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Performance Testing of Hot Mix Asphalt Modified with Recycled Waste Plastic

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16. Abstract

Plastic pollution has become one of the major concerns in the world. Plastic waste is not biodegradable, which makes it difficult to manage waste plastic pollution. Recycling and reusing waste plastic is an effective way to manage plastic pollution. Because of the huge quantity of waste plastic released into the world, industries requiring a large amount of material, like the pavement industry, can reuse some of this mammoth volume of waste plastics. Similarly, the use of reclaimed asphalt pavement (RAP) has also become common practice to ensure sustainability. The use of recycled waste plastics and RAP in HMA mix can save material costs and conserve many pavement industries' resources. To successfully modify HMA with RAP and waste plastic, the modified HMA should exhibit similar or better performance compared to conventional HMA. In this study, recycled waste plastic, linear low-density polyethylene (LLDPE), and RAP were added to conventional HMA, separately and together. The mechanical properties of conventional and modified HMA were examined and compared. The fatigue cracking resistance was measured with the IDEAL Cracking (IDEAL CT) test, and the Hamburg Wheel Tracking (HWT) test was conducted to investigate the rutting resistance of compacted HMA samples. The IDEAL CT test results showed that the cracking resistance was similar across plastic modified HMA and conventional HMA containing virgin aggregates. However, when 20% RAP aggregates were used in the HMA mix, the fatigue cracking resistance was found to be significantly lower in plastic modified HMA compared to conventional HMA. The rutting resistance from the HWT test at 20,000 passes was found to be similar in all conventional and modified HMA.

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Executive Summary

Plastics have become an integral part of modern human life. As a result, the production of plastics has increased rapidly. Most of the plastics are non-biodegradable and remain without decomposing for a very long time, creating a massive accumulation of waste plastic. Plastics are a type of polymer and also a petroleum-based product; these characteristics open a new door for the study of recycled waste plastic as an additive to hot mix asphalt (HMA). Reusing waste plastics in HMA can help to manage waste plastic pollution and can save resources. HMA is one of the most recycled products in the USA. HMA are recycled as "reclaimed asphalt pavement" (RAP). RAP is highly used and encouraged for use by many transportation agencies.

In this study, a conventional and plastic modified asphalt binder of Superpave Performance Grade PG 70-22 was used. Further, virgin aggregate and aggregate with 20% of RAP were incorporated in HMA with conventional and plastic modified HMA. A binder content of 5.4% was used in virgin aggregate HMA mix, and 4.9% was chosen for aggregate with RAP HMA mix. Superpave Gyratory Compacted samples with a diameter of 150 mm and a height of 60 mm were prepared for the Superpave design method. Air void of compacted samples was kept within the 7±0.5% range as directed by ASTM D8225 and AASHTO T324 test methods for the IDEAL Cracking test and Hamburg Wheel tracking test, respectively. The mechanical properties of conventional and modified HMA with RAP and recycled waste plastics were compared to assess fatigue cracking resistance and rutting resistance.

The IDEAL Cracking test is a newer test method used to examine the fatigue cracking resistance of HMA compacted samples at an intermediate temperature. Cutting, drilling, notching, or gluing of compacted samples is not required, and tests can be conducted within a minute. After conducting this test, the authors found no significant difference in fatigue cracking resistance between modified plastic and conventional HMA with virgin aggregate. However, when aggregate with 20% RAP was used, there was significantly lower fatigue cracking resistance in plastic modified HMA than in conventional HMA.

The Hamburg Wheel Tracking (HWT) test is a popular test method to examine the rutting resistance of compacted HMA; 20,000 passes were used for this test. At the end of 20,000 passes, all the samples showed similar rut depth. The HMA samples with RAP showed a slightly lower (shallower) rut depth.

These results show that the plastic modified HMA exhibited similar mechanical properties to conventional HMA when virgin aggregates were used. Thus, recycled waste plastic (polyethylene) may be used as a partial substitute for asphalt binder in HMA with virgin aggregate.

1. Introduction

Currently, the world is concerned about environmental degradation more than ever. The level of pollution is increasing each year. Among different pollutants, plastics are one of the major sources of environmental degradation. The quantities of waste plastics and their non-biodegradable nature make it very hard to manage plastic waste pollution. Even still, due to the high demand for plastics, plastic production has not decreased. Recycling and reusing plastic is one of the most effective ways to manage plastic waste. However, to reuse a huge quantity of plastic, an industry requiring a massive quantity of materials is needed.

The pavement industry satisfies this requirement. More than a billion tons of Hot Mix Asphalt (HMA) is produced worldwide annually.[1] There is always a need for materials. Asphalt binder, a petroleum product, is an expensive component compared to other materials in HMA. Similarly, various polymer additives are used to enhance HMA performance. The price tag of those additives is highest among all the components of HMA. Since plastics are polymers and petroleum-based products, plastics may potentially be used as additives to HMA. Using recycled waste plastics in HMA can reduce the volume of waste plastics as well as the cost of paving materials, and this recycling can also play a significant role in conserving resources. To successfully modify HMA with plastic, either plastic modified HMA should exhibit similar or higher performance compared to conventional HMA.

When sustainability and resource conservation in HMA are being discussed, Reclaimed Asphalt Pavement (RAP) cannot be missed. Removed or reprocessed pavement materials containing asphalt and aggregate are called RAP. The addition of RAP aggregate to HMA helps to conserve resources. Generally, the repair process of flexible pavement produces a large amount of RAP; if not reused, a large amount of unused RAP aggregate can fill landfill sites rapidly when it is disposed of at a landfill site. RAP aggregate use up to a certain percentage showed similar performance to the HMA with virgin aggregate. Many state-level transportation departments have encouraged the use of RAP and have published guidelines regarding the use of RAP.

