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A new paradigm in rutting evaluation: The concept of rutting tolerance temperature (RuTT) for asphalt mixtures

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ABSTRACT

Rutting is a primary distress in flexible pavements caused by excessive traffic loads and high temperatures leading to permanent deformation along wheel paths. Ensuring rutting resistance requires careful selection of asphalt binder, aggregate type, and aggregate structure. While SUPERPAVE high-temperature performance grading (PG) selects binders based on stiffness (G*/sin δ), binder properties alone are insufficient as aggregate characteristics also significantly influence mixture performance. Evaluating rutting at a single temperature provides only comparative performance and does not determine the mixture's tolerance under field conditions. This study introduces the Rutting Tolerance Temperature (RuTT) as a comprehensive metric integrating binder and aggregate properties to assess rutting resistance. Four binders (VG30, VG40, PMB40, CRMB60) and three aggregates (Dolomite, Granite, Sandstone) were used. Binder performance was assessed via high PG test, while aggregate effects were evaluated through uncompacted void content (UVC) and angle of repose (AoR). Asphalt mixtures were tested using IDEAL-RT, Hamburg wheel tracking (HWTT), and high-temperature indirect tensile strength (HT-IDT). RuTT was established from IDEAL-RT and validated with HWTT and HT-IDT results. Polymer-modified binders demonstrated superior rutting resistance while Dolomite with higher angularity and surface texture outperformed Granite and Sandstone. RT_{index} values increased with UVC and AoR highlighting the role of aggregate interlocking. RuTT results revealed that the same binder exhibited different tolerance temperatures with different aggregates; for example, VG30 (PG 58) showed RuTT values of 52°C, 58°C, and 46°C for Dolomite, Granite, and Sandstone. The study confirms RuTT as a reliable parameter for screening and selecting asphalt mixtures based on actual temperature conditions.

1. Introduction

Flexible pavements are most common type of pavement used for construction of road to provide smooth and durable surfaces [1–4]. The performance of flexible pavements is significantly affected by traffic loads and environmental conditions, leading to various types of distresses such rutting, fatigue cracking, and moisture damage [5–8]. Among these distresses, rutting is one of the major distresses in flexible pavement generally characterized by the permanent deformation of the pavement surface along the wheel path [9,10]. Total rutting in pavement surface can be a result of cumulative permanent deformation of various layers in pavement such asphalt layer, base, subbase, and subgrade [11]. The focus of current study is only aligned with rutting of asphalt layer, which primarily occurs due to excessive traffic loading and temperatures. The most severe condition for rutting is excessive traffic loading under high-temperature conditions, where the asphalt mixture loses its structural integrity. Consequently, rutting can degrade ride quality and increase the risk of hydroplaning potentially leading to traffic accidents [9].

There are various factors responsible for the rutting failure of asphalt layer such as excessive traffic loading, excessive temperature condition, softer grade of binder, poor aggregates etc [7,12,13]. Although, traffic loading and environmental conditions are duly considered in pavement design; however, their actual occurrence, magnitude, and variability remain beyond the control of pavement engineers. From a material selection and mixture design point of view, rutting can be controlled by

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providing higher stiffness or polymer modified binder and better aggregate skeleton having high internal angle of friction [5,14,15]. These two factors play major role in determining the rutting performance of asphalt mixtures. Past studies highlighted that the use of polymer modified binder and high stiffness binder results into better rutting performance of asphalt mixture [9,16–18]. Research by Airey et al. has further emphasized the influence of binder modification, particularly with elastomeric polymers, in improving rutting resistance [19]. Studies by Shenoy and Zoorob & Suparma have also demonstrated that crumb rubber-modified asphalt exhibits better rutting performance due to its ability to enhance binder elasticity and high-temperature stiffness [20,21]. Additionally, Yildirim (2007) reviewed the effectiveness of polymer-modified binders, confirming their superiority in rut resistance compared to conventional asphalt binders [22].

To characterize the asphalt binder for rutting, the Superpave performance grading system introduced the parameter, G*/sin δ based on complex shear modulus (G*) and phase angle (δ). This parameter was improved with the introduction of non-recoverable creep compliance and elastic recovery [23–26]. Field Studies have shown that asphalt binders with a specified performance grade may still experience rutting failure before reaching their designated temperature [27–29]. For example, it is not uncommon that a binder with high PG of 64 fails in rutting before reaching that particular temperature especially in a tropical country like India. This suggests that either the specifications limits for binder grading must be calibrated using local conditions or the aggregate type and structure play a dominant role in dictating overall rutting performance of the asphalt mixture. The focus of study is on the latter. Previous studies have demonstrated that binder stiffness alone is insufficient to predict rutting performance accurately and emphasised the need for a comprehensive rutting evaluation at mixture level approach [30–33]. Kim et al. have shown that the consideration of impact of aggregate gradation and shape on permanent deformation is important factor for ensuring better rutting resistance of asphalt mixture [34]. Other recent studies have also shown that the same asphalt binder showed different value of stability with aggregate having different angle of repose (AoR) and uncompacted void content (UVC) [35–37]. This implies the consideration of aggregate properties for characterising the rutting performance of asphalt mixture. Past studies also suggest the use of shape tests, angle of repose, uncompacted void content, angularity test for aggregate for better rutting performance of asphalt mixture [35, 37–40]. Again, aggregate tests alone are not sufficient to fully characterize the rutting potential of asphalt mixtures as they do not account for the complex interactions between aggregates and binders under traffic loads and varying environmental conditions. A comprehensive assessment requires for entire asphalt mixture to better predict its rutting resistance based on performance testing. To this end, various performance indicator tests such as Hamburg wheel tracking test, flow number test, dynamic creep test, Ideal shear asphalt rutting test, etc have been developed for selection of asphalt mixture for better rutting performance [41–46]. These tests screen an asphalt mixture for rutting by adopting a threshold value at one particular temperature.

Evaluating rutting performance of asphalt mixture at a particular high temperature (for example 60 °C) does not necessarily indicate the suitability of an asphalt mixture for actual temperature conditions in field. Testing asphalt mixture for rutting at a single high temperature only gives comparative performance of asphalt mixture to see which one perform better but does not establish the temperature tolerance limit of the asphalt mixture. A mixture that performs well at one temperature may still fail under prolonged temperature changes and traffic conditions in field. Therefore, temperature tolerance limit of asphalt mixture could be assessed under a wider range of real-world conditions to define failure temperature of asphalt mixture in addition to the asphalt binder. This can be possible by introducing the concept of rutting tolerance temperature (RuTT) of asphalt mixture. In this study, the concept of rutting tolerance temperature has been introduced for selection of asphalt mixture according to temperature. RuTT is the temperature of asphalt mixture at which an asphalt mixture fails in rutting after being subjected to loading regimen. The use of rutting tolerance temperature gives better idea about suitability of asphalt mixtures under actual temperature and traffic conditions. The concept of RuTT is being proposed as a novel approach to integrate both binder and aggregate properties into a single performance parameter offering a more holistic way for ensuring better rutting resistance. It is expected that the inferences of the present study would help in selecting the appropriate asphalt mixture according diverse field conditions.

2. Methodology and objectives

This study assessed the rutting performance of various asphalt binders at both binder level and mixture level using various tests. The primary objective of this study was to established the concept of RuTT for asphalt mixtures. For this study, 4 different asphalt binders, 3 different aggregates were used to address the objectives of the present study. Initially, the asphalt mixture was prepared by incorporating various aggregates and asphalt binders using Marshall mix design method. At binder level, the rutting performance of all binders was assessed using high performance grade. At mixture level, IDEAL RT test was used to assessed the rutting performance of asphalt mixture prepared using various binder and aggregates over the temperature range of 46°C-82 °C. To investigate the effect of aggregate properties on rutting performance of asphalt mixture, angularity and packing of aggregate gradation were evaluated through various test such as uncompacted void content (UVC) and angle of repose (AoR) test. The relationship between aggregate properties and RT_{index} was subsequently studied to understand the effect of aggregate properties on rutting performance of various binder. Thereafter, the outcomes of IDEAL RT were used to determine the rutting tolerance temperature (RuTT) based on RT_{index}. Further, the concept of rutting tolerance temperature was validated using Hamburg wheel tracking test (HWTT) and high temperature indirect tensile test (HT-IDT). Finally, the results of test were analysed in order to improve the guidance and knowledge about the high temperature suitability of asphalt binders for flexible pavement. Fig. 1 illustrates the work plan of the study. The objectives of current studies are as follows:

- To investigate the influence of type of asphalt binders and aggregate properties on rutting performance of asphalt mixture.
- To study the relationship between aggregate properties and various rutting parameters such RT_{index}, rut depth, and HT-IDT.
- To provide insights into determining the rutting tolerance temperature based on rutting parameters at mixture level.

