement to a predetermined depth and this material is then mixed with foamed bitumen or emulsion. As the RAP is used as it is at ambient temperature, CIR with foamed bitumen limits further degradation of RAP. With CIR process, the construction time is also reduced when compared to alternative rehabilitation methods. This results in reduced construction cost and traffic disruption to users.

Even though there are substantial benefits with CIR with foamed bitumen process, there are certain issues to be addressed, while using it. Several researchers have pointed out that RAP contributes bitumen to recycled mixtures to a certain extent (Li, Hao, Liu, Xu, & Chen, 2016; Oluwaseyi, 2010; Technical Guideline-2, 2009). Further, the heterogeneity of RAP itself contributes to significant variability in Foamed Bituminous Mixtures (FBMs) performance. The use of RAP makes each recycled FBM performance unique and modelling its mechanical response a challenge. The purpose of this study was to study the effect of RAP and its constituents on the mechanical behaviour of FBM. In this study, several bitumens commonly used in India were used for producing foamed bitumen and FBM. The percentage of RAP was varied within each mixture. Finally, these mixtures were tested for their mechanical and volumetric properties.

*Corresponding author. E-mail: *akswamy@civil.iitd.ac.in*

## 1. Literature review

Csanyi from Iowa State University was first to introduce bitumen foaming technology using steam (Csanyi, 1957). Later Mobil oil used water at ambient temperature instead of steam to produce foamed bitumen. The use of water at ambient temperature made the foaming process more practical for field application (Jones, Fu, Harvey, & Halles, 2008; Wirtgen, 2012). In the mid-1990's, Wirtgen developed an injection system where hot bitumen, air, and water were introduced into the pressurized chamber to produce foamed bitumen (Wirtgen, 2012). Foamed bitumen is produced when cold water is added to hot bitumen under controlled conditions. During this foaming process, the volume of bitumen expands up to 15–20 times its initial volume. The ratio of the maximum volume of foam relative to its initial volume is commonly referred to as Expansion Ratio (ER). Half Life (HL) is defined as the time taken by the foam to collapse to half of its maximum volume. During this foamed state, aggregate at ambient temperature is added to foamed bitumen and mixed well to produce FBM. Published literature in the area of FBM indicated that properties of constituent materials (bitumen, aggregate), aggregate gradation, and properties of RAP affect FBM properties significantly. This section presents a brief overview of these interrelationships among constituent material properties and mechanical properties of FBM.

### 1.1. Effect of gradation on foamed bituminous mixtures

One of the important factors that affect the performance of FBM is the gradation of the aggregate. Kuna, Airey, and Thom (2016) reported that for better mixture performance filler (<0.075 mm) content has to be above 5%. Abdullah and Wahhab (2015) reported that the percentage of filler was more important when compared to the plasticity of filler in FBM. Sakr and Manke reported that FBMs with higher percentages of fines had higher stability values and reported that aggregate interlock has a larger effect compared to the viscosity of bitumen on stability values (Martinez-Arguelles, Giustozzi, Crispino, & Flintsch, 2015). Research by Jenkins indicated that the sand fraction was of importance to FBM and minimum voids in the mineral aggregate of this part provided the most desirable mix properties (Jenkins, 2000).

### 1.2. Mixture design

The main objective of mixture design of foamed bitumen mix is to determine the number of individual components i.e. foamed bitumen, water (for dispersing the recycling agent), aggregates and RAP material. A wide variety of mix design procedures have been developed by various researchers (Austroads, 2013; IRC: 37, 2013; Technical Guideline-2, 2009; Wirtgen, 2004) for finding the optimal percentage of constituent materials for FBM. Most of these procedures emphasize on the determination of foamed bitumen content and water content. However, these procedures differ in specimen size specification, bitumen content optimization, curing conditions, and compaction methodologies. One of the widely used compaction methods is the Marshall Design approach (with suitable modifications to suit cold mixtures). Published literature indicates that FBM compacted with Marshall Approach results in optimum bitumen content, which is associated with the maximum density (Kim, Lee, & Heitzman, 2007; Modarres & Ayar, 2016). Recently, there has been a shift in design methods from Marshall Mixture design to performance tests like an indirect tensile test, resilient modulus test and moisture resistance test (Loizos & Papavasiliou, 2006).