To examine the possibility of modifying HMA with recycled waste plastic and RAP, the performance of modified HMA should be tested. Fatigue cracking and rutting are common failures for flexible pavement. There are many methods available to examine cracking and rutting resistance. In this study, the IDEAL Cracking (IDEAL CT) test is employed to measure the fatigue cracking resistance. This method can be conducted in less than a minute and does not require cutting, drilling, or notching. Similarly, the Hamburg Wheel Tracking (HWT) is selected to test the rutting resistance. This is a popular and effective test to examine the rutting resistance of compacted HMA samples. The conventional and modified HMA samples were tested according to these test methods, and conclusions were drawn from the results given by those tests, as presented in the following chapters.

2. Literature Review

Plastics have become an essential part of the modern world. The use of plastics is greater than ever before. As a result, the production of plastic has skyrocketed in recent years. The global production of plastics has increased from two million tons in 1950 to 368 million tons in 2019.[2] The major problem with the use of plastics is their non-biodegradable nature. Plastic wastes can remain on the Earth without degrading for many years. Plastic wastes are not biodegradable, and they emit toxic gases when burned, creating a dire problem in plastic waste management. Most of the waste plastic ends up in the ocean, causing severe problems in the planet's aquatic ecosystem.[3] The approaches of reducing, reusing, and recycling plastics are said to be effective ways to reduce plastic wastes. The pavement industry has the potential to reuse a huge quantity of recycled plastic waste. Recycled plastics, mainly polyethylene (PE), have been used as an asphalt modifier since the 1980s. Polyethylene is generally preferred as an asphalt additive over other types of recycled plastic polymer because its melting point is lower than the asphalt processing temperature. PE modified asphalts are available with different trade names such as Novophalt, Ditescpesa, Polyphat, etc.[4] The low blending capability of PE with asphalt binder has caused the lesser use of PE modification compared to other polymer modifications. Nevertheless, due to growing awareness of sustainability and environmental conservation, PE modified asphalts have grabbed attention in recent years.

Many studies have been conducted about PE modified binders. Researchers found that the homogenous blending of PE with binder depends on several parameters. The blending temperature and duration play critical roles in the binder's properties. A two-stage mixing process was recommended by Yousefi et al.; the first stage consists of high-shear mixing at high temperatures for a short period, and the second stage involves low-shearing mixing.[5] Dalhat et al. found that the LDPE modified binder reached a uniform viscosity after 30 minutes of blending at a shear speed of 5,000 rpm, whereas it takes 60 minutes for HDPE and PP modified binder.[6] Uniform viscosity indicates a homogeneous dispersion of the polymer in the binder. Polymers with smaller particle size disperse easily and partially dissolve into the binder due to enhanced polymer particle swelling with large surface areas. In another study, Polacco et al. discovered that asphalt with high aromatic content has better compatibility with PE than asphalt with low asphaltene content.[7] For the asphalt modification with LDPE, the mixing temperature of 160–180°C, blending speed of 1,300 rpm, and blending duration of 30–120 minutes was recommended. Additionally, LDPE concentration in the range of 3–5 wt% of bitumen was found to be the optimum concentration.[8]

Phase separation is one of the main concerns with the PE modified binder. Phase separation describes the polymer's separation from the binder during Polymer Modified Bitumen (PMB) transport and storage. It disturbs the homogeneity of the binder and affects the viscosity. Differences in molecular structure, density, molecular weight, and the polymer modified asphalt components' viscosity are the reasons behind the low compatibility between the polymer and the binder. According to Naksar et al., a recycled polymer content of 7 wt% shows behavior incompatible with asphalt binder.[9] The use of 4 wt% of waste HDPE pipe showed no phase separation for a long time.[10] Also, the recycled PE concentration should not exceed 5 wt% for paving applications.[11]

The polymer size also affects the compatibility of PE with the binder. The smaller particles can help to overcome the phase separation and stabilize the blend.[12] In a study by Ho et al., researchers found that the polymers with low molecular weight provide better compatibility and mixing with the asphalt binder.[13]

Similarly, storage stability refers to the tendency of PE to separate from asphalt binder during storage. It provides the degree of chemical compatibility between two individual components. Storage stability was not shown by the Novopalt binder, produced with a 7 wt% PE content.[14] In another study conducted by Cuadri et al., the storage stability time was increased from 1 hour to 4 hours by decreasing the LDPE content from 4 wt% to 2 wt%.[15]

Researchers used chemical, organic, and clay modifiers to improve the compatibility between bitumen and polymers. Liang et al. used a steric stabilization technique whereby PE was stably incorporated into asphalt using a styrene-butadiene-styrene (SBS) copolymer and an ethylene-vinyl acetate copolymer to produce an asphalt mixture known as Polyphat.[16] Another PE modified binder called Ditecpesa was introduced by adding silica gel and fine carbon black to stabilize the LDPE modified binder.[17]

Farahani et al. observed that the PE modified binders were more thermally stable than virgin binders, as shown by their weight loss.[18] The addition of PE increased softening point and viscosity value and decreased penetration and ductility. PE belongs to the plastomers group, which increases the stiffness but doesn't change elastic recovery. Dalhat et al. reported that for every two-percent increment in PE content, performance grade (PG) high temperature increased at least by one level.[19] However, that study also reported that the PE modified asphalt binders failed to meet elastic recovery criteria. The use of chemical additives like MA-g-PE and GMA-g-PE showed a positive effect on low-temperature properties, increased penetration and ductility, and enhanced high-temperature stability and compatibility between the polymer and binder.[20] The addition of Low-Density Polyethylene (LDPE) and Polyphosphoric acid (PPA) in HMA improved the fatigue resistance and rutting resistance.[21] Kishchynskyi et al. found that polymer additives of SBS type impart elasticity, increase cohesive strength and heat resistance, and improve its low-temperature behavior.[22] These studies showed that PE modified asphalt could increase the low-temperature and high-temperature performance.