2.1. Materials

Four different types of asphalt binders: two viscosity grade binders: VG30 and VG40, one polymer modified binder (PMB40) and one crumb rubber modified binder (CRMB60) have been used in this study. Three types of aggregate: Granite, Sandstone, and Dolemite have been selected for preparation of asphalt mixtures. The physical properties of selected binders and aggregates are shown in Table 1.

2.2. Mix design

Asphalt mixes were prepared using the Marshall mix design, in accordance with Asphalt Institute specification (MS-2), utilizing bituminous concrete (BC) gradation with a nominal maximum size of aggregate −19 mm as mentioned in Ministry of Road Transport and Highways (MoRTH) [47]. The mid-point gradation was adopted for preparation of asphalt mixtures. The gradation adopted for the study is shown in Fig. 2. The sample was mixed at their respective mixing temperatures as shown in Table 2. A loose asphalt mixture was prepared and

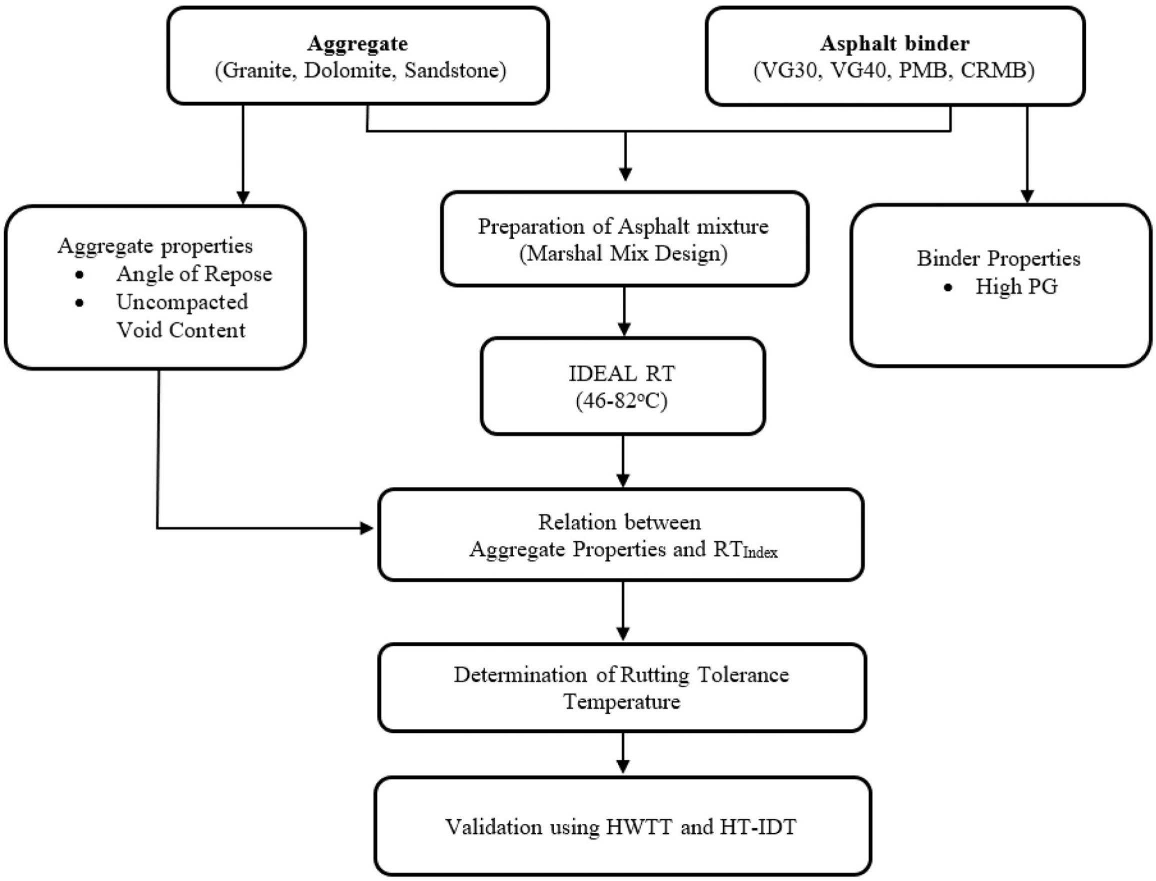


Fig. 1. Workplan adopted for the study.

Table 1
Material selection summary.

Material	Type	Asphalt binder properties				
		Penetration value (dmm), ASTM D5	Softening Point (°C), ASTM D36	Absolute viscosity at 60° C (Poise), ASTM D2171	Elastic recovery of half thread in ductilometer at 15°C (%), ASTM D6084	High Performance Grade, ASTM D7175
Asphalt Binder	VG30	55	49	2847	-	PG58
	VG40	44	57	3980	-	PG64
	PMB40	41	72	-	92	PG76
	CRMB60	45	62	-	71	PG76
Aggregate	Type	Aggregate properties				
		Specific gravity, ASTM C127	Aggregate impact value (%), ASTM D5874	Combined elongation and flakiness index (%), ASTM D4791	Los Angeles abrasion value (%), ASTM C131	
	Granite	2.721	18.5	22.5	22	
	Dolomite	2.734	13.4	20	18.9	
	Sandstone	2.651	23	24.5	28.1	

subjected to short-term aging (STA) by conditioning in a draft oven for 4 h at the respective compaction temperatures (Table 2), following the AASHTO R30 protocol. The Marshall Compactor was used to compact the conditioned loose mixtures into cylindrical specimens. For determination of optimum binder content (OBC), specimens were compacted using 75 blows per side. For performance testing (IDEAL-RT, Hamburg Wheel Tracking Test, and HT-IDT), specimens with approximately 7 % air voids were required. To achieve this, a compaction trial was conducted by plotting the relationship between air voids and the number of blows. For 100 mm diameter specimens (IDEAL-RT and HT-IDT), 33 blows were required for sandstone mixes, 35 blows for granite mixes, and 36 blows for dolomite mixes. For 150 mm diameter specimens (Hamburg Wheel Tracking Test), 39 blows were required for sandstone mixes, 42 blows for granite mixes, and 44 blows for dolomite mixes to achieve the target air voids. The OBC for each mixture was determined corresponding to 4 % air voids. Marshall mixture design parameters corresponding to OBCs for each mixture are shown in Table 2. The OBC of all asphalt mixtures varied from 5.2 % to 5.4 % (corresponding to 4 % air voids). Asphalt content of 5.3 % for preparation of asphalt mixture was deliberately kept constant to nullify the effect of asphalt content on rutting performance of asphalt mixture. Air voids corresponding to bitumen content of 5.3 % was measured and found to be 3.83–4.15 %. The variation in air voids is statistically insignificant (p-value>0.05). The voids in mineral aggregates (VMA) ranged from 13.2 % to 13.8 %. The voids filled with bitumen (VFB) ranged from 69.3 % to 72.1 %. All the volumetric properties of asphalt mixtures satisfied the criteria

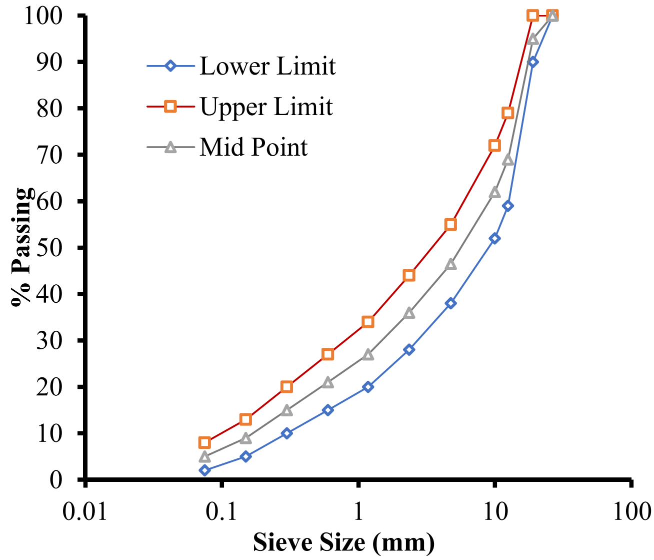


Fig. 2. Aggregate gradation adopted in the study.

mentioned in the Ministry of Road Transport and Highways (MoRTH 2013) guidelines [47].

