

CHAPTER 3. MATERIALS AND RESEARCH METHODOLOGY

3.1 Preface

This chapter encapsulates the information related to the materials used and basic properties, rejuvenators selected and their physical properties, approach adopted for the simulating RAP in the laboratory, fabrication of recycled binder blends and experimental methodology in the following sections.

3.2 Material properties

3.2.1 Asphalt binder

Asphalt binder or bitumen is a binding material that holds the aggregates (of different sizes) together and imparts the viscoelastic property to the asphalt mixes [144]. As specified in section 1.1, asphalt binder is a dark brown or black cementitious material and is obtained from the fractional distillation of crude oil. A viscosity grade (VG) 30, implying the binder with absolute viscosity (at 60°C) of 3000 (± 600) poises, as per IS 73:2013 [145] is used in the present study is. As per superpave PG grading [146], it's equivalent grade is PG 64 i.e. it can be used in the location having average seven-day maximum temperature of 64°C. Physical tests are conducted on the asphalt binder and the results are presented in Table 3-1.

Table 3-1 Asphalt binder properties

<i>Property</i>	<i>Code</i>	<i>Limit</i>	<i>VG 30</i>
Penetration value at 25°C, 0.1 mm	IS 1203 [147]	45 (minimum)	67
Softening point, °C	IS 1205 [148]	47 (minimum)	48.5
Kinematic viscosity at 135°C, cSt	IS 1206 [149]	350 (minimum)	476.52
Viscosity at 60°C, Poise	IS 1206 [149]	2400-3600	2654
Flash Point, °C	IS 1209 [150]	220 (minimum)	235

Solubility in trichloroethylene, %	IS 1216 [151]	99 (minimum)	99.8
High temperature performance grade	AASHTO	-	64°C
Intermediate temperature performance grade	M320 [146]		19°C

3.2.2 Aggregates

Aggregates forms the skeleton of the asphalt mix and plays key role in resisting the vertical load from vehicles that results in permanent deformation [144,152]. As per the availability, three aggregate stockpiles of granite origin are collected from a proximate quarry. Granite is an igneous rock type with high content of silica. The properties of aggregates, as shown in Table 3-2, are well within the limits for use in the binder layer (dense bituminous macadam (DBM)), as per Ministry of Road Transportation and Highway (MoRTH) guidelines [153].

Table 3-2 Physical properties of aggregate

<i>Property</i>	<i>Code</i>	<i>Limit (Maximum)</i>	<i>Result</i>
Impact value	IS 2386 (Part IV)	24%	15.2%
Abrasion value	IS 2386 (Part IV)	30%	20.77%
Combined flakiness and elongation value	IS 2386 (Part I)	35%	25.97%
Bulk specific gravity	IS 2386 (Part III)	-	2.666

3.3 Rejuvenators description

A total of four rejuvenators are considered in this study. Two most common waste type rejuvenators (WR): waste cooking oil (W) and waste engine oil (E) and two commercial rejuvenators (CR): R and B. W is a plant-based bio-oil, whereas E is a petroleum-based oil. R is of unknown type, which is designed to work as both rejuvenator and anti-stripping agent,

while B is a bio-oil based product. The basic physical properties of the rejuvenators are shown in Table 3-3. All the rejuvenators are liquid at room temperature, each with its own characteristic smell. W and B rejuvenators have similar colour, specific gravity, PH, and flash points. Although E and R have different specific gravities and flash points, they are both alkaline (basic) and have similar colour and smell.

Table 3-3 Rejuvenator properties

Rejuvenator	Physical state at room temperature	Colour	Specific gravity at 25°C	PH	Flash point
B	Liquid	Pale yellowish	0.92	6	>200°C
W	Liquid	Pale yellowish	0.92	6	>250°C
E	Liquid	Dark blackish	0.82	9	>200°C
R	Liquid	Dark blackish	0.95	10	>150°C

3.4 Simulating RAP in laboratory

Aged binder used in the study is attained by aging the VG 30 binder in the laboratory using RTFO (rolling thin film oven) [154] and one PAV (Pressure aging vessel) [155]. As elaborated in section 2.2, aging of asphalt binder happens in two stages i.e. short-term aging (STA) and long-term aging (LTA). STA starts right from the point of heating asphalt binder in storage tanks and continues during mixing with aggregates till laying and compaction of asphalt mix in the field. RTFO is developed to simulate the effect of STA on the asphalt binder, that happens in the field. LTA starts after the construction process of asphalt layer and till the end of service life. PAV is intended to simulate the LTA effect on the asphalt binder. It is assumed that aged binder simulated using PAV is equivalent to aged binder extracted and recovered from field RAP. While the applicability of PAV in simulating field aging is an ongoing area of research, this assumption is considered valid based on validation done in previous studies [156–161]. Additionally, artificial aging is chosen in this study to due to the drawbacks of variability

of field RAP and residual solvent, as elaborated below, and hence to evade their influence on the test results.

3.4.1 Field RAP

Variability and moisture content are inevitable issues that influence the applicability of RAP in HMA. Variability implies the inconsistency in the aggregate gradation, binder content, and binder properties. Stockpiling methods also may result in variation, in addition to the inherent materials, due to the segregation [29]. Variability in the materials can also lead to performance variability and increases with the RAP content depending on the source [162,163]. Initially, variation is determined to limit the maximum percentage of RAP to be incorporated. Over the years, measures were taken to limit variability and increase the percentage of RAP to be included. Asphalt pavement history and policies of road management also affect RAP variability.

The ripping and breaking process used for full depth removal results in large lumps or chunks, which needs to be crushed. These lumps from different projects are often stored together, and crushing helps obtain consistent desired aggregate sizes. RAP obtained from milling can be used directly without any processing since milling is usually employed to remove the upper layer of pavement and in a controllable manner. Storing the milled recycled materials obtained from a single layer or a specific project together in a separate stockpile seems appropriate. However, space constraints do not permit or encourage these separate stockpiles [40]. Experience shows that blending of RAP from different sources using front end loaders or bulldozers and then crushing helps achieve homogenous or consistent materials [164]. It is expected that blending helps in averaging out the variations in RAP [34]. But crushing the materials to pass through a single size screen should be avoided since it results in higher dust contents. Excessive crushing is also advised to be avoided; it also creates more dust and limits the percentage of fines incorporated [25].