Studies have been conducted on PE modified Hot Mix Asphalt (HMA) prepared from the dry method. Plastiphalt is prepared by a dry method where recycled plastics partially replaced aggregate.[23] In the dry method, plastics are not mixed into the binder. Instead, they are added to hot aggregate/asphalt mix at the hot mix asphalt (HMA) plant. Thus, testing the modified binder is not possible, and mixture performance can only be determined at the final pavement stage. This reduces quality control. The cracking resistance of the PE modified mixture produced by the wet method was found to be better than the PE modified mixture produced by the dry method.[24] Another shortcoming of the dry method is that the polymer size reduction is not achieved like in a wet method from high-shear blending.[25] Thus, the wet method is preferable to the dry method.

The use of PE modified asphalt binder by the wet process dates back to 1987. In 1987, the runway of Hobby International Airport (Houston, Texas) was constructed using recycled LDPE following the Novophalt technology.[26] Novophalt technology was again used in the construction of a runway and taxiways of Kuala Lumpur International Airport in 1996. Similarly, Novophalt technology was found to be suitable for the construction of the Al Kharkheer Military Airfield Project in the Kingdom of Saudi Arabia (1999).[27] In 2005, Dubai International Airport used LDPE modified binder in Phase 1 and continued to use it in the Phase 2 expansion after the material met the required specification.[28] Another technology called Ditecpesa was used for the construction of a large-scale road project in Spain in 2010.[29] The PE modified binder showed better rutting resistance in most of the studies. Therefore, PE modified binders are generally used in rutting susceptible areas such as runways and in hot climatic environments.

Reclaimed Asphalt Pavement (RAP) helps to conserve resources and plays a crucial role towards future sustainability.[30] RAPs are frequently used these days in HMAs. Many transportation state agencies allow the use of RAP up to 29%.[31] The mix design becomes complex when more than 25% of RAP is used because of the asphalt binder properties in the RAP.[32] Researchers have found better rutting resistance with the use of 20% RAP.[33]

Earlier studies generally focus on the rheological and mechanical properties of PE modified asphalt binder, and few investigations have been conducted on compacted HMA. Similarly, the effects of incorporating the plastic modified binder and RAP to conventional compacted HMA mix have not been studied extensively. This study will focus on the mechanical properties of compacted conventional and modified HMA with recycled waste plastic and RAP. Fatigue cracking resistance and rutting resistance will be tested with the IDEAL Cracking (IDEAL CT) test and the Hamburg Wheel Tracking (HWT) test, respectively.

3. Objectives

This study aims to examine the effect of recycled waste plastic and RAP on HMA, individually and together, when used as an additive. Fatigue cracking resistance and rutting resistance will be analyzed using the IDEAL Cracking Test and Hamburg Wheel Tracking Test, respectively. Results between conventional HMA and recycled waste plastic modified HMA with and without RAP will be compared according to the factorial in Table 1.

Table 1. Testing Factorial

Conventional Binder	Plastic Modified Binder
Virgin Aggregate Conventional Binder (VCM)	Virgin Aggregate Plastic Modified Binder (VPM)
Aggregate with RAP Conventional Binder (RCM)	Aggregate with RAP Plastic Modified Binder (RPM)

4. Materials

Aggregate, asphalt binder, and air voids are the major constituents of Hot Mix Asphalt (HMA). Aggregate occupies about 90 to 95% of the mix's total weight and is responsible for stability. Another constituent, asphalt binder, acts as a gluing material for aggregates and is also responsible for the mix's durability. Similarly, air voids represent the air volume entrapped in HMA during compaction. Air voids play a vital role in the mix design and performance of HMA.

4.1 Aggregates

The aggregates provided by Vulcan Materials were used in the study. Aggregates include sand, gravel, slag, and crushed stones. Two types of aggregate were selected. One was virgin aggregate, and the other contained 20% of RAP. Both types of aggregates have a Nominal Maximum Aggregate Size (NMAS) of 12.5 mm (1/2").

4.2 Gradation

Table 2 shows the gradations used in this study.

Table 2. Aggregates Gradations both Virgin and RAP Containing Aggregate

Sieve	% Passing		Specifications	
	Virgin	RAP	Virgin	RAP
3/4" (19mm)	100	100	100–100	100–100
1/2" (12.5 mm)	96.1	96.1	95–100	95–100
3/8" (9.5 mm)	86.2	86.5	72–88	72–88
#4 (4.75 mm)	52.4	53.1	46–60	46–60
#8 (2.36 mm)	36	36.8	28–42	28–42
#16 (1.18 mm)	26.8	27.8		
#30 (0.6 mm)	19.2	20.3	15–27	15–27
#50 (0.3 mm)	12.4	13.3	10–20	10–20
#100 (0.15mm)	6.6	7.6		
#200 (75 μm)	4.4	5.2	2–7	2–7
Pan	0	0	0	0

4.3 Asphalt Binder

Asphalt binder is a petroleum product and is the most expensive among the components of conventional HMA mix. It mixes with mineral filler to form mastic, which binds aggregates with each other. Conventional binders and plastic modified binders are used in this study. The conventional binder consists of 1.3% of ELVALOY™ RET EP1177 and 0.26% of Polyphosphoric acid (PPA) by binder weight. Similarly, the plastic modified binder consists of 1.5% of recycled linear low-density polyethylene (LLDPE), 0.6% of ELVALOY™ RET EP1177, and 0.2% of Polyphosphoric acid (PPA) by weight of the binder. Both asphalt binders for this study are provided by Asphalt Martin Company, and both binders were of PG 70-22 grade. Table 3 shows the properties of the conventional and plastic modified binder of PG 70-22.