3. Experimental plan

3.1. High temperature performance grading

In this study, the high temperature PG was determined using a dynamic shear rheometer. The purpose of the test is to evaluate the temperature up to which all binders are suitable for rutting. In the present research work, only the high-temperature PG was evaluated. High temperature performance grade of different binders was assessed using the rheological parameter, G*/sinδ. This property of asphalt binder was related with the rutting performance of the binder [48,49]. The performance grade test was performed on the short term aged asphalt binders considering the strain level of 10 % and frequency of 1.59 Hz as per ASTM D7175 [50]. The test was performed using a parallel plate geometry with a 25 mm diameter and 1 mm gap width. The temperature at which G*/sinδ is greater than 2.2 kPa is considered as true failure temperature. The lowest PG corresponding to the true failure temperature is reported for the asphalt binder. In this study, the true failure temperature and performance grade was evaluated for all the binders. It is noted that, according to the standard PG system, the upper high temperature grade is typically determined considering both unaged and short-term aged binder criteria. However, in this study, the upper PG was determined solely from the short-term aged binder using G*/sinδ (ASTM D7175). This approach was adopted to reflect realistic field conditions as rutting generally occurs after the binder has undergone short-term aging during production and construction. Furthermore, since the Rutting Tolerance Temperature (RuTT) of mixtures in this study was also determined after short-term aging, this methodology ensures consistency and provides a more application-oriented evaluation of the binder's high-temperature performance.

3.2. Aggregate characterization

One of the objectives of this study was to assess the effect of aggregate properties on rutting performance of asphalt mixture. Aggregate characterization was carried out to determine the properties of aggregate used in the study. Two properties: Uncompacted void content (UVC) and angle of repose (AoR) were measured in this study for aggregates.

3.3. Uncompacted void content

In this study, the uncompacted void content (UVC) of different aggregates was evaluated using the fine aggregate angularity test for aggregates. The UVC gives idea about angularity and surface texture (sphericity) of aggregates used in asphalt mixtures [36]. UVC is important because higher number of rounded aggregates can lead to rutting failure. The lower UVC indicates higher rounded particles and vice-versa. The higher UVC of aggregate is desirable for better performance against rutting [35]. In this study, the UVC measurements of different aggregates were performed using specific equipment represented in Fig. 3. The equipment functions as a larger version of the fine aggregate angularity test equipment specified in ASTM C1252. This equipment consists of a 145 mm diameter x 200 mm high holding container which features a hinged gate located at its base section. The testing equipment utilized a known-volume metal cylinder positioned below the holding container to collect aggregates that fell from the holding container. To measure UVC, a five kg blended aggregates was poured into a holding container and levelled. The hinged gate was then opened, allowing the aggregate to fall into a metal cylinder. Excess material was levelled and the weight of collected aggregates was recorded. UVC was calculated using Eq. 1 based on mass of aggregate filled in cylinder (M), volume of cylinder (V), and specific gravity of aggregate blend (SG).

$$UVC = \frac{V - \frac{M}{SG}}{V} \times 100 \tag{1}$$

3.4. Angle of repose

Angle of repose (AoR) of aggregate can be used as a measure of in-

Table 2
Asphalt mix design parameters.

Binder type	Mixing temperature (°C)	Compaction temperature (°C)	Aggregate type	Mixture ID	OBC (%)	Bitumen content for asphalt sample preparation	Air Voids (%)	VMA (%)	VFB (%)
VG30	163	148	Granite	GV30	5.3	5.3	4.0	13.5	70.3
			Dolomite	DV30	5.4	5.3	4.1	13.6	69.9
			Sandstone	SV30	5.35	5.3	4.0	13.4	69.8
VG40	168	153	Granite	GV40	5.25	5.3	3.9	13.3	70.3
			Dolomite	DV40	5.3	5.3	4	13.4	70.1
			Sandstone	SV40	5.35	5.3	4.0	13.5	69.9
PMB40	173	156	Granite	GP	5.2	5.3	3.9	13.7	71.5
			Dolomite	DP	5.4	5.3	4.1	13.7	69.7
			Sandstone	SP	5.4	5.3	4.1	13.8	70.3
CRMB60	175	158	Granite	GC	5.35	5.3	4.05	13.2	69.3
			Dolomite	DC	5.2	5.3	3.85	13.8	72.1
			Sandstone	SC	5.2	5.3	3.83	13.7	72.0
Minimum specified limits					5.2		3–5	Min.12	65–75

Fig. 3. Experimental setup for UVC.

ternal angle of friction between aggregates [37,51]. The higher angle of repose is an indicator of more angular aggregates which are favourable for rutting resistance of asphalt mixtures [51]. Therefore, higher angle of repose of aggregates is desirable for better performance against rutting. This study involved measurement of angle of repose for aggregates greater than 2.36 mm (coarse aggregates). The coarse aggregates were considered due to the fact that the shape and texture of coarse aggregate is important for better rutting performance of asphalt mixture. Apparatus was fabricated in lab based on ASTM C1252 for measuring the angle of repose (AoR) of aggregates larger than 2.36 mm. The study measures only external angle of repose as shown in Fig. 4. It consists of a cylindrical container with a diameter of 300 mm and a height of 310 mm, with a metal disk featuring a 130 mm internal opening as the base plate. A raised circular plate beneath the holding cylinder captures aggregates that fall through the hinged gate, forming a heap. The height of the heap (h) and the diameter of the circular plate (d) are then used to

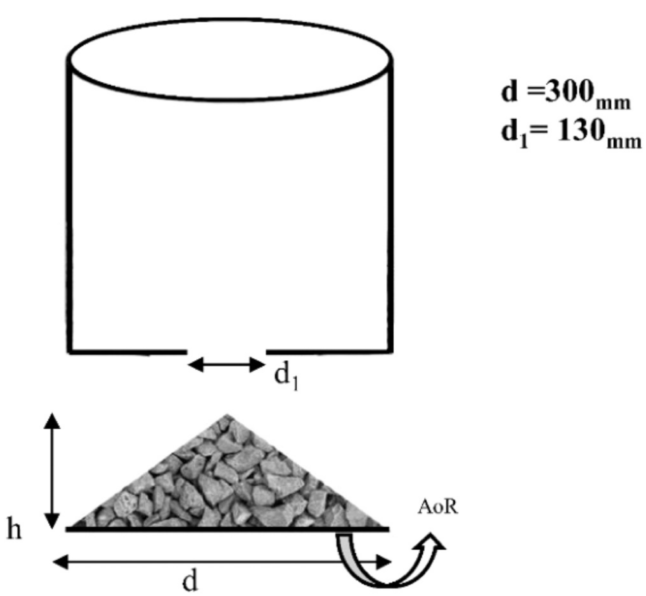


Fig. 4. Schematic of experimental setup for angle of repose.

compute the angle of repose (AoR) using Eq. 2.

$$AoR = \tan^{-1}\left(\frac{2h}{d}\right) \tag{2}$$

To measure the AoR, aggregates were filled to a consistent height in the holding container, levelled, and the hinged gate was then opened to allow aggregates above the opening to fall while those closer to the periphery remain in place. The heap was formed on circular plate beneath the holding cylinder. The height of the heap was measured at least three times (spaced 90 ° apart) during each trial. The averaged value from these measurements is used for calculations of AoR.