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Fractionation is one of the best techniques in minimizing variability and attaining better control over gradation and binder content and is much recommended for high RAP contents [165]. It involves separating RAP into coarse and fine fractions of different sizes. The sieve used to separate the coarse and fine fractions varies from one agency to another [166]. Fractionating RAP into coarse and fine aggregates and limiting the fines helps achieve the volumetric criteria to meet mix design [167,168]. Multiple stockpiles must be maintained for each source, and characterization must be done separately due to the variation in binder content in fine and coarse fractions. Fractionation may result in additional cost since it requires extra bins to feed different fractions simultaneously [66]. Fractionation also enhances the effectiveness of RAP in the final asphalt mixes, thus increases the strength and stiffness [169]. From the evaluation of plant-produced mixes, it was observed that even at high percentages of the RAP, desired performance can be achieved using fractionation [170]. Nevertheless, Sabahfer and Hossain [171] studied the fractionation on the two RAP sources and percentages and concluded that fractionation does not improve the Superpave mixes' performance. Hence, the fractionation's effectiveness varies from one source to another and depends on the percentage of the fine aggregates, binder content, degree of binder aging, and binder properties.

Moisture is also of significant concern affecting production rates and efficiency of RAP in HMA. RAP usually tends to grasp water and does not shed over time [172]. Wet RAP tends to stick in feeders, crushers, blind screens, belts, and accumulates under the conveyor. Henceforth additional maintenance of processing units and feeder systems is required [25,34]. Various practices that effectively control or minimize moisture content are adopting conical stockpiles, storing on paved and sloped surfaces, and covering stockpiles under a roof [25,173]. Storing stockpiles on paved and sloped surfaces helps in draining moisture and prevents absorbing moisture from the ground. It also helps in minimizing the contamination when front-end loaders collect RAP close to grade [173].

3.4.2 Drawbacks of the existing characterisation methods

There are some concerns regarding the extraction and recovery of asphalt binder using solvents [174–177]

- The solvent may present in the binder even after recovery, affecting binder properties. RAP consists of an aged binder adhered (coated) strongly to the aggregates. Completely removing the aged binder will be difficult due to its strong interaction with the aggregates.
- Hardening of binder from overheating and loss of volatiles during the recovery process
- Reactions between solvent and binder are termed solvent aging or negative hardening (increases with temperature and time of exposure)
- Applicability of solvents to RAP (modified and unmodified) binders
- Health issues and environmental safety.

Although bio-solvents are harmless and biodegradable, the following disadvantages make them unreliable to use: the requisite for modification of extraction procedure, less accuracy or need of longer extraction time, expensive and requirement of high quantity, and high boiling point [178,179].

Binder content and binder properties also vary depending on the combination of extraction and recovery methods adopted. Centrifuge extraction with rotary evaporation recovery and the SHRP process give consistent results [177]. General and apparent drawbacks of the extraction and recovery methods are that test results are sensitive to the residual solvent or mineral matter, aging of the binder when hot extraction methods are used, labour-intensive, and health and environmental risks. It should be realized that the actual properties of the asphalt binder before the extraction and recovery, especially in the case of RAP, are unknown, and the contradictions associated with the test methods cannot be evaluated precisely. In the case of the ignition

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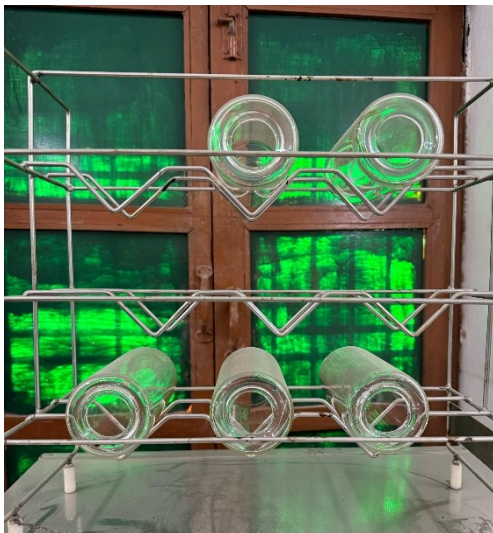
furnace method, loss of aggregate at elevated temperatures is of major concern for some aggregate types.

3.5 RTFO

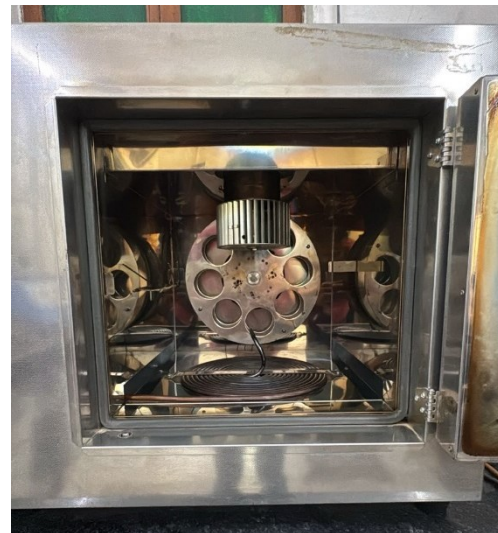
During and after the mixing process (till laying and compaction process), asphalt binder exists in the form of a thin film around the aggregates at high temperatures. This is simulated in the RTFO (refer Figure 3-1 (a)) test by pouring around 35 ± 0.5 g of hot asphalt binder ($\leq 150^\circ\text{C}$) into a glass container and then rotating horizontally such that binder coats the glass container and forms a thin film. The glass containers (refer Figure 3-1 (b)) are then placed horizontally inside the slots available in the carriage (refer Figure 3-1 (c)) inside the RTFO. Now, the thin film of binder is exposed to air flow of 4000 ± 200 mL/min at a temperature of 163 ± 0.5 °C for 85 min while the carriage holding glass containers is rotated at a speed of 15 ± 0.2 r/min. After the completion of test, STA binder is collected from the glass containers using a scraping tool (knife with a handle) and then LTA is performed on the sample using PAV.



(a) RTFO equipment



(b) Glass containers



(c) Carriage

Figure 3-1 Images of Rolling Thin Film Oven

3.6 PAV

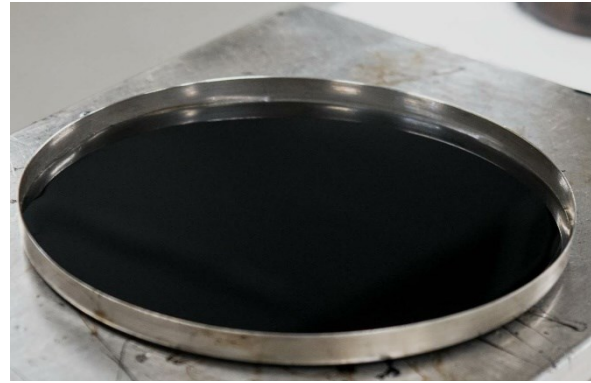
Long term aging (LTA) takes place after the pavement is open to traffic and continues till the end of service life. Various mechanisms that take place during LTA are elaborated in section 2.2. PAV (Figure 3-2 (a)) is designed to simulate the LTA in laboratory by subjecting the STA binder to a specific temperature for a period of $20 \text{ h} \pm 10 \text{ min}$ and pressure of $2.1 \pm 0.1 \text{ MPa}$. Temperature is chosen based on the climatic condition of location in which the binder is going to be used. Since PAV is used to generate artificial aged binder, time and temperature of 20 h