Table 3. Asphalt Binder Properties

Property	Conventional Binder (PG 70-22)	Plastic Modified Binder (PG 70-22)
Rotational Viscosity (Pa-s)	0.74	0.7
Elastic Recovery %	62.5	40
Dynamic Shear Rheometer Original at 70 °C	1.11	1.12
Dynamic Shear Rheometer RTFO at 70°C	3.03	3.73
Dynamic Shear Rheometer PAV at 25°C	3,090	4,980
BBR Stiffness S at -12°C	173	210
BBR Slope (m-value) at -12°C	0.313	0.3
Softening Point, °F	129	126
Penetration, dmm	70	60

5. Methodology

A series of processes is required for preparing the samples before the tests are conducted. Mixing of materials, short-term aging of HMA mix, compaction, and fabrication of samples are those processes.

5.1 Mixing

Aggregates were batched to meet the target gradation for the mix. Conventional and plastic modified asphalt binder of grade PG 70-22 were selected. For virgin aggregate HMA mix, a binder content of 5.4% by total weight of HMA mix was used, whereas a binder content of 4.9% by total weight of HMA mix was used for aggregate with 20% of RAP.

Aggregates, asphalt binder, mixing bucket, mixer paddle, and spatulas were heated at a mixing temperature of 165°C (329°F) for two hours as shown in Figure 1 before mixing the aggregates and the asphalt binder. After that, the aggregates were poured into the mixing bucket and weighed on the scale; 5.4% or 4.9% of asphalt binder by total mix weight was added for virgin aggregate and aggregate with RAP in the mix, respectively. Then, the mixing bucket was aligned with the mobile bucket mixer, and mixing was initiated. The aggregates started to become coated with asphalt binder. The mixing was continued until the homogenous mix was obtained where aggregates were entirely coated by asphalt binder. Once a homogeneous mix is obtained, the mixing was stopped, and the HMA mix was transferred in a tray. The HMA mix was spread to an even thickness of 1 to 2 inches during transfer to a tray.

Figure 1. (a) Aggregate, Binder, Mixing Bucket, Spatula, and Mixing Paddle Conditioned at Force Draft Ovens; (b) Mobile Bucket Mixer with Mixing Bucket

5.2 Aging

Short-term aging is a laboratory procedure used to simulate the effects of HMA aging and binder absorption that occur during the pre-compaction phase of the construction process. After HMA mix preparation, the mix should undergo a short-term aging process to simulate the real field scenario.

The AASHTO R30 test method was implemented for short-term aging of HMA mix. Following this test method, the HMA mix was sprayed in a pan to an even thickness between 1 to 2 inches. For the mechanical property testing procedure, the HMA mix was placed in a forced-draft oven for 4 hours at a temperature of 135°C. The HMA mix was stirred at one-hour intervals to maintain uniform conditioning.

5.3 Compaction and Fabrication

Twenty-eight compacted HMA samples were prepared for the study. HMA samples were compacted with a Pine Superpave Gyratory Compactor (SGC). Fourteen compacted HMA samples made with a conventional binder and fourteen samples made with a plastic modified binder were prepared. For the IDEAL CT test, compacted HMA samples should have a diameter of 150 mm and a thickness of 60 mm, as shown in Figure 2. In the HWT test, 60-mm-thick SGC compacted samples were required to be cut according to the procedure given by AASHTO T324. Air voids in all compacted samples must be within the range of 7% (±0.5%). A series of volumetric tests was followed to prepare the sample with those specifications. Four main standard tests used were:

- AASHTO T 209: Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm})
- AASHTO T 312: Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor
- AASHTO T 166: Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Hot Mix Asphalt using the Saturated Surface-Dry Method
- AASHTO T 269: Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures.