### 1.3. Mechanical performance

Stabilization of RAP materials with foamed bitumen has been widely used by many countries for pavement reconstruction work. Kuna et al. (2016) reported that foamed bitumen stabilization offers a rapid form of road rehabilitation where failed pavement materials are reused to obtain a new flexible pavement base. Recent literature indicated factors like bitumen content, active filler type and content, aggregate composition and particle size distribution, moisture content, compaction effort, and curing regime to affect the strength and durability of FBM (Technical Guideline-2, 2009). According to Chomicz-Kowalska, Gardziejczyk, and Iwański (2016), the water-sensitivity of foamed asphalt is improved by adding 1% to 2% lime. Recent guidelines and literature have recommended a minimum value of Indirect Tensile Strength (ITS) and wet ITS is 225 kPa and 100 kPa, respectively (Chomicz-Kowalska & Maciejewski, 2015; IRC: 37, 2013; Wirtgen, 2012). As per Technical Guideline-2 (2009) and IRC: 37 (2013), the minimum accepted value of tensile strength ratio is 70% and 44%, respectively. Nosetti, Pérez-Jiménez, Martínez, and Miró (2016) found that foamed asphalt mixture was significantly affected by water infiltration and resistance to water increased with increase in foamed bitumen content. Modarres and Ayar (2016) reported that foamed asphalt treated RAP materials including 1.5% Portland cement showed higher in-situ stiffness values than those of the limestone base layer. Dal Ben and Jenkins (2014) reported that FBM containing RAP materials resulted in a better value of resilient modulus when compared to control mixtures. Many researchers reported that foamed bitumen stabilization increases the resilient modulus value of the mix compared to the unbound material (Cazacliu et al., 2008; Khosravifar, Schwartz, & Goulias, 2015). As per literature, the accepted values of voids and resilient modulus in FBM range from 10% to 15% and from 2500 MPa to 4000 MPa, respectively (Chomicz-Kowalska & Maciejewski, 2015; Wirtgen, 2004, 2012).

### 1.4. Sustainability analysis of foamed bituminous mixtures

Studies have reported that for every 10 °C increase in mix production temperature, the amount of green house gas (GHG) emissions becomes two fold (Iwański, Chomicz-Kowalska, & Maciejewski, 2015). Usage of foamed bitumen in full depth recycling offers certain advantages like faster construction, better structural integrity, reuse of aggregates and lower life cycle cost (Huan, Siripun, Jitsangiam, & Nikraz, 2010). Thenoux, González, and Dowling (2007) concluded that less energy is consumed by CIR with foamed bitumen, which is around 15% to 35% and 60% to 70% when compared to bituminous overlays and reconstruction projects, respectively. Caltrans recorded around 40% to 50% savings in cost against traditional rehabilitation projects in cold recycling project using foamed bitumen (Bowering & Martin, 1976).

## 2. Experimental investigation

### 2.1. Experimental programme

From the published literature, it was clear that physical properties of bitumen and amount of RAP affect mechanical properties of FBM significantly and are very specific to constituent materials and FBM produced. Thus, it was decided to investigate the mechanical properties of FBM mixtures produced as per Indian specifications. The experimental investigation was conducted in four phases namely:

- characterization of constituent materials (RAP, virgin aggregate and bitumen),
- assessment of the foaming properties of different grade bitumens,
- mixture design of FBM, and
- evaluation of mechanical properties of FBM with different percentages of RAP.

The sequence of various tests conducted in this study is presented in Figure 1.

### 2.2. Characterization of RAP material and virgin aggregate

In this study, RAP material was collected from Narela, a suburb of Delhi and virgin aggregate from a local quarry near Delhi. Initially, bitumen content in RAP material was determined to be 3.6% (by weight of total mix). The penetration value at 25 °C and softening point were observed to be 3.7 mm and 61.2 °C, respectively. The apparent viscosity of bitumen at 60 °C and 135 °C was found to be 2800 poise and 875 poise, respectively.

The recovered aggregate and virgin aggregate were tested for its physical properties as per Indian standards. The test method and results are presented in Table 1.

To determine the combined flakiness and elongation index, representative flaky stones sample were separated out. Flakiness index (FI) was then calculated by dividing the weight of flaky aggregates by total weight of the aggregate sample. Elongation index (EI) is the weight of elongated aggregate particles divided by total weight of non-flaky aggregate particles. FI and EI (both expressed as a percentage) are added together to get combined Flakiness and Elongation index. Aggregate impact test was conducted on aggregate sample passing 12.5 mm sieve and retained on 10 mm sieve. Impact resistance was determined by subjecting the sample to 15 number of blows or impact of a standard weight. The aggregate impact value was expressed as the percentage of the fines formed in termed in terms of the total weight of the sample. The coarse aggregate specific gravity test (Figure 1) was used to calculate the specific gravity of a coarse aggregate sample by determining the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water. The stripping value of aggregates was determined by static immersion of bitumen coated aggregate into the water.

### 2.3. Characterization of virgin bitumen

Three virgin bitumen binders (of VG 10, VG 30 and VG 40 grade) conforming to Indian standard (IS: 73, 2012) were used in this study. These bitumen binders were procured from a reputed refinery in the northern part of India. VG 20 was prepared by blending of requisite quantity of VG 10 and VG 30. The physical properties of bitumens are given in Table 2.