3.5. Rutting test: ideal shear asphalt rutting test (IDEAL-RT)

The rutting performance of various asphalt mixtures were assessed using simple performance test such IDEAL-RT test. This test measures the shear strength of asphalt mixture as a surrogate measure of rutting performance [42,43,52]. The shear fixture which has two supports at bottom has been used for the test, as shown in Fig. 5(a). This Shear fixture created two shear planes to induce shear stress inside specimens for simulating rutting failure. This setup was designed to reproduce shear failure mechanisms which occur during rutting. This test was performed on asphalt mixtures prepared using asphalt binders used in the study by applying loading rate of 50 mm/min as per ASTM D8360. In this study, the test was carried on asphalt mixture at various temperatures ranges from 46 °C to 82 °C with increment of 6 °C in temperatures as done in SUPERPAVE high performance grading. The samples were conditioned at test temperature using conditioning chamber. These temperatures regimes where selected to determine the rutting tolerance temperature of asphalt mixture based on rutting tolerance index (RT_{index}) parameter. The details of rutting tolerance temperature are discussed in subsequent section. The test involved calculation of shear strength based on load-displacement curve using Eq. 3 mentioned in ASTM D8360–22. Fig. 5(b) shows typical load-displacement curve obtained from IDEAL RT test. The rutting tolerance index (RT_{index}) based on shear strength was calculated using Eq. 4, outlined in ASTM D8360–22.

$$T_f = 0.356 \times \frac{P_{max}}{h \times w} \tag{3}$$

$$RT_{index} = 6.618 \times 10^{-5} \times \frac{T_f}{1Pa} \tag{4}$$

Where,

T_F = Shear strength (Pa)
h = thickness of sample (m)
w = width of upper loading strip (m)
P_{max} = Maximum load carried by sample up to failure (N)
RT_{index} = Rutting tolerance index

3.6. Determination of rutting tolerance temperature

Rutting Tolerance Temperature (RuTT) is a parameter proposed based on rutting performance of asphalt mixture. It is defined as the temperature at which an asphalt mixture loses its ability to resist rutting. Unlike traditional SUPERPVAE performance grading, which is based solely on asphalt binder properties (G*/sinδ), rutting tolerance temperature is determined based on the rutting resistance of the asphalt mixture. The RuTT followed the concept of SUPERPAVE Performance Grading (PG) system to grade asphalt binders, but it uses the properties of asphalt mixtures. The concept of RuTT was introduced due to fact that the asphalt binder having particular high PG value may perform differently at mixture level due to variation in aggregate matrix and angularity properties. Therefore, it is beneficial to grade at mixture level in addition to the binder level. Establishing a RuTT parameter for different mix designs will allow material engineers to make more

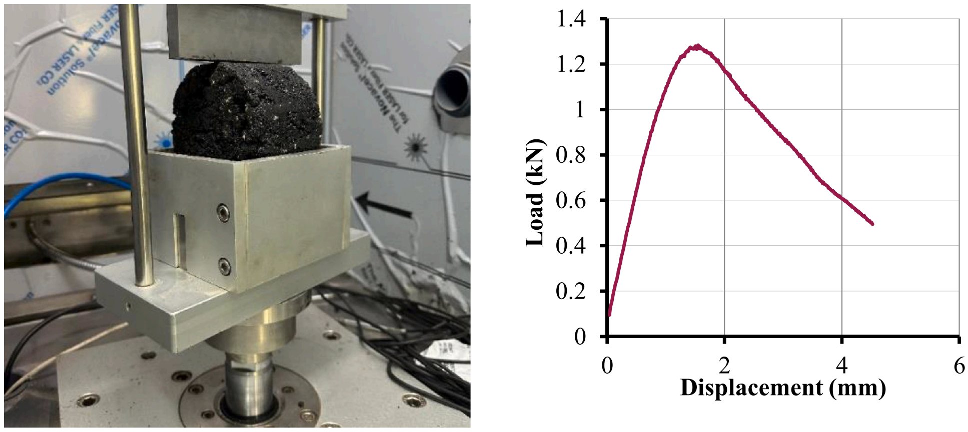


Fig. 5. IDEAL RT test a) experimental setup for IDEAL RT test b) typical load-displacement curve during IDEAL RT test.

efficient use of overperforming or slight, underperforming mixtures. Beyond experimental observations, the RuTT concept is mechanistically supported by the viscoelastic behavior of asphalt mixtures. As temperature increases, binder stiffness decreases, aggregate interlock weakens, and the mixture's ability to resist shear stresses reduces. The point at which the applied shear stresses exceed the mixture's temperature-dependent load-bearing capacity corresponds to a sharp reduction in its rutting tolerance. RuTT therefore represents the critical temperature at which the mixture transitions from a structurally stable state to a rut-susceptible state. This theoretical basis aligns with the fundamental mechanics of permanent deformation in asphalt mixtures.

To determine RuTT, the threshold value of rutting parameter (RT_{index}) is required. In this study, the rutting tolerance temperature is defined as the temperature at which rutting parameter (i.e. RT_{index} in this study) reduced to the prescribed threshold value. This threshold-based approach ensures that RuTT reflects a mechanistic limit where internal resistance mechanisms (binder stiffness and aggregate interlock) collectively become insufficient to resist permanent deformation. The determination of rutting tolerance temperature is discussed in subsequent section.

3.7. Validation of RuTT

To check the suitability of this concept for determination of RuTT at mixture level, validation is necessary. In this study, the validation was carried out using two tests: Hamburg wheel tracking test (HWTT) and high temperature indirect tensile strength test (HT-IDT), shown in Fig. 6. Hamburg wheel tracking test is found to be best test for rutting evaluation of asphalt mixture and has a good correlation with field rutting [53–55]. Thus, it is chosen for validation of RuTT. For validation purpose, the HWTT was performed only on asphalt mixtures prepared using VG40 asphalt binder and all three types of aggregates. The focus of validation was to highlight the effect of aggregate type on rutting performance. Only VG40 was used for validation purpose to avoid redundancy in the presentation of results as similar trends were expected with other binders. The test was performed in accordance with AASHTO T324. The samples used for the test was conditioned at testing temperature of 46 °C, 52 °C, 58 °C, and 64 °C for 1 h prior to testing. The test was performed at specified temperature by applying load of 705 N with rate of 52 pass/minutes on the set of two samples (having 7 % air voids) as used in HWTT. The test was stopped when rut depth reaches to 20 mm or 20000 passes, whichever occurs first. In this test, rut depth (in mm) was measured at each specified temperature when samples reached to 20000 passes. Lower value of rut is desirable for better performance against rutting. To gain further confidence in this concept, validation was also carried out using the High-Temperature Indirect Tensile Test (HT-IDT). Unlike the IDEAL-RT test, which directly characterizes the shear failure of the mixture, HT-IDT provides an indirect assessment of rutting potential by evaluating the stiffness of asphalt mixtures at elevated temperatures. Although it is a qualitative test and does not precisely measure permanent deformation, it offers useful insights into the mixture's stiffness and overall resistance to rutting [56,57]. Past

(a) (b)

Fig. 6. Experimental setup a) Hamburg wheel tracking test b) High temperature indirect tensile strength test.

studies correlate this stiffness with rutting performance of asphalt mixture [56,58,59]. As qualitative and validation aspect, the HT-IDT was performed on cylindrical specimen of asphalt mixtures prepared using VG40 binder and all three types of aggregates by applying monotonic load of 50 mm/min. The test was performed at various temperature ranges from 46 °C to 82 °C with increment of 6 °C. The higher of HT-IDT is better for superior rutting performance.

4. Results and discussion

4.1. High temperature performance grading

Table 3 presents the true failure temperature and corresponding performance grading (PG) of various asphalt binders based on G*/sinδ parameter using DSR. Since VG40 binder has higher viscosity (stiffness) as compared to VG30 binder, its true failure temperature was found to be 67.9°C which higher than VG 30 (60.2°C). The corresponding performance grade of VG30 and VG40 was PG58 and PG64, respectively. Generally, the modified binders (PMB40 and CRMB60) exhibit higher performance grade as compared to viscosity grade binders due to presence of polymeric network of elastomers and crumb rubber particles in them which imparts stiffness to the base binder and increases their rutting performance [6,60]. Both PMB40 and CRMB60 exhibited superior high-temperature performance with failure temperatures of 80.1°C and 78.8°C, respectively. Both the modified binders were graded as PG76.

4.2. Aggregate characterization

As discussed earlier, one of the objectives of this research was to assess the effect of aggregates properties on rutting performance of asphalt mixtures. The variation of UVC and angle of repose for various aggregates are presented in Fig. 7. It can be observed that the Dolomite aggregates showed higher UVC and AoR followed by Granite and Sandstone aggregates. This can be due to higher angularity and rough surface texture of Dolomite aggregates as compared to Granite and Sandstone aggregates. The UVC of Granite, Dolomite, and Sandstone was measured to be 47.6 %, 53.2 %, and 41.1 %, respectively. In case of UVC measurement, each individual aggregate particle tries to settle into its most favourable equilibrium position when poured into metal containers. Aggregate particles with smooth surfaces and rounded shapes (like Sandstone in this study) create denser compaction through the impact of other aggregates from falling from above holding container as compared to rough aggregates. This compaction (settling) mechanism can be a reason for reduction in UVC of aggregates with increase in aggregate smoothness from Dolomite to Sandstone. In case of angle of repose measurement, AoR of Granite, Dolomite, and Sandstone was measured to be 47.6 %, 53.2 %, and 41.1 %, respectively. Dolomite showed higher AoR as compared to other aggregates. This can be due to the fact that the Dolomite aggregate (angular aggregates) particles did not facilitate sliding of particles, results in proper formation of heap and slope of cone structure. The aggregate angularity shifts from high (Dolomite) to low (Sandstone) resulted in decreasing trends for AoR. The UVC and AoR properties of aggregate were used as a metrics to compare the aggregates of different surface texture and angularity, which has a major impact on rutting performance of asphalt mixtures. It is expected that the aggregate with higher UVC and AoR will exhibit better rutting performance. The effect of these aggregates properties on rutting performance has been discussed in next section.