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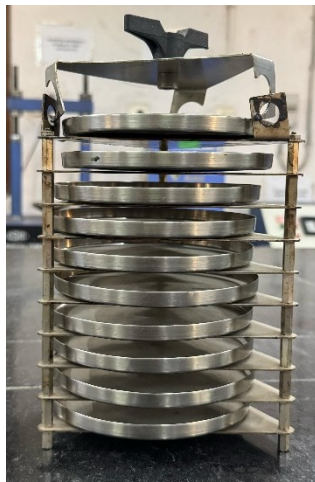
and 100°C are used, respectively, simulating the in-field aging of 5 to 10 years [180,181]. Test procedure involves filling the pan(s) uniformly with 50 ± 0.5 g of STA binder as shown in Figure 3-2 (b). After filling all the pans with the binder, pans along with pan holder (Figure 3-2 (c)) are placed inside the pressure vessel (Figure 3-2 (d)) and lid is closed by tightening the screws such that temperature and pressure are maintained. After the completion of test, vacuum degassing of the samples is done using a vacuum oven. All the binder from the ten pans are transferred to four bowls and placed in vacuum oven for a period of 15 ± 1 min at a temperature of 170 ± 5 °C and then at absolute pressure of 15 ± 2.5 kPa is maintained for 30 ± 1 min. Now the artificial aged binder is considered as RAP binder and is further used to prepare recycled binder blends.



(a) PAV equipment



(b) Uniformly spread STA binder in pan



(c) Pans along with pan holder



(d) Pressure vessel lid with tightened screws

Figure 3-2 Images of Pressure Aging Vessel

3.7 Recycled binder blends fabrication

Recycled binder blends are prepared by blending the aged binder, virgin binder and rejuvenators. As can be seen from Table 3-4, different temperatures, times, shear rates and approaches are adopted. Range of shear rates implemented by researchers varied from 200 rpm to 5000 rpm and temperatures from 130 to 180°C, whereas time from as low as 50 s to 2 h (considering binder modification only). Blending temperature should be selected such that further aging of aged binder or virgin binder or rejuvenator is prevented [180]. Also it is expected that adding rejuvenator to the new (virgin) binder can help in increasing the aging resistance [143].

Table 3-4 Rejuvenator blending conditions adopted in literature

Reference	Rejuvenator added to	Blending equipment, shear rate, time and temperature
Ji eat al. [182]	Extracted RAP binder	Using propeller mixer at 200 rpm and 130°C for 30 min
S. Im et al. [136]	Blend of virgin binder and extracted RAP binder	NA
I. Boz and M. Solaimanian [183]	Virgin binder	Hand stirring at 135°C for 2 min
R. Zhang et al. [180]	(Laboratory) Aged binder	Using high-speed shear mixer at 135°C and 5000 rpm for 15 min
M. Ameri et al. [184]	Extracted RAP binder	Using mixer at 150°C for 10 min
Bu"chler et al. [128]	RAP	During mixes preparation in laboratory mixer for 30 s to RAP heated at 140°C for 4 h
M. Elkashef et al. [185]	Extracted RAP binder	Manually blended using a glass stirrer for 3–5 min at 180°C
H. Ziari et al. [60]	RAP	During mixes preparation to RAP heated at 163°C for 2 h
G. Guduru et al. [132]	Blend of extracted RAP binder and virgin binder	Using blender at 1000 rpm and 140°C for 15 min
A. Samieadel et al. [186]	(Laboratory) Aged binder	Hand-blending at 135°C for 5 min

N. Nciri et al. [187]	Extracted RAP binder	Using high shear mixer at 3000 rpm and 180°C for 2 h
D. Daryae et al. [188]	Extracted RAP binder	Using mechanical mixer at 150°C for 10 min
P.A. Dokandari, A. Topal and D. K. Ozdemir [189]	Extracted RAP binder	Using a laboratory blender at 700 rpm and 140°C for 5 min
S. K. Pardhan and U. C. Sahoo [190]	Extracted RAP binder	Using a mechanical stirrer at 160°C for 15 min
A. I. Rajib et al. [191]	(Laboratory) Aged binder	Hand blending at 135°C for 5 min
M.A. Dalhat et al. [192]	RAP	During mixes preparation to RAP for minimum duration of 2 min
Z. H. Al-Saffar et al. [193]	Blend of extracted RAP binder and virgin binder	Using a laboratory mixer set at 1500 rpm and 145°C for 30 min
L. Wang et al. [194]	Extracted RAP binder	At 165°C for 50 s
G. Yaseen and I. Hafeez [195]	Extracted RAP binder	Using a mechanical mixer at 3000 rpm and 140°C for 15 min
M. Alae et al. [196]	Extracted RAP binder	Using shear mixer at 500 rpm and 165°C for 15 min
S.-Y. Lee and T.H. Minh Le [197]	RAP, Virgin aggregates and virgin binder	Using a mechanical mixer at 160°C for 2-3 min

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Based on the broad literature review, the following mixing sequence is implemented in this study, in order to simulate the hot mix plant conditions. Virgin binder is initially kept in the hot air oven at 130°C for 30 min and transferred to a container. Rejuvenator is then added to virgin binder and hand mixing is done for 15 minutes while maintaining the temperature of 125 ± 5 °C. Then aged binder which is kept in the oven at 140°C for 30 min, is mixed with the blend of virgin binder and rejuvenator using a mechanical stirrer at 1500 (± 500) rpm for 20 minutes at 140 ± 5 °C. If the rejuvenator is blended in the bitumen tank and then is added to the mix of aggregates (virgin and recycled) in the pug mill, a similar condition is expected.