### 2.4. Characterization of foamed bitumen

With the increase in water content and bitumen temperature, the expansion ratio of foamed bitumen increases, while half-life decreases (Technical Guideline-2, 2009; Wirtgen, 2012). To determine the optimum foaming water

Table 1. Physical properties of aggregates

| Property | Test Results | | MoRTH, 2012 specifications | Test method |
|---|---|---|---|---|
| | Virgin aggregate | Recovered aggregate | | |
| Aggregate Impact Value | 20.60% | 27.50% | 30% max | IS: 2386 (Part IV) |
| Combined (EI + FI) Index | 21.20% | 25.70% | 30% max | IS: 2386 (Part I) |
| Water absorption | 0.70% | – | 2% max | IS: 2386 (Part III) |
| Specific gravity | 2.66% | – | – | IS: 2386 (Part II) |
| Stripping | 98% retained coating | 95% | ≥ 95% | IS: 6241 |

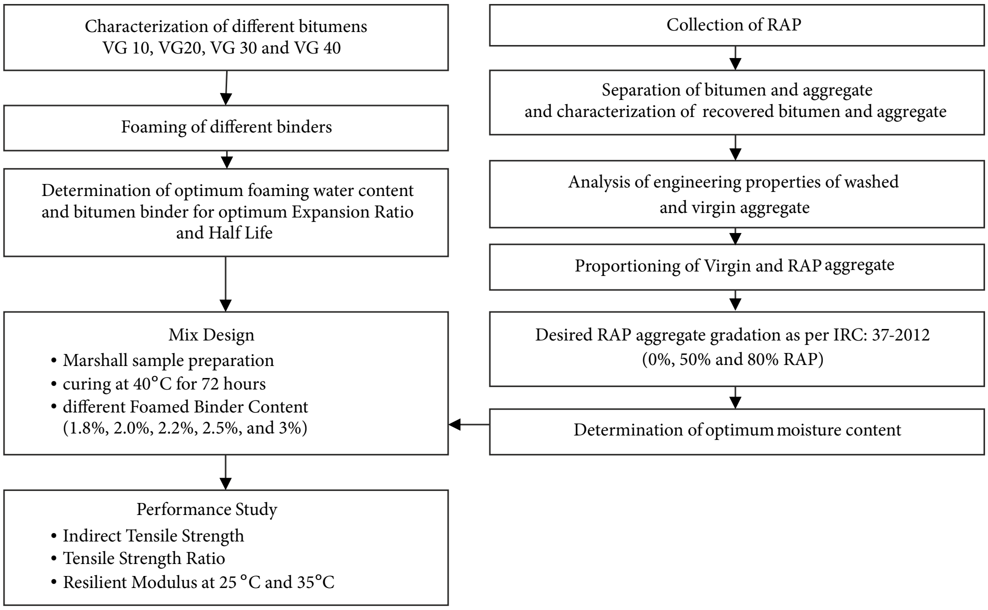


Figure 1. Experimental program

Table 2. Properties of virgin bitumen binders (As per IS: 73, 2012)

| Properties | Viscosity grade | | | |
|---|---|---|---|---|
| | VG 10 | VG 20 | VG 30 | VG 40 |
| Penetration, (25 °C, 100 g, 5s), 0.1 mm | 81 | 72 | 47 | 37 |
| Softening point (Ring and Ball), °C | 42 | 44 | 48 | 53 |
| Viscosity at 60 °C, poise | 1150 | 1980 | 3230 | 4750 |
| Viscosity at 135 °C, cSt | 450 | 500 | 575 | 725 |
| Temperature of 1.01 kPa G*/Sin δ of unaged bitumen, °C | 68 | 71 | 73 | 77 |
| Temperature of 2.2 kPa G*/Sin δ of RTFOT residue, °C | 73 | 74 | 76 | 81 |

content and foaming temperature, foamed bitumen characteristics were determined over a range of temperature and water content. The temperature of bitumen was varied between 120 °C, and 180 °C (at increments of 10 °C). Further, foaming water content chosen in this study was 2%, 4%, 6%, 8%, 10% and 11% by weight of bitumen. The air and water pressure used in this study were 550 kPa, and 600 kPa, respectively. During each foaming process, 500 g of bitumen was fed into foaming chamber at the rate of 50 gm/sec. The optimum water content and temperature was chosen to meet minimum criteria of ER≥8 times and HL≥6 seconds as specified by Technical Guideline-2 (2009) and Wirtgen (2012). The optimized water content and foaming temperature and corresponding foaming parameters (ER and HL) for all bitumen grades are summarized in Table 3.

Table 3. Optimum Expansion Ratio and Half Life of different grades of bitumens

| Bitumen | Temperature, °C | Optimum Water content, % | ER, % | HL, s |
|---|---|---|---|---|
| VG 10 | 130 | 8.5 | 15 | 15 |
| VG 20 | 140 | 6.0 | 18 | 18 |
| VG 30 | 160 | 6.0 | 19 | 19 |
| VG 40 | 180 | 8.0 | 15 | 15 |

## 3. Mixture design

### 3.1. Gradation of mix

The aggregate obtained from RAP during the bitumen extraction process was washed and dried in an oven for 24 hours. The washed aggregate was followed by sieve analysis to determine aggregate gradation presented in Figure 2. Reclaimed asphalt pavement aggregate was blended with virgin aggregate to satisfy the graduation requirements. Aggregate blends containing maximum 80% RAP material and 1% active filler (cement of 43 grade) met the grading requirements for recycled FBM. The particle size distribution of recycled FBM containing 0%, 50% and 80% RAP along with gradation limits is presented in Figure 2.