Table 3
True failure temperature and high temperature PG based on G*/sinδ parameter using DSR.

Binder Type	True Failure Temperature (°C)	High PG
VG30	60.2	PG58
VG40	67.9	PG64
PMB40	80.1	PG76
CRMB60	78.8	PG76

4.3. Ideal shear asphalt rutting test (IDEAL-RT)

The results of RT_{index} obtained from IDEAL-RT test for various asphalt mixture for temperature ranges from 46 °C to 82 °C are shown in Fig. 8. It can be observed that the RT_{index} values decreased with increase in temperature, irrespective of all binders and aggregates. This is due to the reduction in stiffness of the asphalt binder. The results of RT_{index} were used to evaluate the influence of asphalt binder and aggregate properties on rutting performance of asphalt mixtures. The high value of RT_{index} of asphalt mixture is desirable for better performance against rutting.

4.4. Effect of binder type

Fig. 8(a), Fig. 8(b), and Fig. 8(c) show the variation of RT_{index} with temperature of all asphalt binders for Granite, Dolomite, and Sandstone, respectively. It can be observed that the RT_{index} values were higher for PMB40 followed by CRMB60, VG40, and VG30 for a given aggregates type. This is expected due to higher stiffness of modified binders as compared to viscosity grade binders. For any given binder type and temperature, the value of RT_{index} were higher Dolomite followed by Granite and Sandstone aggregates. From these results, it can be found that the extent of decrease in RT_{index} values for various binder was depends upon the aggregates type. The effect of binder and aggregate type was investigated using three-way ANOVA and the results showed that the binder and aggregate type significantly affects the RT_{index} (as $p < 0.05$). The results of statistical analysis are discussed in subsequent section.

4.5. Effect of aggregate type

Fig. 9, shows the variation of RT_{index} with temperature of VG40 binder for asphalt mixture prepared using Granite, Dolomite, and Sandstone aggregate. It can be seen that the Dolomite showed higher RT_{index} values as compared to Granite and Sandstone aggregates indicating superior rutting performance of Dolomite as compared to other aggregates. This can be attributed to the higher angularity (AoR) and rough texture (UVC) of Dolomite as compared to other aggregates. This can clearly be seen from Fig. 10 (a) and Fig. 10 (b). The values of RT_{index} were increased with increase in UVC values indicating that the rough texture aggregates offered higher frictional resistance results into better performance against rutting in comparison with smooth aggregates. From Fig. 10 (b), it can be observed that the increase in AoR of aggregates increases RT_{index} value of all asphalt binders showing that the aggregates with better interlocking (angularity) exhibited superior rutting performance in comparison with low angular aggregates. Fig. 11 reinforces this observation by showing that even a high-performance modified binder paired with Sandstone (a weak skeleton) performs worse than a lower-grade VG binder combined with Dolomite (a strong skeleton). This clearly demonstrates that aggregate skeleton quality can dominate rutting performance, often outweighing binder grade. Similar trends were observed for other binders and temperatures (not shown for brevity). For same VG40 binder, different RT_{index} values were observed for different aggregates. This difference in RT_{index} values for particular aggregate can be attributed to the packing mechanism during compaction, frictional resistance of particles and better interlocking between aggregates. In addition, it also indicates that the same binder performed differently against rutting when it is used with aggregates having different packing and interlocking nature. This behaviour of binder with aggregates changes the suitability of asphalt binder for high temperature. Thus, results showed that it is better to grade asphalt binder at mixture level than binder level. To grade the asphalt binder at mixture

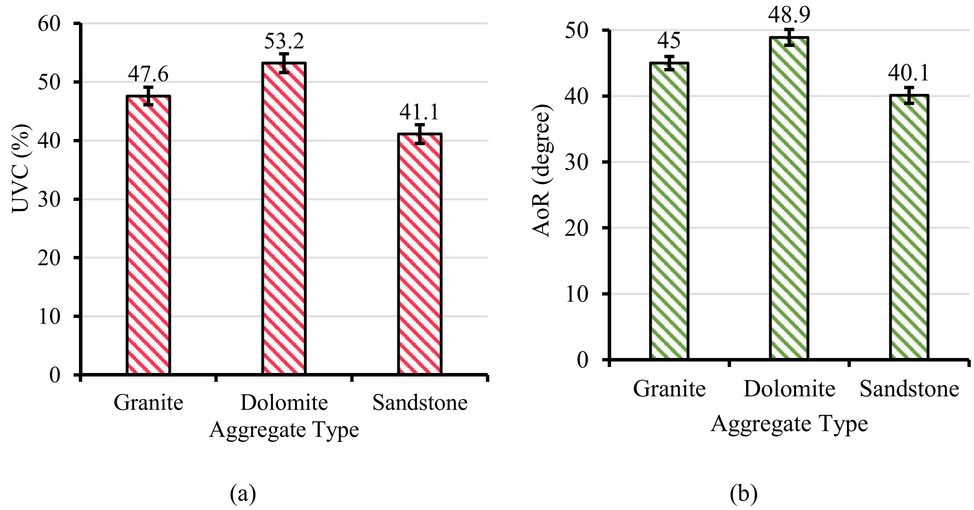


Fig. 7. Aggregate properties a) UVC b) AoR.

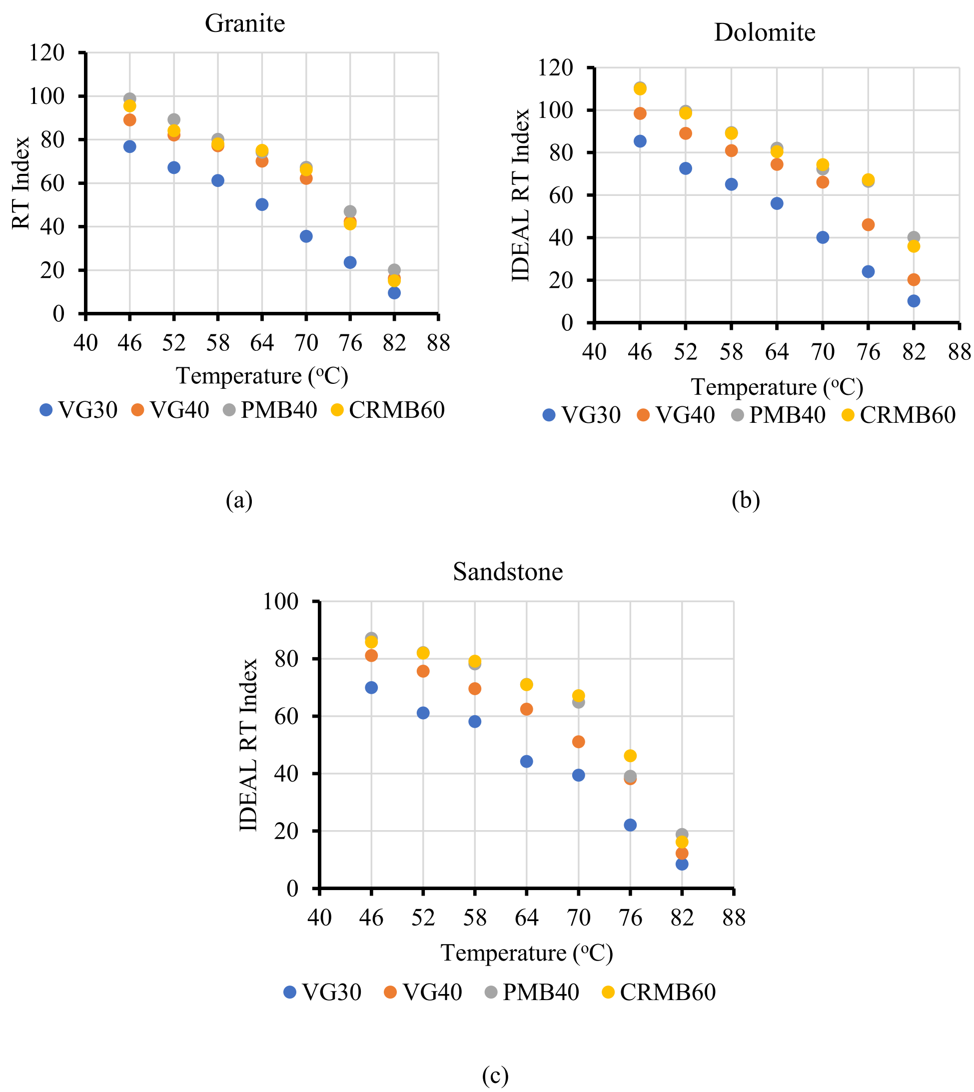


Fig. 8. RT_{index} variation with temperature for mixtures prepared with different binders using (a) Granite, (b) Dolomite, and (c) Sandstone aggregates.