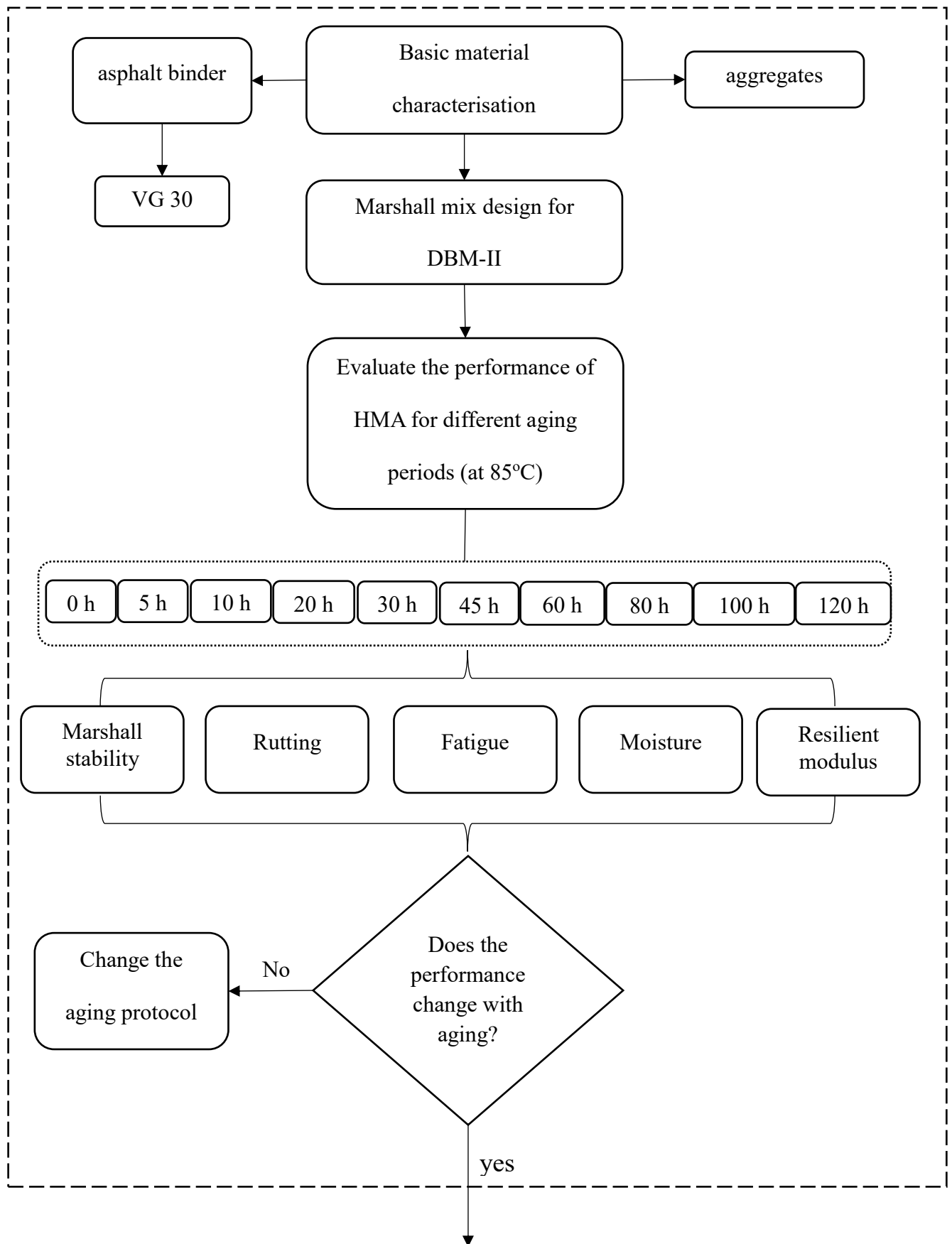
3.8 Experimental methodology

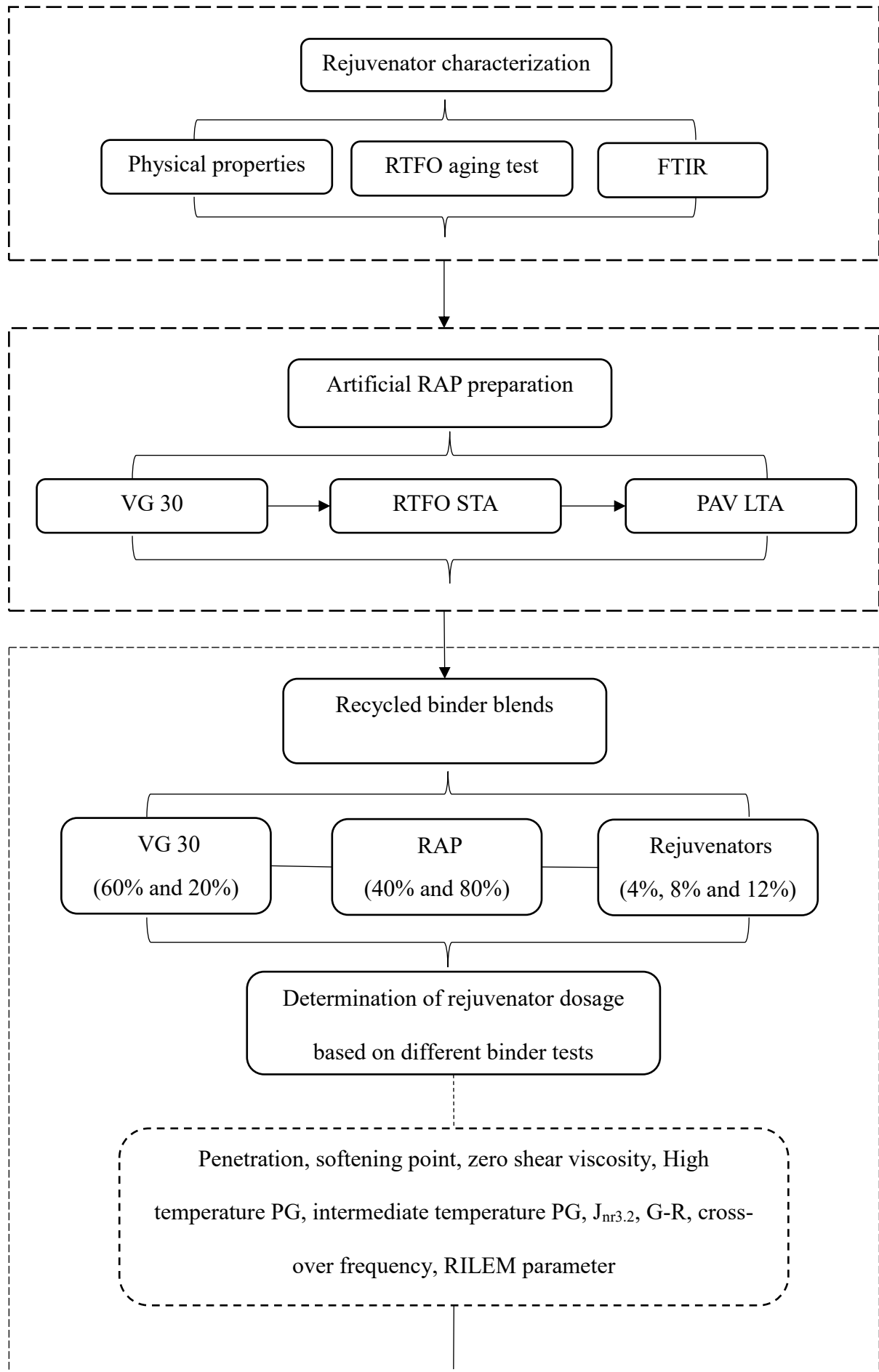
A series of experimental testing's and theoretical analysis have been performed to understand the efficacy of rejuvenators as shown in Figure 3-3. Four different rejuvenators, one commonly used base binder (viscosity graded (VG), 30) and one aggregate type (granite) are selected to complete the objectives of the present study. In order to assess the durability of rejuvenators, initially the aging protocol is to be carefully chosen. For this, the suitability of the standard aging protocol of AASHTO (American Association of State Highway and Transportation Officials) R30 i.e. 85°C for 120 h is evaluated based on the performance of virgin mixes at different aging periods such as 0, 5, 10, 20, 30, 45, 60, 80, 100 and 120 h at 85°C. After selecting the aging protocol, rejuvenators are characterized by assessing the physical properties such as specific gravity, flash point, viscosity and aging resistance. Also, the chemical composition of each rejuvenator is evaluated by conducting Fourier Transformed Infrared Radiation (FTIR) test and identifying the functional groups.