### 3.2. Determination of Optimum Moisture Content

The moisture content in RAP was determined to be 0.12% by oven drying the RAP. Optimum Moisture Content (OMC) of this untreated blend was determined using the moisture-density relationships according to AASHTO

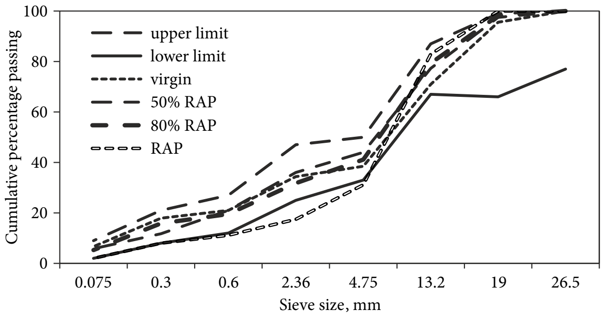


Figure 2. Aggregate gradation of foamed bituminous mixtures used in present study

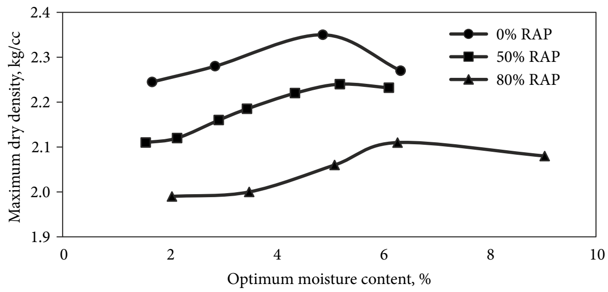


Figure 3. Variation of dry density of foamed bituminous mixtures with moisture content

T180 (2001) specifications. Loose mixtures (with different moisture contents) were prepared by adding different quantities of water. These loose mixtures were mixed well and were compacted using Proctor method of compaction. The variation of dry density of compacted mixtures with moisture content is presented in Figure 3. The moisture content corresponding to maximum dry density was designated as prewetting water and was used in subsequent specimen fabrication and testing. This OMC for 0% RAP, 50% RAP and 80% RAP mixtures was found to be 4.8%, 5.0%, and 6.2%, respectively. Moisture content present in RAP was deducted for while adding prewetting water.

### 3.3. Compaction and sample preparation

After determining the OMC, optimization of foamed bitumen in the aggregate blend was carried out. During this optimization process, 10 kg of aggregate blend satisfying gradation specification was weighed and foamed bitumen was added. The percentage of foamed bitumen content was varied between 1.8% and 3%. This resultant mixture was mixed well using Wirtgen WLM 10 pug mill mixer. This mixture was further divided (using a splitter) to obtain the weight of mixture that is just sufficient to fill the Marshall mould. The loose mixture in Marshall Mould was compacted using Marshall Compactor with 75 number of blows on each face. This compacted mixture was then demoulded after 24 h and cured for 72 h at 40 °C in an oven.

### 3.4. Test methods

To assess the performance of the FBMs, several performance-based tests were conducted in the laboratory. The tensile properties of FBM were evaluated using ITS. Indirect Tensile Strength test was conducted using the compacted cylindrical specimens under diametric loading condition at 25 °C as per *ASTM D6931-12* specifications. Using failure load, and specimen dimensions, ITS was calculated using Eq. (1).

$$\sigma_t = \frac{2P}{\pi D t}, \quad (1)$$

where $P$ – maximum load, N; $D$ – diameter of the specimen, mm; $t$ – thickness of the specimen, mm.

To evaluate moisture damage susceptibility of FBMs, Tensile Strength Ratio (TSR) was determined according to *ASTM D4867* (2009) specifications. Six specimens were compacted, of which three were used to determine ITS under the unconditioned condition and rest three were tested after proper conditioning. After proper curing, the unconditioned specimens were tested for ITS at 25 °C. For conditioning, the specimens were placed in a water bath at 60 °C for 24 hours and then placed in an environmental chamber maintained at 25 °C for 2 hours. After 2 hours of conditioning at 25 °C, ITS was determined using these three specimens. Eq. (2) computes the Tensile Strength Ratio (TSR) of the specimen:

$$TSR = \frac{\sigma_{t,\ conditioned}}{\sigma_{t,\ unconditioned}}, \quad (2)$$

where $\sigma_{t,conditioned}$ – average ITS of conditioned specimens; $\sigma_{t,unconditioned}$ – average ITS of unconditioned specimens.

To check the response of FBM under the dynamic condition, resilient modulus was determined according to *ASTM D4123* (2009) specifications. The specimens were conditioned for 5 hours in the environmental chamber at the test temperature and then subjected to repeat loading pulse width of 0.1 sec, and pulse repetition period of 1 sec at an assumed Poisson's ratio of 0.35 to measure the resilient modulus value.