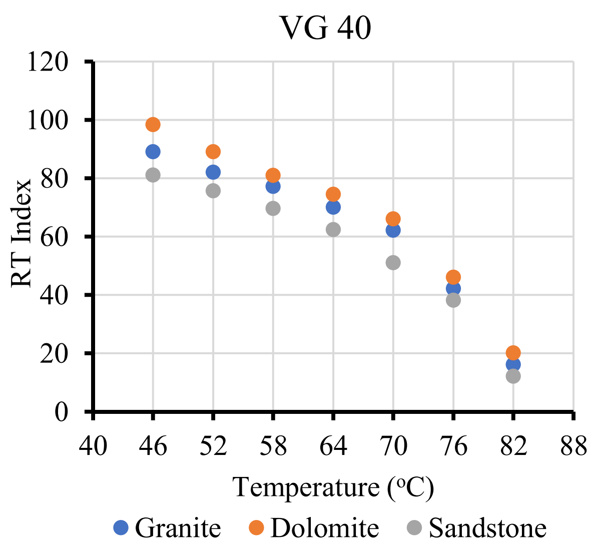


Fig. 9. Variation in RT_{index} with temperature for VG40 binder.

level, the concept of Rutting tolerance temperature (RuTT) was introduced. The determination of RuTT was done on the basis of RT_{index} versus temperature curve and selected threshold value for $RT_{index.}$ The discussion regarding determination of RuTT is found in next section.

4.6. Statistical analysis

Three-way Analysis of Variance (ANOVA) was performed to study the effect of aggregate type, binder type, and temperature on rutting parameter RT_{index}. The aggregate type, binder type, and temperature were considered as the independent variables whereas RT_{index} was considered as dependent variables. The results of statistical analysis appear in Table 4 with a confidence level of 95 % with $\alpha = 0.05$. All three independent factors including aggregate type and binder type alongside temperature strongly influence RT_{index} as shown in Table 4. This showed the importance of these parameters in governing the rutting performance of asphalt mixture. It can be observed that among the all-independent variables, as expected temperature has most significant effect on RT_{index} (as it has lower P-value). The significance of each variable on RT_{index} can be more easily understood through the 95 % confidence level main effect plots shown in Fig. 12. More importantly, the main effect plot shows that for any type of asphalt mixture, the type of aggregate is an important factor that dictates mixture rutting performance, in addition to the other two well-known factors i.e., binder type and temperature.

4.7. Determination of rutting tolerance temperature

The rutting tolerance temperature was determined using RT_{index} versus temperature curve. To determine the rutting tolerance temperature, the threshold value of RT_{index} is required. From the previous

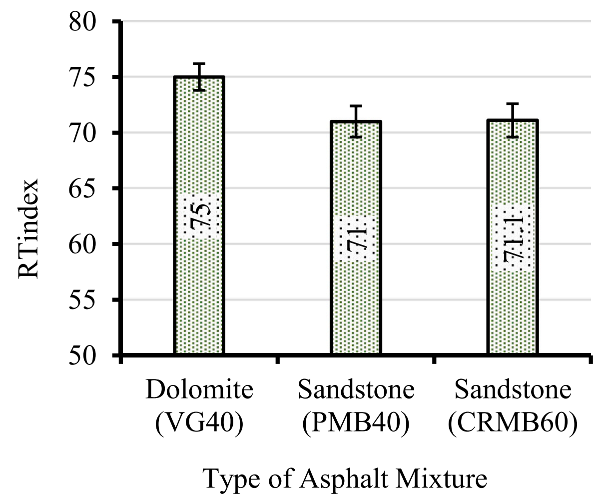
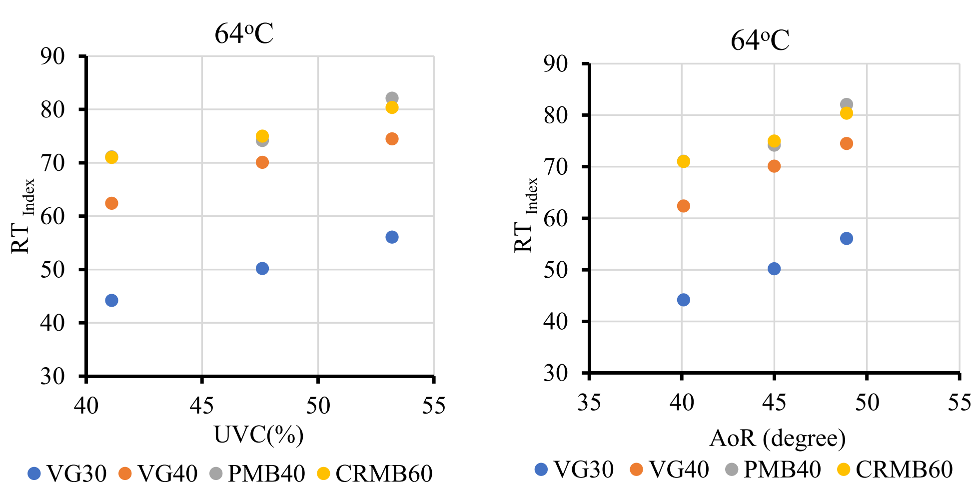


Fig. 11. Comparison of RT_{index} for various combination of binder and aggregates.

Table 4
Brief of three-way ANOVA at 95 % confidence level.

Parameter	Source	df	Mean Square	F-calculated	P- value
RT_{index}	Aggregate Type	2	1211.60	120.61	0.000002
	Binder Type	3	2509.84	249.84	0.0000151
	Temperature	6	7452.71	741.86	0.0000001
	Error	36	10.5		
	Total	83			



(a) (b)

Fig. 10. RT_{index} variation with aggregate properties at 64°C for all binder types: (a) UVC and (b) AoR.

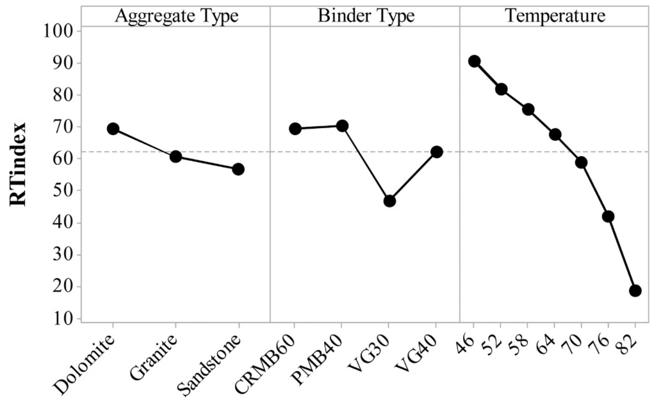


Fig. 12. Main effect plot.

Table 5
Rutting tolerance temperature (RuTT) for different asphalt binders based on RT_{index}.

Aggregate Type	Binder Type	True RuTT (°C)	Nominal RuTT (°C)
Granite	VG30	53.99	52
	VG40	66.2	64
	PMB	70.5	70
	CRMB	70.2	70
Dolomite	VG30	58	58
	VG40	71.1	70
	PMB	76.1	76
	CRMB	76.2	76
Sandstone	VG30	50.1	46
	VG40	60	58
	PMB	69.2	64
	CRMB	70.4	70

studies, it has been found that the RT_{index} value greater than 65 ensures better performance of asphalt mixture against rutting [42,43]. Therefore, RT_{index} value of 65 has been considered for determination of RuTT. This threshold of 65 was used based on previous work [42,43,61]. The temperature at which the RT_{index} value of 65 intersects the RT_{index} versus temperature curve is referred to as the rutting tolerance temperature. The testing temperature corresponding to the rutting tolerance temperature is defined as the rutting tolerance temperature (RuTT). In other words, RuTT represents the temperature at which different asphalt mixtures are expected to provide comparable resistance to rutting. Fig. 13 shows the illustration of determination of rutting tolerance temperature based on linear relationship between RT_{index} and temperature.