Artificial aging of VG 30 binder is done in the laboratory using rolling thin film oven (RTFO) and pressure aging vessel (PAV). This artificial long-term aged binder is considered as the RAP in this study and is used to prepare recycled binder blends and mixes. The best parameter to evaluate the optimum dosage of rejuvenators is recognized based on basic properties tests

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such as penetration value, softening point and rheological properties such as zero shear viscosity, high and intermediate temperatures performance grades (true fail temperatures), Non-recoverable creep compliance, Glover-Rowe parameter, crossover frequency are evaluated using dynamic shear rheometer. Dosage corresponding to each parameter is calculated and Tukey post-hoc analysis is performed to group the parameters that results in similar dosage. Finally, rutting and fatigue performance of rejuvenators is evaluated for each group and the dosage that resulted in similar performance as virgin mix is selected as the optimum dosage and the corresponding parameter is suggested. Also, ranking is done to study the property of rejuvenator that have best correlation with the performance of recycled mixes. Durability of recycled mixes in comparison with virgin mixes is studied by assessing the performance at all the aging periods as per the initially selected aging protocol.





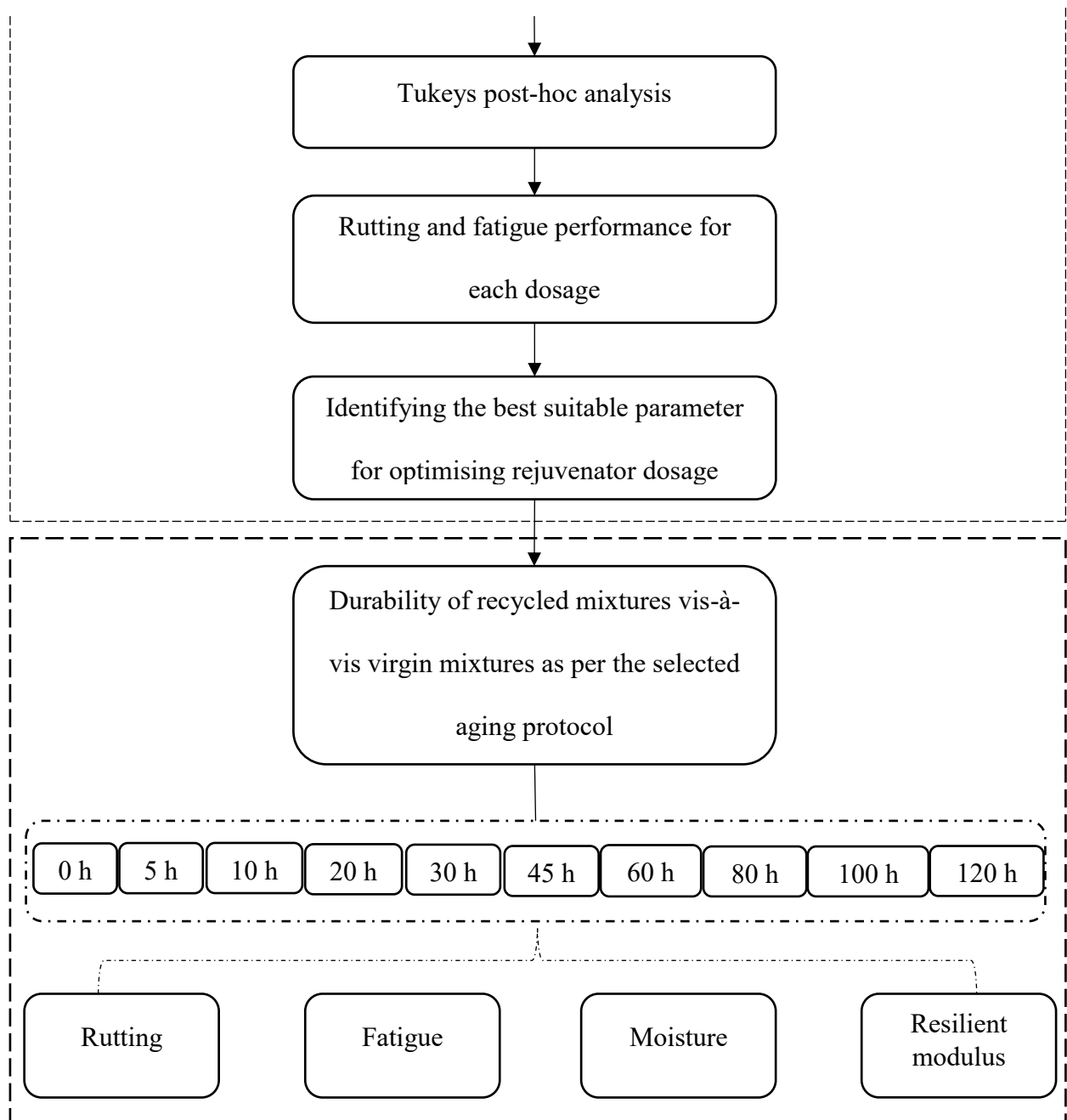


Figure 3-3 Outline of the research work

3.8.1 Tests

3.8.1.1 FTIR Spectroscopy

Electromagnetic spectrum consists of different bands, each having specific characteristics (frequency, energy and wavelength). Among them, electromagnetic waves present in the region of 13,000 to 10 cm^{-1} (approximately) wavenumbers is termed as infrared radiation.