## 4. Test results and discussion

### 4.1. Compaction characteristics

As mentioned previously, the compaction characteristics of FBM was determined using modified Proctor test. As seen in Figure 3, with increasing moisture content the dry density of compacted specimens increased to a certain level and then decreased. This was true for all mixtures evaluated in this study. However, the maximum dry density and corresponding moisture content were different for all three mixtures. Increase in RAP content resulted in a reduction in dry density and the corresponding increase in OMC of all mixtures. The decrease in dry density can be attributed to:

– the weak interlock between RAP and the virgin aggregate;

- the poor texture of RAP material (high value of elongation and flakiness index);
- slippage of aggregate/RAP particles during compaction.

A closer examination of Figure 2 indicates that particles small than 4.75 mm sieve are more in 0% RAP mixture, while particles bigger than 4.75 mm sieve are more in 80% RAP mixture. The voids created by larger particles in 80% RAP mixture are filled up with water rather instead of finer particles. Thus, higher RAP content mixtures had lower density and required higher water content to achieve maximum density.

### 4.2. Indirect Tensile Strength

The variation of ITS with RAP content and bitumen content for VG 10, VG 20, VG 30 and VG 40 grade bitumens are presented in Figure 4a through 4d, respectively. In general, the dry ITS value was observed to increase with the addition of RAP for all bitumen grades except VG 30. For a particular foamed bitumen content and RAP content, higher ITS was observed with mixtures prepared with higher viscosity grade. This is attributed to higher stiffness provided by bitumen. For a particular grade of bitumen and RAP content, with increasing foamed bitumen content, ITS value increased to a certain value and then decreased. At lower foamed bitumen content, bitumen was insufficient to provide proper lubrication during compaction. However, at higher foamed bitumen content, higher bitumen thickness decreased the dry ITS value.

### 4.3. Tensile Strength Ratio

The Tensile Strength Ratio was measured, to evaluate moisture resistance of FBM. The variation of TSR with RAP percentage and foamed bitumen content for VG 10, VG 20, VG 30 and VG 40 is presented in Figure 5, respectively. Most of the mixtures (except 0% RAP, 1.8% moisture content) have TSR values above 70%. One of the reasons for higher TSR is curing of Portland cement, which was added as filler. For a particular grade of bitumen and foamed bitumen content, most of the mixtures (except 1.8%, 2.0% foamed bitumen and VG 10, VG 40) exhibited maximum TSR at 50% RAP content. Four mixtures prepared with VG 10 and VG 40 grade bitumen and 1.8% and 2.0% foamed bitumen content showed maximum TSR at 80% RAP content. For a particular bitumen grade and RAP content, increasing TSR was observed with increasing foamed bitumen content. This is because foamed bitumen improves coating on aggregate or uniform spot welds at the aggregate interface. This, in turn, increased moisture resistance and subsequent TSR of mixtures.