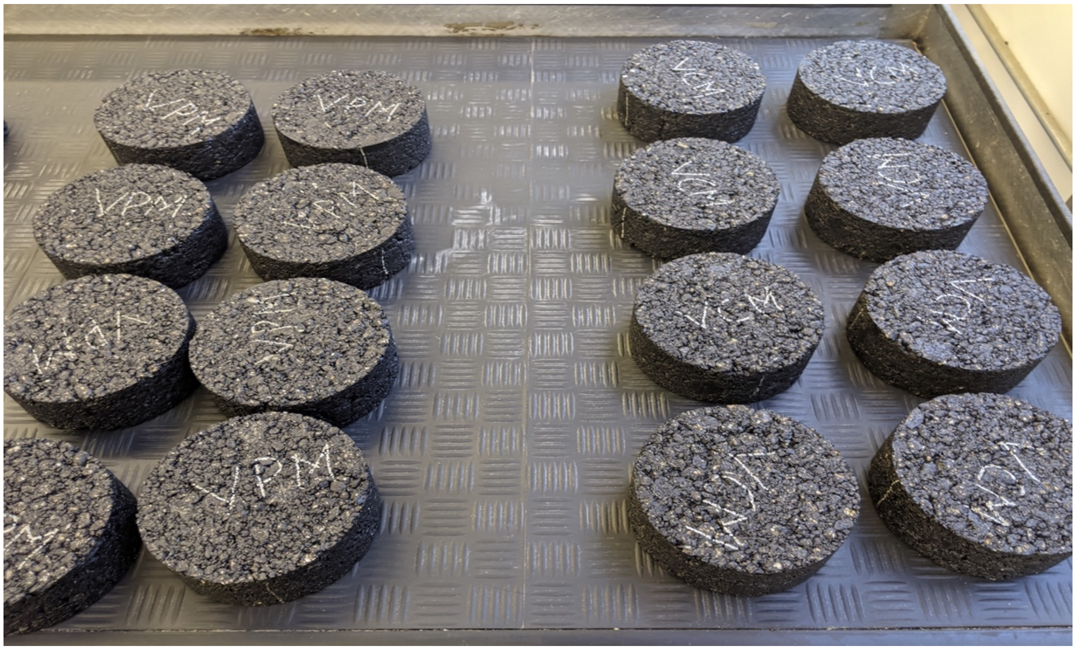


Figure 2. Superpave Gyratory Compacted Samples

The first test includes determining the theoretical maximum specific gravity (G_{mm}) of the HMA mix according to AASHTO T209. The NMAS in this study is 12.5 mm. Thus, 1,500 gm of short-term aged HMA mix was taken. G_{mm} is measured on the loose mix. Therefore, HMA particles were separated by hand. Proper care was taken while separating the particles to ensure particles were separated without fracturing. At no point was a significant amount of asphalt binder stuck to the container or the researchers' hands, and it was ensured that the fine aggregate portion was not larger than a quarter inch. First, the pycnometer was completely filled with water at 25°C and the researcher measured the corresponding weight. After that, the pycnometer was emptied, and the sample was placed into the pycnometer. The sample inside the pycnometer was submerged into the water at 25°C. Vacuum pressure of 27.5±2.5 mmHg was maintained for 15 minutes. A mechanical shaker provided continuous agitation while applying that pressure to force the air voids out of the loose mix and replace them with water. After 15 minutes, the pressure was released at a rate of no more than 60 mmHg per second. The apparatus for this test is shown in Figure 3. When atmospheric pressure was achieved, the pycnometer was partially filled with water and the samples was completely filled with water. The researchers measured the mass of the pycnometer and sample with the vessel completely filled with water. Once all three measurements had been taken, equation 1 was used to determine the G_{mm} of the HMA mix.

$$G_{mm} = \frac{A}{A + D - E}$$

(1)

G_{mm} = theoretical maximum specific gravity

A = mass of oven-dry sample in air, g

D = mass of pycnometer filled with water at 25°C, g

E = mass of pycnometer filled with the sample and water at 25°C, g.

Figure 3. Apparatus Setup Consisting of Pycnometer, Vacuum Pump, and Mechanical Shaker for Determining G_{mm}

The next step involves the compaction of the HMA mix using SGC to measure the bulk specific gravity of the compacted HMA mix. A Pine Superpave Gyratory Compactor (SGC) was used for the compaction, and AASHTO T 312 was followed. The compaction mold, base plates, funnel, spatula, and loose HMA mix were heated at compaction temperature of 135°C for at least 30 minutes, as shown in Figure 4. After that, the HMA mix was poured into the compaction mold in one lift with the help of the funnel. The charged mold was placed into the SGC. Pressure of 600 kPa was applied with an internal angle of 1.16°. The height of the compacted HMA sample was set to 60 mm.

HMA is a visco-elastic material. This characteristic makes HMA rebound after compaction. Therefore, samples were subjected to squaring time of 4 minutes, wherein the samples stayed in place until the rebound period was over. After the squaring time, the compacted HMA sample was extracted from the mold and left to cool down to room temperature.

(a) (b)

Figure 4. (a) HMA, Compaction Molds, Funnel, Spatula Conditioned at Mixing Temperature; (b) Pine Superpave Gyratory Compactor

The bulk specific gravity of compacted HMA samples must be determined to calculate the air void in the compacted HMA sample. AASHTO T166 was used to determine the bulk specific gravity. According to this test method, the researchers weighed the recently compacted HMA samples. Later, the compacted HMA sample was immersed in the water bath at 25°C for 4 minutes, and the immersed mass was recorded. Finally, the surface-dry mass was taken by removing the sample from the water bath and damp drying the sample by blotting it with a damp towel. The surface-dry mass was recorded within 15 seconds after the sample was removed from the water bath. Equation 2 was used to determine the bulk specific gravity.

$$G_{mb} = \frac{A}{B - C}$$

(2)

G_{mb} = bulk specific gravity

A = mass of sample in air, g

B = mass of surface dry sample in air, g

C = mass of sample submerged in water at 25°C, g.

Finally, air void in compacted HMA sample was determined according to AASHTO T 269; $G\ \ mm$ and $G\ \ mb$ are required. Air voids were calculated using equation 3.

$$V_a = 100\left[1 - \frac{G_{mb}}{G_{mm}}\right]$$

(3)

V_a = percent air void

G_{mb} = bulk specific gravity

G_{mm} = theoretical maximum specific gravity.

Air void of 7% (±0.5%) is required in SGC compacted samples. To achieve this percent air void, a trial and error basis was implemented, and multiple trials were needed to achieve the proper specifications of the gyratory compacted sample. Initially, 2,400 gm of loose HMA sample was compacted and the G_{mb} of the compacted sample was determined. Based on the percent air void that resulted from the G_{mb} of the compacted sample, the loose sample mass was varied until the target air void was achieved. Table 4 shows the volumetric properties of the HMA mix.

Table 4. Volumetric Properties

Mix Type	Binder Content (%)	G_{mm}	Air Voids (%)	VMA (%)	VFA (%)
VCM	5.4	2.501	7±0.5	18.52	62.58
VPM	5.4	2.503	7±0.5	18.66	62.63
RCM	5.4	2.478	7±0.5	17.28	61.05
RPM	5.4	2.482	7±0.5	17.46	60.65

After compacting the sample with 7% (±0.5%) air void, the samples were ready for the IDEAL CT test. However, for the HWT test, the compacted samples need to be cut according to the procedure given by AASHTO T324. The compacted samples were marked to be cut as shown in Figure 5 and sent for saw cutting. Three compacted samples were prepared for each type of mix for the IDEAL CT test, and four compacted samples of each mix type were prepared for the HWT test.