Table 5 shows the rutting tolerance temperature determined for all binder based on RT_{index}. In this study, two terms are used to report the rutting tolerance temperature: "True RuTT" and "Nominal RuTT." True RuTT refers to the exact temperature at which the RT_{index}-temperature curve intersects the threshold value (RT_{index}=65), obtained through linear interpolation with decimal precision. Nominal RuTT refers to the practical engineering value derived by rounding the True RuTT to the nearest whole number for ease of reporting, comparison, and mixture grading. It is evident that RuTT varies with both binder grade and aggregate type. Dolomite consistently provides higher RuTT due to its superior angularity and surface roughness, enhancing aggregate interlocking and frictional resistance, whereas Sandstone exhibits the lowest RuTT values, reflecting weaker skeleton stability. This indicates that aggregate properties can significantly influence rutting resistance, sometimes compensating the binder grade. For example, a high-performance binder (CRMB60) combined with Sandstone may perform inferior than a lower-grade binder (VG30) with Dolomite. These trends emphasise that binder-level PG alone is insufficient to predict high-temperature performance accurately. The variation of True RuTT and Nominal RuTT for the same binder across different aggregates also illustrates how mixture-level assessment is necessary for reliable rutting evaluation. For instance, VG30 (PG58) shows RuTT differences of 52°C, 58°C, and 46°C with Dolomite, Granite, and Sandstone, respectively. By introducing RuTT as a mixture-level parameter, this study provides a more accurate framework to assess high-temperature suitability, accounting for both binder and aggregate effects. To verify this aspect, the validation is necessary. The results of validation are discussed in next section.

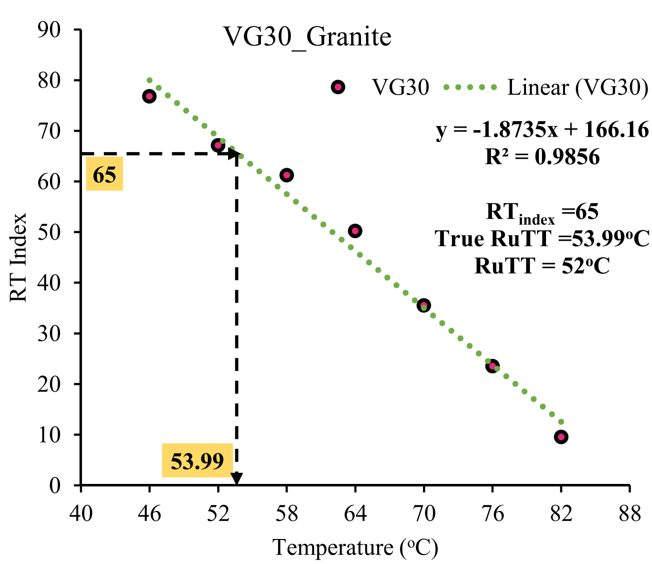


Fig. 13. Illustration of RuTT determination for VG30-Granite mixture.

4.8. *Validation of RuTT*

As mentioned above the validation of RuTT was carried out using Hamburg wheel tracking test and HT-IDT. Fig. 14 shows the variation in rut depth with temperature for all asphalt mixtures prepared using VG40 binder and three different types of aggregates. For any particular temperature, rut depth was found to higher for Sandstone as compared to other aggregates indicating poor rutting performance. This can be attributed to the smooth surface and lower angularity of Sandstone

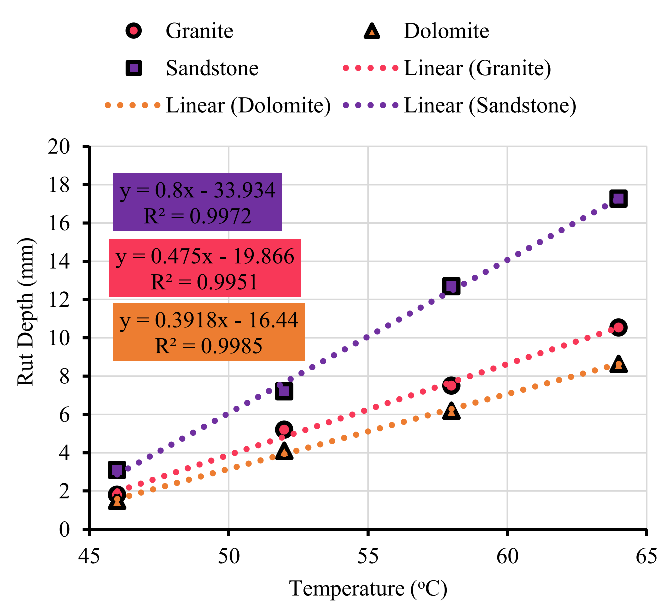


Fig. 14. Rut depth variation with temperature for VG40 mixtures using three aggregate types.

aggregates which offers less internal friction forces to resist rutting of asphalt mixture. This can be confirmed from Fig. 15. It showed that the rut depth decreased with increase in AoR and UVC of aggregates. This again reinforces that the properties of aggregates are important for understanding the rutting behaviour of asphalt mixtures. The rut verses temperature curve for various aggregates types shown in Fig. 14 was used to determine RuTT based on rut depth. To determine RuTT, the threshold value is necessary. According to previous studies, the threshold for rut depth was found to 12.5 mm, below which asphalt mixtures ensures better rutting performance [62,63]. Thus, the threshold of 12.5 mm was used in this study to determine RuTT. The temperature at which rut depth of 12.5 mm occurs is defined as true RuTT and corresponding lower testing temperature is marked as RuTT. Table 6 presents RuTT of VG40 for various asphalt mixtures. The true RuTT of VG40 for Granite, Dolomite, and Sandstone was observed to be 68.1 °C, 73.8 °C, and 58.1 °C, respectively and corresponding RuTT was found to be 64 °C, 70 °C, and 58 °C, respectively. The Dolomite showed higher RuTT as compared to other aggregates due to higher AoR and UVC. The results of RuTT obtained from HWTT was found to be comparable with IDEAL RT test. The RuTT obtained from both tests were similar indicating better validation of concept.

To gain more confidence in validation of the RuTT, a qualitative high-temperature indirect tensile test (HT-IDT) was also conducted. The indirect tensile strength (in kPa) was determined for asphalt mixtures, shown in Fig. 16. It can be observed that the HT-IDT values decreased with temperature, irrespective of aggregate types due to reduction in stiffness of asphalt mixture as results of binder softening. The rate of reduction in HT-IDT with temperature found to be lower for Dolomite aggregates due to their higher angularity and rough surface textures. Fig. 17 shows the variation of HT-IDT with aggregate properties (AoR and UVC) at 64 °C. It can be seen that the HT-IDT values increase with increase in AoR and UVC indicating that the aggregate with higher angularity and better interlocking ensures superior rutting performance. The HT-IDT verses temperature curve for various aggregates types shown in Fig. 16 was used to determine RuTT based on HT-IDT. The threshold value of 300kPa was used in this study to determine RuTT as suggested by previous literature [58,59]. The same concept was adopted as used in HWTT to determine RuTT. Table 7 presents RuTT of VG40 for various asphalt mixtures. The true RuTT of VG40 for Granite, Dolomite, and Sandstone was observed to be 66.7 °C, 70.1 °C, and 60.1 °C, respectively and corresponding RuTT was found to be 64 °C, 70 °C, and 58 °C, respectively. Dolomite demonstrated superior RuTT performance compared to other aggregates, primarily due to its higher AoR and UVC values. The RuTT results from the HT-IDT test closely aligned with those from the IDEAL-RT test. The similarity in results between the two tests reinforces the validity of the concept. It is noted that this study does not

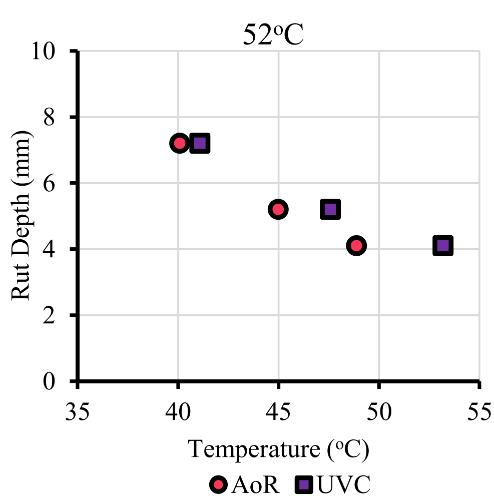


Fig. 15. Effect of Aggregate Properties on rut depth at 52°C.