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Spectroscopy that utilises infrared radiation is a widely used technique to analyse the chemical constituents of a molecule. Chemical bonds present in a material can be identified based on the principle that the arrangement and vibration of molecules at specific frequencies will affect the absorption of the infrared spectra [198,199]. Functional groups (structural fragment) present in a molecule always absorb the infrared radiation in same frequency range without depending on the rest of the molecule [200]. Thus the absorption spectra are a powerful tool that can be used to identify the principal functional groups present in any unknown substance. Fourier transformed infrared (FTIR) spectroscopy test is conducted in this study using a commercial spectrometer as shown in Figure 3-4.

Test is done using potassium bromide (KBr) pellet method [201,202]. Pellets are made by adding and mixing one drop of potassium bromide solution with rejuvenator. After some time, thin film is obtained by placing pellets inside a dissector and applying 100 kg/cm² force. Then sample is placed inside the transmittance chamber and interferogram of the rejuvenators is collected using an interferometer, which includes a beam splitter. The resulting wave pattern, termed as interferogram, is generated by measuring the intensity of radiation received at varying positions using fixed and movable mirrors. The FTIR spectrometer digitizes the interferogram and applies Fourier transform to produce the final spectrum.



Figure 3-4. Fourier Transformed Infrared test setup

3.8.1.2 Marshall stability

The resistance of asphalt mixes to the plastic flow when loading is applied perpendicular to the cylindrical axis is measured as per ASTM D6927 following method B [203]. Marshall stability (MS) is the maximum load sustained by a sample subjected to a standard (constant) rate of deformation (50.8 mm/min). It should be highlighted that MS is not the absolute measure of the strength but the ability of the mix to resist load without shear flow [204]. The amount of lateral stresses developed during testing is dependent on the angle of internal friction, vertical load, friction between sample and testing heads, and shear resistance of the mix [205]. Thus, for a constant rate of loading and maintaining similar friction between sample and testing heads, lateral stresses developed (and, in turn, MS) depend on the angle of internal friction and shear resistance of the mix. It is also reported that MS is sensitive to the viscosity of the binder [206]. Therefore, it is presumed that different levels of aging should affect the MS value and is considered in this study to assess the impact of aging.

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3.8.1.3 *Rutting performance*

3.8.1.3.1 Dynamic creep compression test

Rutting, also known as permanent deformation, is the gradual accumulation of material movement due to the recurring traffic load [207,208]. Simple laboratory tests, such as repeated load or dynamic creep tests, can be implemented to evaluate the rutting resistance of asphalt mixes [209]. Dynamic creep compression (DCC) test is conducted as per EN12697-25 [210] for assessing the rutting resistance of recycled mixes. Repeated load tests can also capture the influence of different mix parameters attributed to aggregates and binder [211]. Test is done using a Dynamic testing system (DTS) 30 and the test set-up is shown in Figure 3-5.

The test sample is conditioned in the temperature controlled chamber at 60°C for 2 h prior to the testing. After conditioning, sample is placed in between two plane parallel loading platens and then two LVDT's (Linear Variable Differential Transformer) are placed on the top of upper platen as shown in Figure 3-5. First the sample is subjected to a preload of 10 ± 2 kPa for 10 minutes and then cyclic load of 100 ± 2 kPa of frequency 0.5 Hz is applied for 3600 cycles. The response of sample i.e. cumulative axial strain, as function of number of loading cycles, as shown in Figure 3-6, is termed as creep curve. Generally, three stages can be observed in a typical creep curve i.e. stage 1 (primary stage), stage 2 (secondary stage) and stage 3 (tertiary stage). In primary stage, slope of the curve decreases with the increase in loading cycles, in which quick accumulation of strain takes place. During the secondary stage, slope of the curve is constant i.e. strain increases with a constant slope. In the tertiary stage, slope of the curve increases continuously with number of cycles, samples deform continuously.



Figure 3-5 Dynamic creep compression test

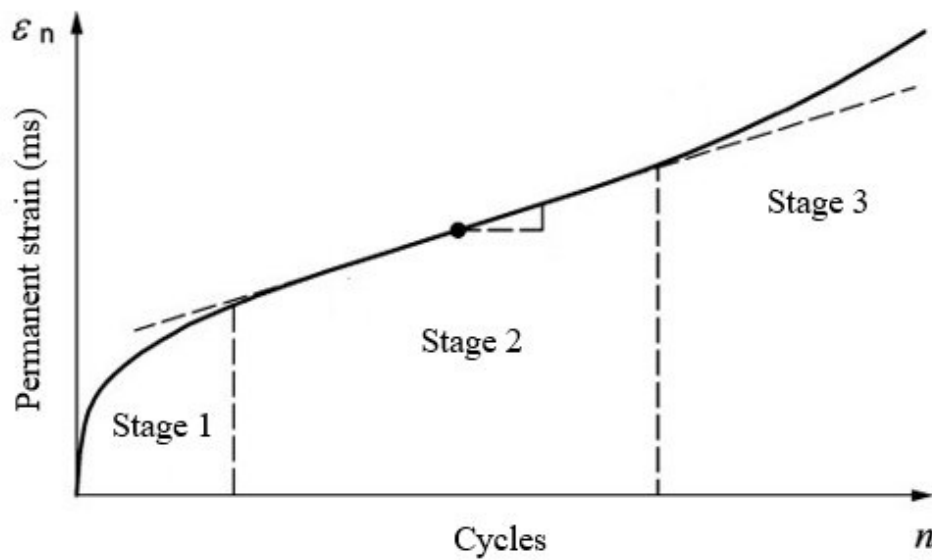


Figure 3-6 Typical creep curve

Asphalt mixes exhibit complex viscoelasticity behaviour, and the response under constant repeated loading captures both time-dependent and independent deformation. The loading and rest period is the typical pattern (cycle) followed in dynamic creep testing. The resultant strain during the testing is shown in Figure 3-7 [212–214]. After applying the load, there will be instantaneous elastic strain and plastic strain. As long as the constant load is sustained, visco-

elastic strain and visco-plastic strain are also observed. At the moment the load is removed, and during the rest period, some part of the strain is recovered because of its elastic nature. The resultant permanent strain is the sum of the plastic and visco-plastic strains. In the present study, the permanent strain (cumulative) parameter is used to quantify the rutting resistance. Loading and resting times will affect the elastic and plastic response of the asphalt mix [215]. Therefore, these times are kept constant for all the mixes tested and the results are expected to depend only on the aging levels of the mix.