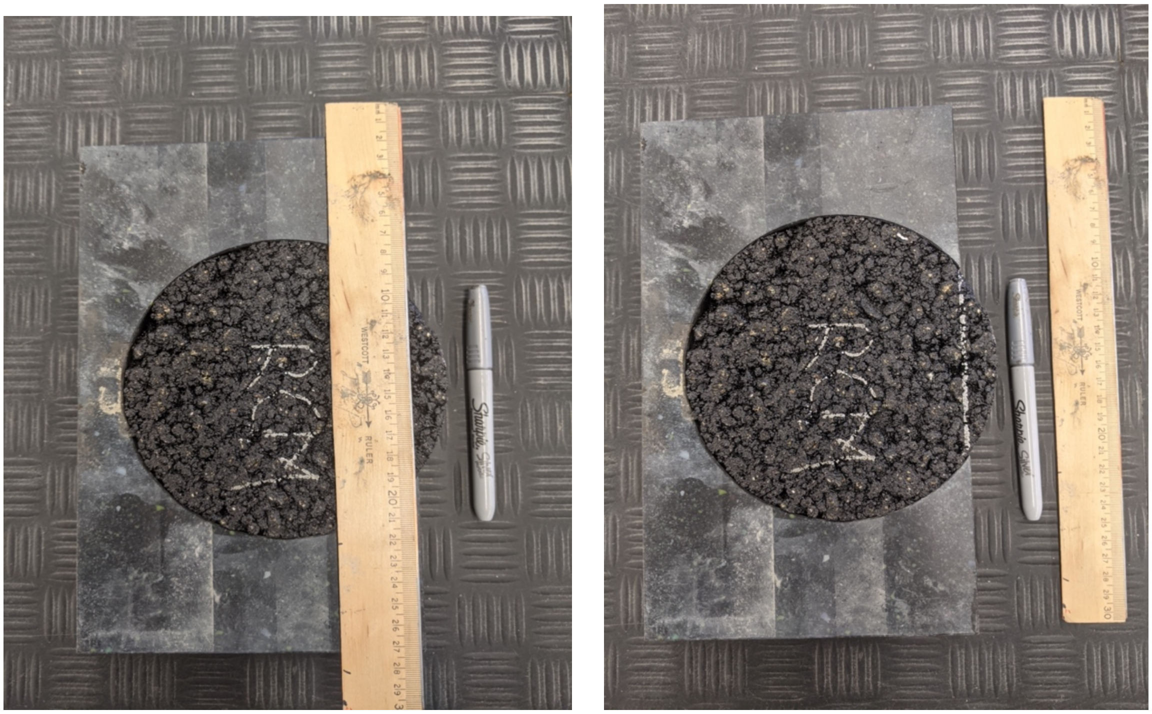


Figure 5. Marking of Cut Line for Hamburg Wheel Tracking Test

6. Testing

This study examines the fatigue cracking resistance and rutting resistance of conventional and plastic modified compacted HMA. The test method used to determine the fatigue cracking of the compacted HMA mix was ASTM D8225-19: Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature. Similarly, to examine the rutting resistance of compacted HMA mix, the researchers chose to follow AASHTO T 324: Standard Test Method for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures.

6.1 IDEAL Cracking Test

Figure 6. IDEAL CT Testing Machine

The IDEAL-CT test was conducted first. The researchers followed ASTM D8225:19: Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature. The DTS-30 from Pavetest with indirect tensile loading frame was used, as shown in Figure 6. The machine consists of an axial loading device, a load cell, loading strips, samples deformation measurement device, temperature-controlled chambers, and a data control and acquisitions system. The load cell has a resolution of 10 N and a capacity of at least 25 kN. This test required a minimum of three SGC compacted samples with a diameter of 150 mm and a thickness of 60 mm. For a sample with a nominal diameter of 150 mm, the loading strip should be 19.05 mm wide, and the length should be greater than the thickness of the sample. Notching, cutting, gluing, or drilling of compacted samples is not required. Therefore, it is simple and easy to fabricate the samples. IDEAL-CT test measures the fatigue cracking resistance through a fracture-mechanics-based parameter: Cracking Tolerance Index (CT_{index}). The CT_{index} is calculated from the failure energy, the post-peak slope of the load-displacement curve, and deformation tolerance at 75% of peak load. The higher the value of CT_{index}, the better the cracking resistance of the sample and vice versa. The fatigue cracking resistance tests are performed at an intermediate temperature. According to D6373, AASHTO M320, or M332, the intermediate temperature for the HMA with binder PG 70-22 is 28°C, so 28°C was selected as the test temperature.

Setting the temperature chamber to 28°C was the first step to initialize the test. Once the temperature stabilized at 28°C, the compacted HMA samples were placed in the chamber for two hours. The indirect tensile frame's contact surface was cleaned so that no debris was present there, since debris may give an incorrect measurement. The samples were then placed in an indirect tensile loading frame that was set up inside the DTS-30 testing machine. The sample was centrally placed so that it made uniform contact on the support, as shown in Figure 7. Inputs of a 50 mm/minute loading rate and a 0.1 kN termination load were fed into the software. After that, the test was initiated.