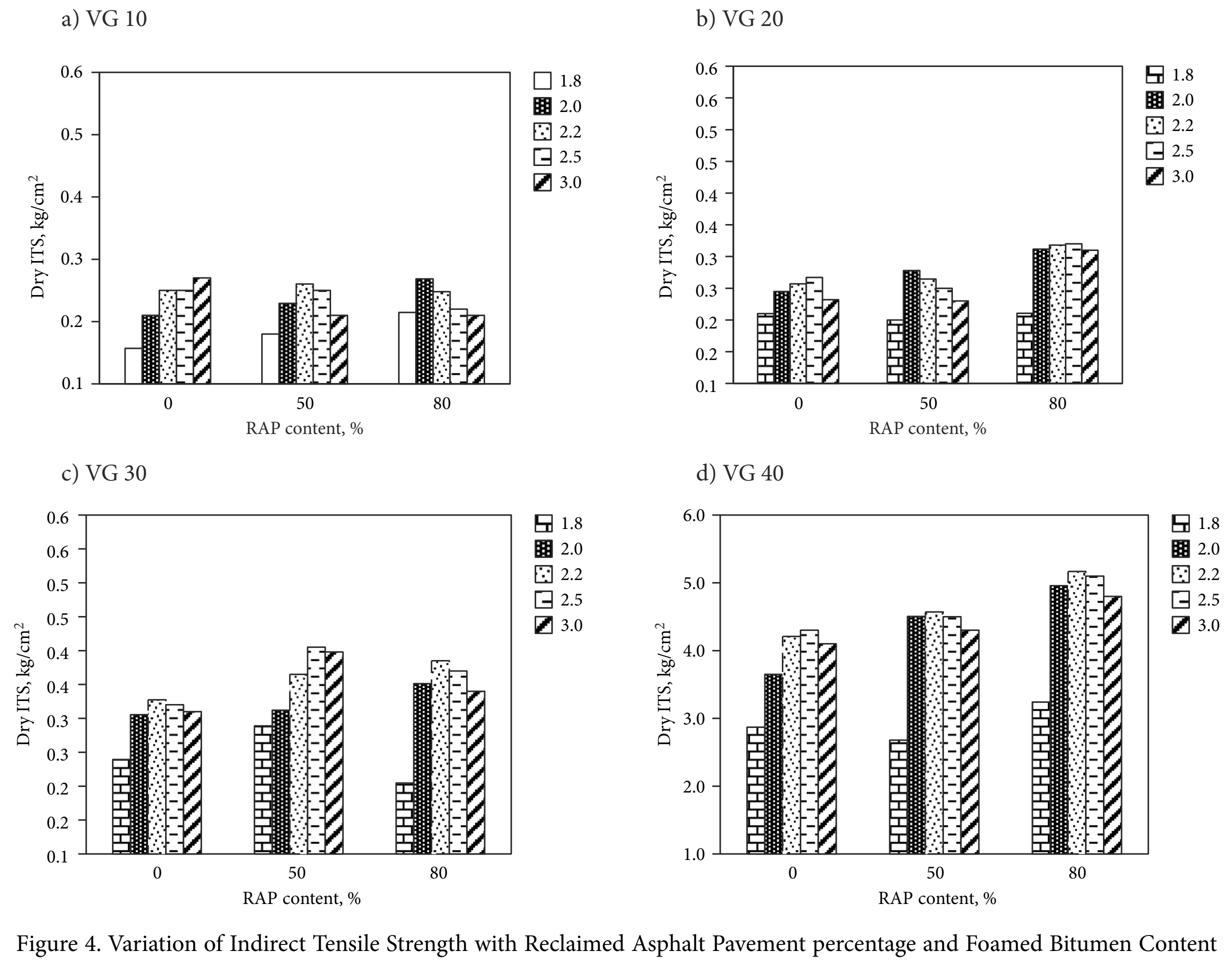


Figure 4. Variation of Indirect Tensile Strength with Reclaimed Asphalt Pavement percentage and Foamed Bitumen Content

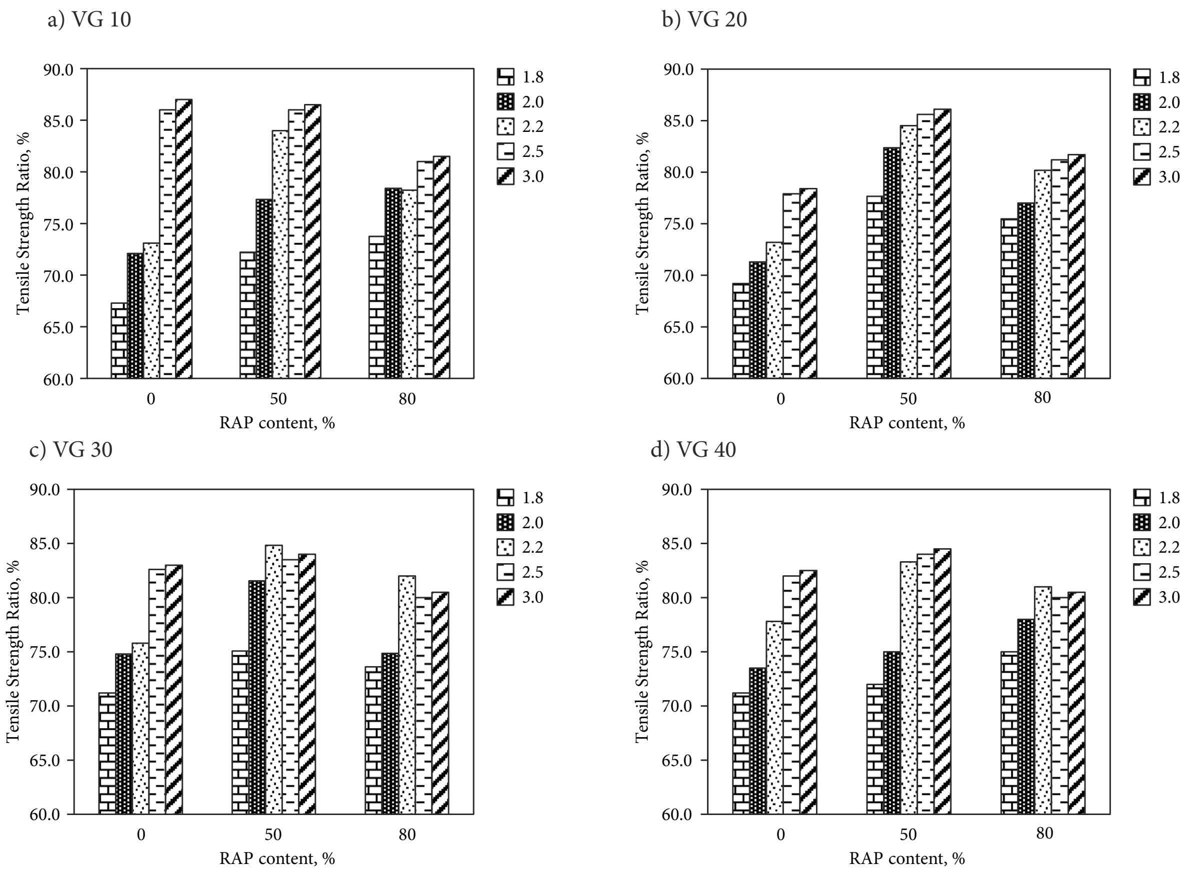


Figure 5. Variation of Tensile Strenght Ratio with Reclaimed Asphalt Pavement percentage and Foamed Bitumen Content