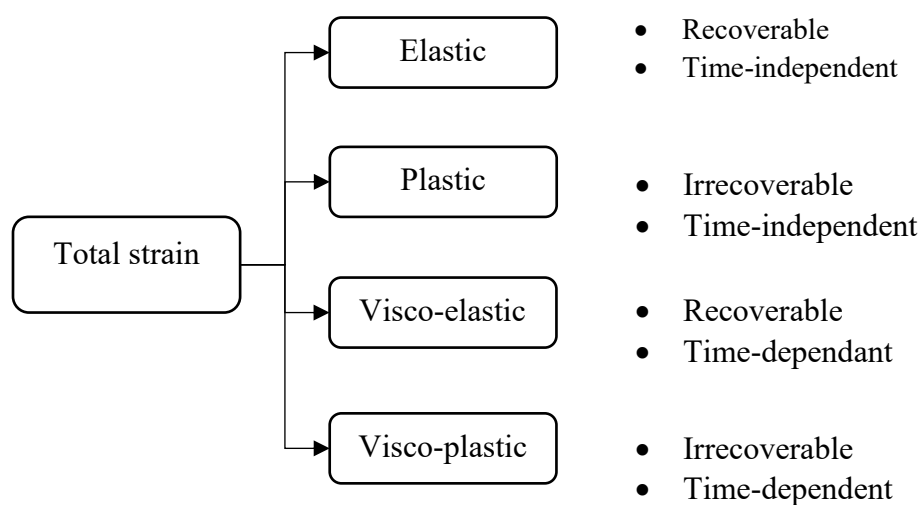


Figure 3-7 Components of strain [212–214]

3.8.1.3.2 Hamburg wheel rut test

Plastic deformation in the asphalt mix due to the application of external load is known as rutting [216]. The Hamburg wheel rut test (HWRT) is conducted to evaluate and compare the rutting resistance of the recycled mixes. Test methodology is followed as outlined in AASHTO T324-14 [217] and executed using the Smartracker Hamburg wheel tracker equipment as shown in Figure 3-8. In this study, HWRT is performed in dry condition (without water bath) at $50^{\circ}\text{C} \pm 1^{\circ}\text{C}$ by means of an air-heating system integrated with the device. It is a destructive test in which permanent deformation is imparted using a steel wheel tyre assembly. Traffic loading is simulated when tyre assembly moves forth and back on the surface of samples at a speed of 52

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(± 2) passes per minute. Three samples of $7\% \pm 0.5\%$ air voids are cut as per the requirement and are placed and held as shown in the Figure 3-9. Test is proved to differentiate mixes prone to rutting and also had good correlation with binder rutting parameters [218,219]. HWRT results are also found to depend on the stiffness of the binder [220].



Figure 3-8 Hamburg equipment

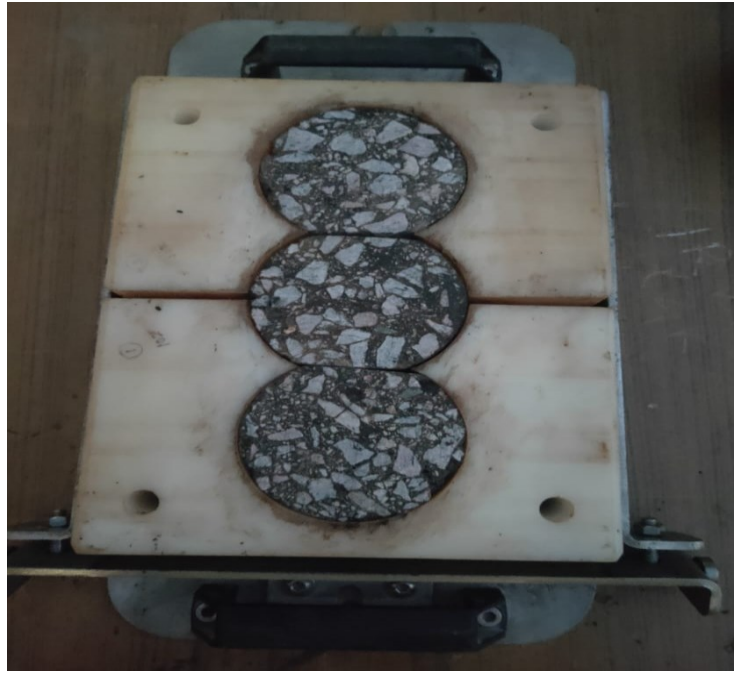


Figure 3-9 Sample setup for Hamburg test

3.8.1.3.3 IDEAL-RT test

In this study, rutting performance of asphalt mixtures is assessed using IDEAL-RT test, in which shear failure is induced in the sample (with the help of a supporting cradle on the lower loading strip, as shown in Figure 3-10). Similar to IDEAL-CT test, it is also developed as a part of the framework of balanced mix design and quality control and acceptance evaluation. Several advantages such as low equipment cost, no sample processing requirement and good repeatability, make this test prevalent in recent times. Good correlation with and similar trend as that of Hamburg wheel rut test [221] and Asphalt Pavement Analyzer test [222] results suggest that IDEAL-RT test can be used as a surrogate test to assess the rutting potential. Results also found to correlate well with field performance and are sensitive to aging [222–224]. Test is conducted as per the ASTM D8360-22, in which a monotonic compressive load is applied at a load-line displacement rate of 50 ± 2 mm/min [225]. Sample is initially conditioned in a standard oven at a temperature of 60 ± 1 °C for a period of 150 ± 10 minutes. From the data, Rutting Tolerance index (RT_{index}) is calculated as follows;

$$RT_{index} = 6.618 \times 10^{-5} \times \frac{\tau_f}{1 Pa} \quad (3-1)$$

$$\tau_f = 0.356 \times \frac{P_{max}}{t \times w} \quad (3-2)$$

Where τ_f is the shear strength of the sample, P_{max} is the maximum load in newton's, t is the sample thickness in meters and w is the width of the loading strip in meters. Higher the value of RT_{index} more will be the shear strength and hence better the rutting resistance. Parameters such as test temperature, rate of loading, aggregate gradation and air voids that can affect test results [226] are kept constant throughout the study.

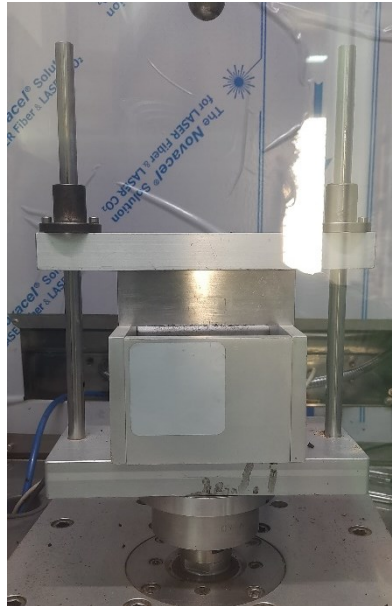


Figure 3-10 IDEAL RT test setup

3.8.1.4 Indirect tensile cracking test

DTS-30 is also used to conduct the indirect tensile cracking test (IDEAL-CT) test, as per ASTM D8225 [227], to evaluate the fatigue resistance of recycled mixes. The test is conducted in strain-controlled mode (50 mm/min) on the long-term aged samples with 7% ($\pm 0.5\%$) air voids and conditioned at 25°C ($\pm 1^\circ\text{C}$) for 2 h (± 10) min. The deformations of the samples with the increase in load are continuously recorded and the load-deformation curves are used