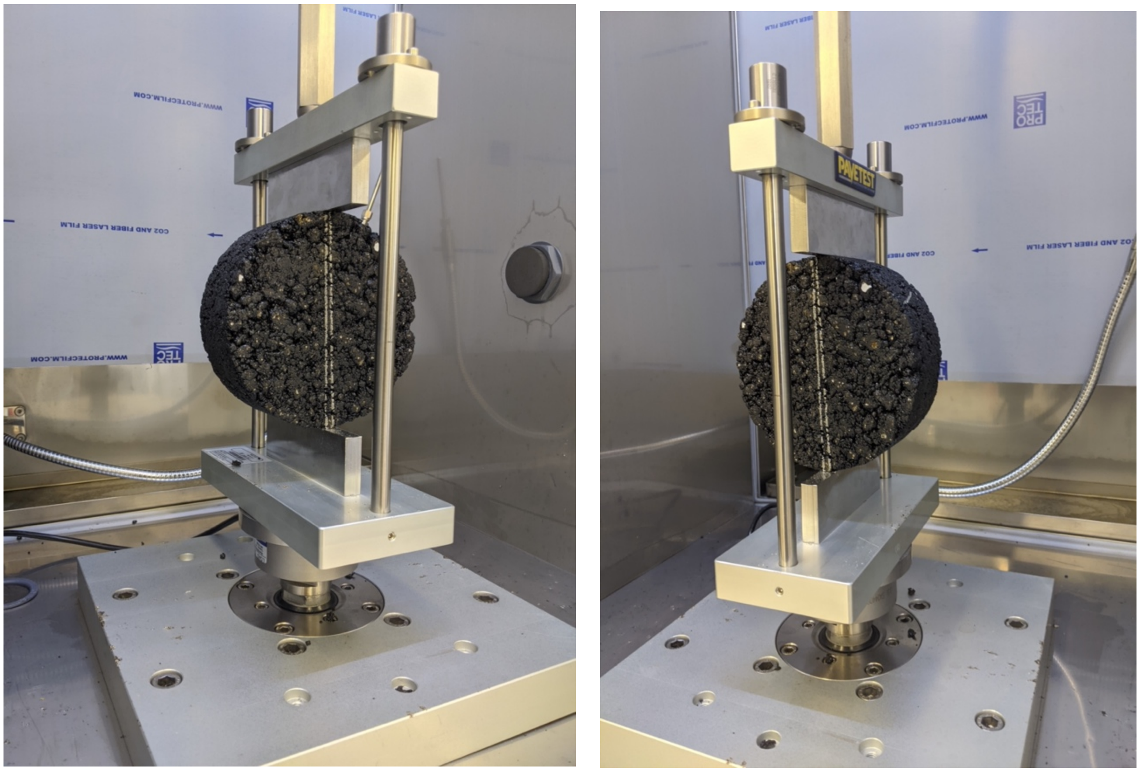


Figure 7. IDEAL CT Samples During Testing

The software records the displacements and corresponding loads. The test stops once failure of the compacted sample takes place. The sample is considered to be failed when there is displacement, even when a load of less than 0.1 kN is applied. The graph is plotted between the load and displacements. The test lasted for less than one minute.

After the load vs. displacement graph was plotted, the work of failure (W_f) was calculated as the area under the load vs. displacement curve through the quadrangle rule, as shown in equation 4.

$$W_f = \sum_{i=1}^{n-1} \left((l_{i+1} - l_i) \times P_i + \frac{1}{2} \times (l_{i+1} - l_i) \times (P_{i+1} - P_i) \right)$$

(4)

W_f = work of failure (joules)

P_i = applied load (kN) at the i load application

P_{i+1} = applied load (kN) at the $i+1$ load application

l_i = LLD (mm) at the i step

l_{i+1} = LLD (mm) at the $i+1$ step.

Another parameter required to determine CT$_{index}$, failure energy ($G \quad f$), can be calculated with the help of work of failure (W_f). Failure energy was calculated by dividing the (W_f) by the cross-sectional area of the sample, as shown in equation 5.

$$G_f = \frac{W_f}{D \times t} \times 10^6$$

(5)

G_f = failure energy (joules/m^2)

W_f = work of failure (joules)

D = sample diameter (mm)

t = sample thickness (mm).

The last parameter, post-peak slope (m_{75}), is the slope of the tangential zone around the 75% peak load point after the peak; it can be calculated using equation 6.

$$|m_{75}| = \left|\frac{P_{85} - P_{65}}{l_{85} - l_{65}}\right|$$

(6)

P_{85} = 85% of the peak load (kN) at the post-peak stage

P_{65} = 65% of the peak load (kN) at the post-peak stage

l_{85} = displacement (mm) corresponding to the 85% percent of the peak load at the post-peak stage

l_{65} = displacement (mm) corresponding to the 85% percent of the peak load at the post-peak stage.

Finally, after calculating these parameters, the CT_{index} can be determined by using equation 7, as shown below.

$$CT_{index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6$$

(7)

CT_{index} = failure energy (joules/m^2)

G_f = failure energy (joules/m^2)

D = sample diameter (mm)

$|m_{75}|$ = absolute value of the post-peak slope m_{75} (N/m)