Table 6
RuTT of VG40 binder for various aggregates using HWTT.

Aggregate type	True RuTT (°C)	RuTT (°C)
Granite	68.1	PG64
Dolomite	73.8	PG70
Sandstone	58.1	PG58

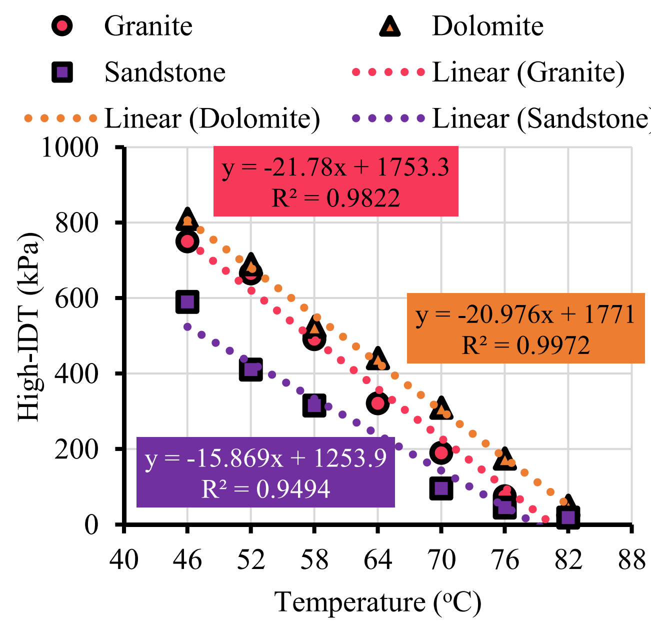


Fig. 16. HT-IDT variation with temperature for VG40 mixtures with three aggregate types.

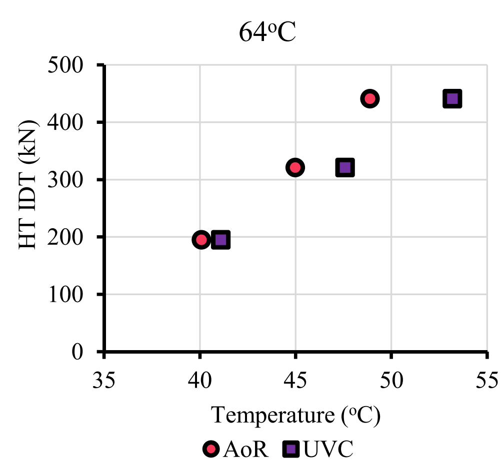


Fig. 17. Effect of Aggregate Properties on HT-IDT at 64°C.

Table 7
RuTT of VG40 binder for various aggregates using HT-IDT.

Aggregate type	True RuTT (°C)	RuTT (°C)
Granite	66.7	PG64
Dolomite	70.1	PG70
Sandstone	60.1	PG58

incorporate durability, long-term aging, and environmental factors beyond temperature because RuTT is a newly proposed mixture-level parameter, these aspects will be addressed in future work to further strengthen its applicability. Furthermore, rutting tends to diminish with aging as the mixture becomes stiffer over time. Finally, the results of all three tests indicated that binders with the same PG displayed varying RuTT values at the mixture level. These findings emphasize the need for pavement engineers to assess binder suitability at the mixture level, rather than relying solely on binder-level evaluations, to ensure better rutting performance for specific locations.

4.8.1. PG at binder level vs rutting tolerance temperature at mixture level

Specifications and standardization have an important role in the growing infrastructures by ensuring better long-lasting performance of pavements. While the existing Performance Grading (PG) system effectively classifies asphalt binders based on high-temperature susceptibility. Variation in field performance of asphalt mixtures suggests that binder grading alone may not be sufficient for precisely envisaging rutting resistance. Authors also recognize that the binder PG is a purchase specification for asphalt binder and although it is necessary to this to produce rut resistance mixture, it is not sufficient to ensure premature rutting failure. This discrepancy emphasises the need for specifications at the mixture level rather than solely at the binder level. Past studies showed that aggregate gradation and properties, especially coarse aggregate angularity, shape, and interlocking, strongly influence rutting resistance. Indicators like Uncompacted Void Content (UVC) and Angle of Repose (AoR) effectively capture aggregate skeleton effects, while fine aggregates mainly affect fatigue and are not considered here. This study introduced the Rutting Tolerance Temperature (RuTT), a mixture-level specification analogous to binder PG High but more comprehensive as it incorporates both binder and aggregate skeleton effects. Validation using HWTT and HT-IDT confirms that mixtures with identical binder PG can exhibit markedly different rutting tolerance temperatures. This establishes RuTT as a reliable parameter for mixture-specific evaluation.

4.8.2. Practical integration: RuTT can be incorporated into specifications by

- Serving as a mixture selection parameter during design,
- Acting as a performance verification criterion for plant-produced mixes, and
- Providing the foundation for a mixture-level high-temperature grading system aligned with climate and traffic demands.

By integrating the RuTT concept into mixture design specifications, pavement engineers can make more informed decisions by ensuring improved rutting resistance under diverse environmental and traffic conditions.

5. Conclusions

The key findings of the present study are as follows:

- Modified binders (PMB40 and CRMB60) showed higher true failure temperatures as compared to viscosity-graded binders (VG30 and VG40) indicating superior rutting resistance.
- Results of UVC and AoR showed that the Dolomite aggregates showed higher angularity followed by Granite and Sandstone. The angularity along with surface texture of aggregates proved to have substantial effects on rutting performance of asphalt mixtures. Dolomite aggregates with higher UVC and AoR values exhibited superior rutting resistance compared to Granite and Sandstone.
- The results of IDEAL RT test showed that the rutting performance of asphalt mixture was function of binder type, aggregate type, and temperature. The same has been confirmed through three-way ANOVA. PMB 40 showed higher RT_{index} followed by CRMB60, VG40, and VG30. The rate of reduction in RT_{index} values were lower for Dolomite as compared to Granite and Sandstone aggregates, irrespective of binder type due to their higher angularity. RT_{index} values showed increasing trends with increase in AoR and UVC values indicating that the rough texture and angular aggregates offered higher frictional resistance and better interlocking which results in better rutting performance.
- The binder with same grade showed different values of RT_{index} indicating that the binder is not alone responsible for rutting failure of asphalt mixture. The aggregate properties play important role in governing rutting performance of asphalt mixtures. With these observations, the concept of RuTT has been introduced demonstrating that asphalt binder performance varies depending on the type of aggregate used. RuTT provided a more comprehensive evaluation of rutting resistance at the mixture level rather than relying solely on binder grading. The results of RuTT showed that the binder having one PG at binder level showed different RuTT due to different properties of aggregates. For example, VG30 has high performance grade of PG58. But it showed different RuTT for different aggregates. RuTT of VG30 for Dolomite, Granite, and Sandstone was found to be 52 °C, 58 °C, and 46 °C.
- The HWTT and HT-IDT results confirmed that RuTT values obtained from the IDEAL-RT test were reliable. The different RuTT values were observed for different aggregates for same binder. The aggregates properties showed good trend with rut depth and HT-IDT values. The aggregates with higher angularity and better interlocking showed lower values of rut depth and higher values of HT-IDT indicating better rutting performance. Higher RuTT values were observed for Dolomite, followed by Granite and Sandstone reinforcing the importance of aggregate in rutting performance of asphalt mixture.

Although this study did not evaluate different gradations, the RuTT concept has the potential to be extended to mixtures that share the same NMAS but differ in gradation characteristics. Future research can investigate how variations in gradation such as aggregate distribution, packing, and internal structure affect the RuTT and whether mixture-specific calibration factors are needed. Similar to high-temperature PG, the mixture RuTT implicitly assumes identical traffic volume and speed when comparing mixtures on the basis of failure temperature. These factors can also be incorporated in future work by calibrating RuTT thresholds for extraordinary traffic volume and speed conditions, thereby strengthening the applicability of the concept across diverse pavement design scenarios. Although the RuTT framework developed in this study is limited to rutting, the underlying concept of defining mixture-specific tolerance thresholds can be extended to other distress modes. For instance, analogous indices may be formulated for fatigue and moisture susceptibility. However, adapting RuTT to other distresses will require careful selection of appropriate testing modes and relevant temperature ranges to ensure meaningful and distress-specific threshold identification.

Compliance with ethical standards

None

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CRediT authorship contribution statement

Vivek Pratap Wagh: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Amit Bhasin:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Ankit Gupta:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Yash Jadhav:** Methodology, Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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