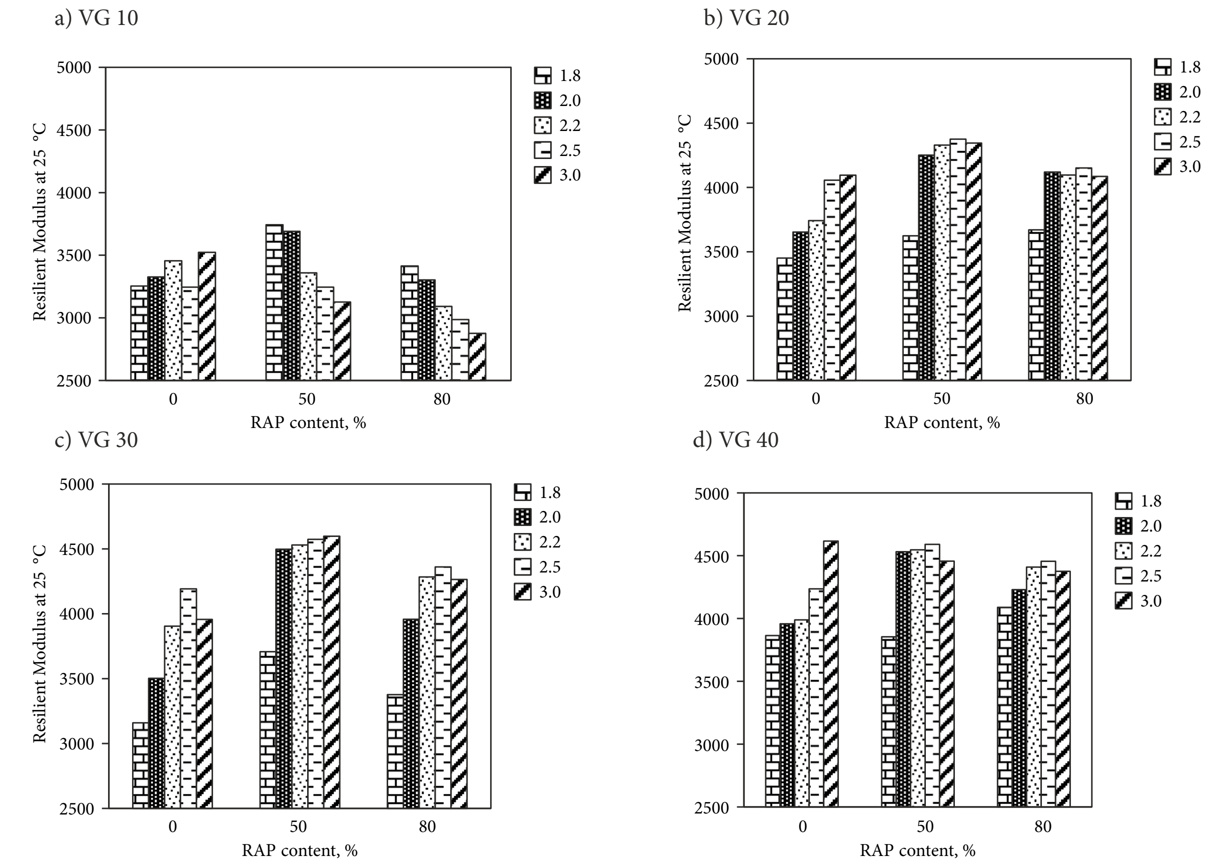


Figure 6. Variation of Resilient Modulus with Reclaimed Asphalt Pavement percentage and Foamed Bitumen Content at 25 °C

### 4.4. Resilient modulus test

The resilient modulus of FBM (with different RAP content, foamed bitumen content) obtained at 25 °C and 35 °C are presented in Figures 6–7, respectively. Other parameters being constant, higher resilient modulus was recorded at 25 °C when compared to 35 °C for all mixtures. For a given bitumen grade, foamed bitumen content and test temperature, maximum resilient modulus was observed at 50% RAP content for all mixtures (except mixture prepared with VG 10 and 3% bitumen content). This is attributed to better aggregate interlock, rejuvenation of aged bitumen in 50% RAP mixture when compared to mixtures containing 0% and 80% RAP. For a particular grade of bitumen, all mixtures containing 0% RAP exhibited increased resilient modulus with increased foamed bitumen content. However, 50% and 80% RAP mixtures exhibited increasing resilient modulus with increasing foamed bitumen content and then decreased. Most of the mixtures prepared with 50% and 80% RAP content, maximum resilient modulus was obtained at 3% and 2.5% foamed bitumen content at 25 °C and 35 °C, respectively.