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to calculate the cracking tolerance index (CT_{index}) of the asphalt mixes. Test setup and typical load-deformation curves are shown in Figure 3-11. CT_{index} is calculated as follows, where t is the sample thickness (mm), l (l_{75}) is the displacement (mm) at 75% of peak load (post-peak), G_f is the fracture energy in J/m^2 , D is the sample diameter (mm), P/l is the slope ($|m_{75}|$) of tangential zone at 75% peak load point (N/m).

$$CT_{index} = \frac{t}{62} \times \left(\frac{l}{D}\right) \times \frac{G_f}{\left(\frac{P}{l}\right)} \quad (3-3)$$

Test has been found to correlate well with field performance and other cracking tests such as the overlay test, Illinois flexibility index test, and semi-circular bending test [222,228,229]. As stated earlier, binder is the only variable in the mixes and the cracking tolerance index (CT_{index}) has proved to capture the effect of binder since it correlates well with the binder fatigue tests such as liner amplitude sweep (LAS) and binder yield energy (BYE) tests [230]. CT_{index} has been found to be sensitive to the air voids and aging [231–233]. Studies have shown that l_{75}/m_{75} , termed as asphalt flexibility ratio (AFR) is more sensitive to (oven and field) aging and a better indicator of mix aging [234,235]. Thus, in the present study AFR was also evaluated in addition to CT_{index} to carefully study the change of cracking resistance with time. Also, Fatigue Index (FI), as proposed by Sukhija et al. [236,237] is the ratio of fracture energy upon the peak load. As elaborated by the authors, a higher value of FI suggests that more energy can be absorbed by the asphalt mixture relative to peak load and, hence, better the fatigue resistance will be. Therefore, FI values can be applied to compare the rejuvenator's ability to impart ductile behaviour.

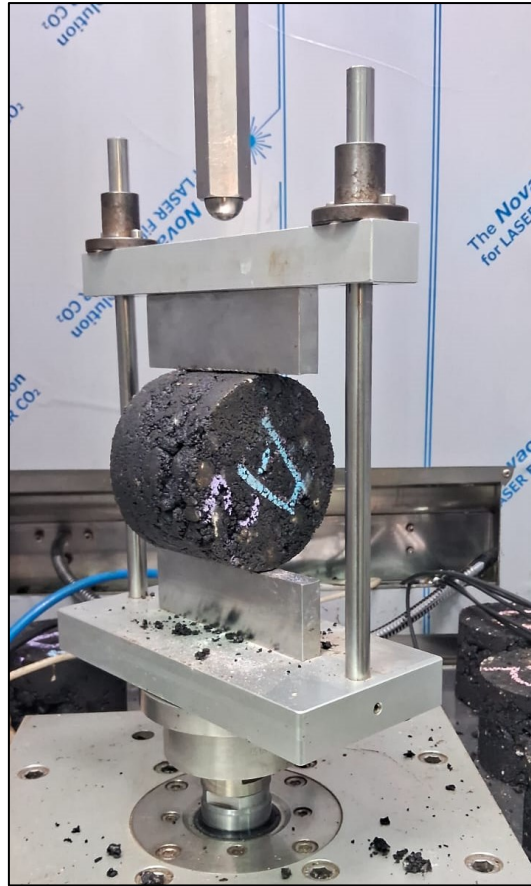


Figure 3-11 IDEAL CT test setup

3.8.1.5 Indirect tensile strength test

Moisture damage, as explained by Lottman et al. [238], is the "Loss in the mechanical properties of asphalt mix due to the disintegration of an intrinsic property of asphalt aggregate layer by moisture entry and may or may not accompanied with the loss of pavement serviceability". Moisture affects the durability of asphalt mixes and is proven to be the cause of major distress [239,240] [241,242]. Modified Lottman test is conducted in this study as per ASTM D4867 [243] to assess the moisture resistance of the recycled mixes. Indirect tensile strength (ITS) of the mixes in dry (ITS_{dry}) and wet (ITS_{wet}) conditions are used to calculate the tensile strength ratio (TSR). In each condition two replicas are tested and average TSR value is reported. Calculations for both ITS and TSR are given in Equations (3-4) and (3-5), respectively.

$$ITS_{dry/wet} = \frac{2000 * P_{max}}{\pi * t * d} \quad (3-4)$$

$$TSR = \frac{ITS_{dry}}{ITS_{wet}} \times 100 \quad (3-5)$$

Where $ITS_{dry/wet}$ = indirect tensile strength in dry or wet condition, P_{max} = maximum load sustained by a mix when loaded at the rate of 50.8 mm/min, t = thickness (height) of the sample in mm, d = diameter of the sample and TSR = tensile strength ratio. ITS_{dry} is the tensile strength of the samples with $7\% \pm 0.5\%$ air voids and conditioned in a water bath at $25^{\circ}\text{C} \pm 1^{\circ}\text{C}$ for $2 \text{ h} \pm 10 \text{ min}$. ITS_{wet} is the tensile strength of the samples with $7\% \pm 0.5\%$ air voids and first conditioned in a water bath at $60^{\circ}\text{C} \pm 1^{\circ}\text{C}$ for $24 \text{ h} \pm 10 \text{ min}$ and then followed by conditioning in water bath $25^{\circ}\text{C} \pm 1^{\circ}\text{C}$ for $2 \text{ h} \pm 10 \text{ min}$. Usually, TSR value should be greater than 80% for a sample to have proper moisture resistance [244].

3.8.1.6 Resilient Modulus

Resilient modulus (M_r) represents the elasticity of an asphalt mix, since the recoverable strain is considered for the calculations [245]. It is evaluated by conducting repeated-load indirect tension tests following the procedure outlined in ASTM D 4123 (2006). M_r is calculated as follows:

$$M_r = \frac{P(\mu + 0.27)}{t * \Delta H} \quad (3-6)$$

where M_r = resilient modulus, P = repeated load applied, μ = Poisson's ratio, t = sample height, ΔH = horizontal deformation. A cyclic load of the pulse (haversine) width of 0.1 s and a repetition period of 1 s is applied to the samples. Load is taken as 10% of ITS load to ensure elastic strains in the sample. Also, the Poisson's ratio is assumed to be 0.35, which is reasonable given the test temperature of 25°C [246,247]. Studies showed that resilient modulus is sensitive to the waveform, test temperature, load (duration and amount), maximum nominal aggregate

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size and frequency [248–251]. Therefore, all the parameters are kept constant throughout the study to ensure values are affected only by aging time.