## Conclusions

The use of foamed bitumen technology along with Reclaimed Asphalt Pavement is gaining popularity across the world. The mechanical properties of these Foamed Bituminous Mixtures containing Reclaimed Asphalt Pavement are highly influenced by constituent material properties and aggregate gradation. This article presents results from a study where Foamed Bituminous Mixtures conforming to Indian specifications were evaluated. Initially, the foaming characteristics of virgin bitumens commonly used in India were studied to optimize for optimum water content and foaming temperature. In the second stage, mixture design was conducted to optimize for foamed bitumen content. Finally, Foamed Bituminous Mixtures containing different percentages of Reclaimed Asphalt Pavement were prepared and evaluated for their mechanical properties. During mixture design, higher Reclaimed Asphalt Pavement content in Foamed Bituminous Mixtures resulted in higher optimum moisture content and lower dry density. The optimum moisture content of Foamed Bituminous Mixtures was dependent on Reclaimed Asphalt Pavement content. For particular foam bitumen and Reclaimed Asphalt Pavement content, higher viscosity grade of bitumen resulted in increased Indirect Tensile Strength. Further, increase in Reclaimed Asphalt Pavement content resulted in corresponding increase in Indirect Tensile Strength. Higher resilient modulus and Tensile Strength Ratio values were observed with mixtures containing 50% Reclaimed Asphalt Pavement when compared to other mixtures. In general, the mechanical and volumetric properties of Foamed Bituminous Mixtures depend primarily on the physical properties of bitumen, Reclaimed Asphalt Pavement content and bitumen content.

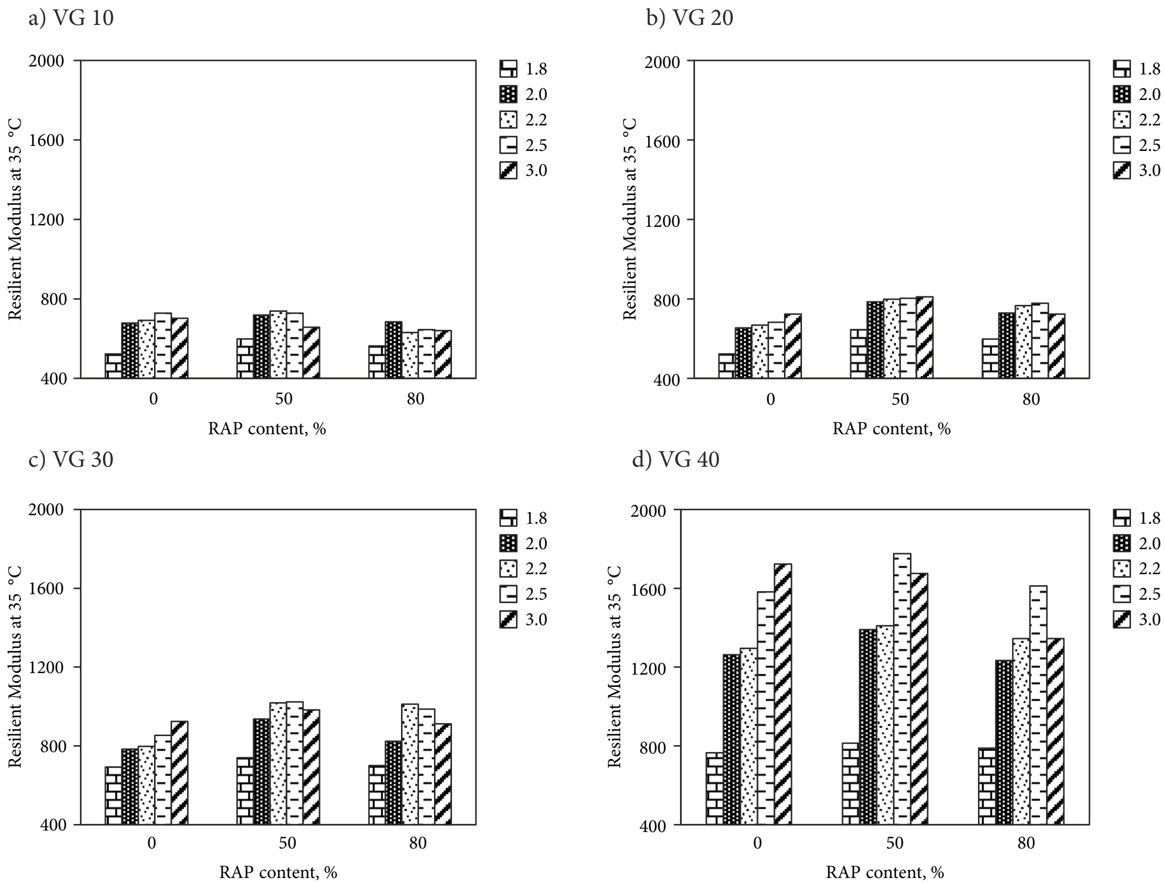


Figure 7. Variation of Resilient Modulus with Reclaimed Asphalt Pavement percentage and Foamed Bitumen Content at 35 °C

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