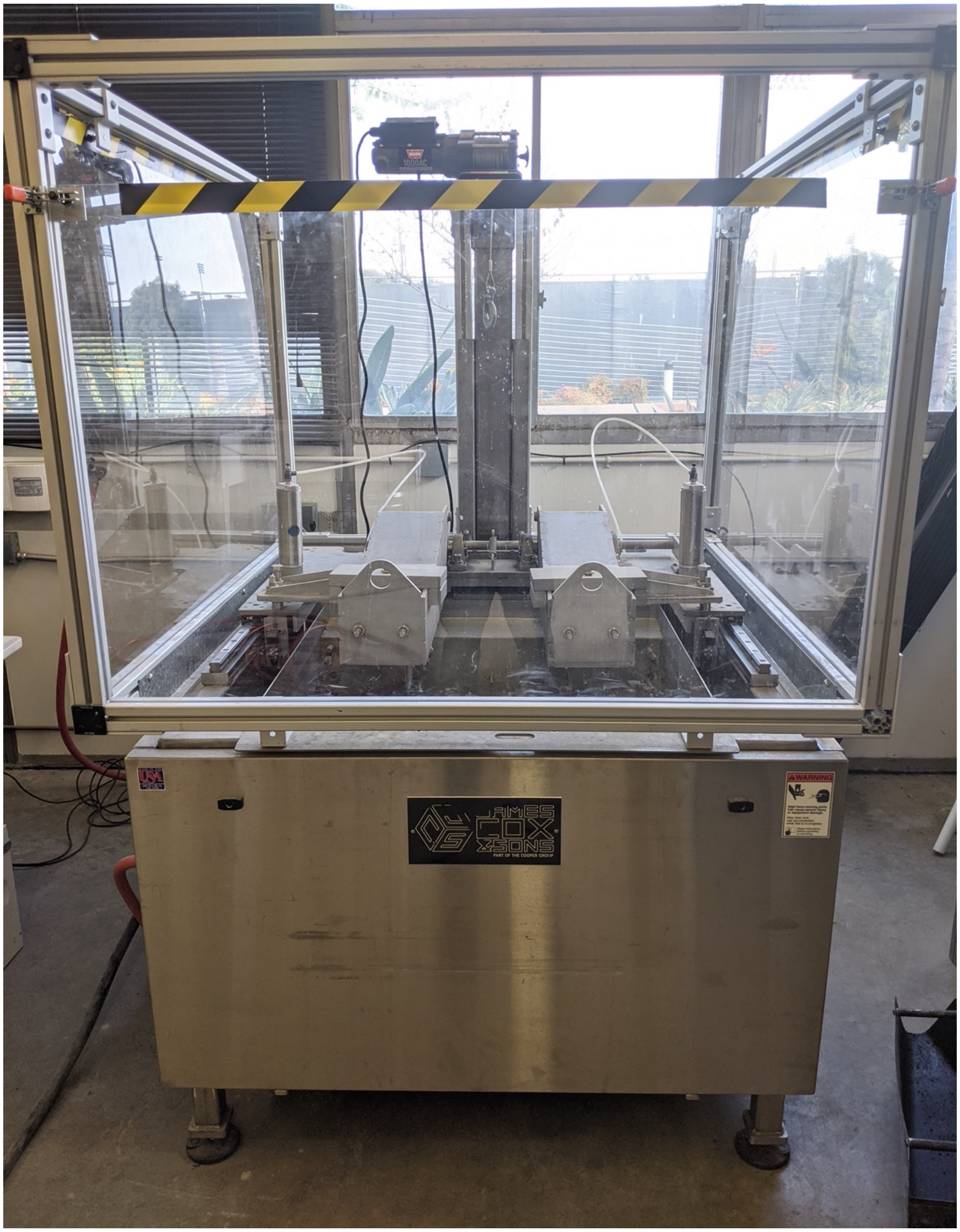
l_{75} = displacement at 75 percent of the peak load after the peak (mm)

t = sample thickness (mm).

The CT_{index} was calculated and prepared for statistical analysis. The load vs. displacement graphs, along with the parameters of the CT_{index}, are listed in the results portion of this report.

6.2 Hamburg Wheel Tracking Test

The second test conducted was the rutting resistance test. For this test, the researchers used AASHTO T 324: Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures. This method describes the testing of submerged, compacted HMA mixture in a reciprocating rolling-wheel device. SGC compacted HMA mixture was repetitively loaded using a reciprocating steel wheel, and the resultant deformation of the samples caused by the repetitive wheel loading was measured.



(a)

(b)

Figure 8. (a) Hamburg Wheel Machine; (b) Samples After Testing

The Cox Hamburg Wheel Tracker Machine was used to conduct this test, as shown in Figure 8. It is an electrically powered machine having steel wheels of diameter 8 inches and width of 1.85 inches. The wheels are capable of making 52 passes per minute by reciprocating the load of 705 N centrally over the compacted HMA samples. This test also measures moisture damage susceptibility since the samples are submerged in a temperature-controlled water bath during the test.

To start the test, the testing machine was turned on along with the software. The tank was filled with water, and the temperature was set to 55°C. The test temperature is based on the PG grade of the binder and HMA. The saw-cut SGC compacted HMA was placed in the molds and secured properly in the mounting tray. When the target temperature was reached, the HMA compacted samples were placed into the machine by submerging the sample in the water and conditioning (submerging) it in that water bath for 45 minutes.

According to the standard, the maximum number of 20,000 passes and maximum rut depth of 12.5 mm was set in the software. The test will end when one of the cases is met. Once everything is ready, wheels are lowered using a hydraulic mechanism onto the compacted HMA sample's edge. Proper care was given to avoid that the wheels placed onto the compacted HMA do not exceed the five-minute mark and the samples are not submerged longer than 60 minutes before starting the test as instructed by AASHTO T 324.

The test was initiated after all the conditions were satisfied. The software records and plots the rut depth versus the number of wheel passes on the sample. The test continues until the predetermined maximum number of passes or maximum rut depth is reached. The samples having a rut depth of more than 12.5 mm are considered to be failed. Once each run of the test was completed, the wheels were raised, and samples and mounting trays were removed. The water was drained out, and debris was cleaned with the vacuum cleaner.

7. Results and Analysis

The researchers conducted the IDEAL Cracking test and Hamburg Wheel Tracking test to examine the fatigue resistance and rutting resistance of conventional and modified HMA. The results obtained from the tests are discussed below.

7.1 IDEAL Cracking Test

In this study, the test tabulated values were imported to Microsoft Excel. The values were arranged in a proper format, and the load vs. displacement curve was constructed.

The work of failure was calculated from the area under the load vs. displacement curve with the help of the quadrangle rule. Similarly, other parameters such as the absolute value of the post-peak slope m_{75}, describing displacement at 75% of the peak load after the peak, were extracted from the curve. After calculating all those values, CT_{index} was determined. The load vs. displacement curves of different HMA compacted samples are shown in the following graphs (Figures 9 through 20).

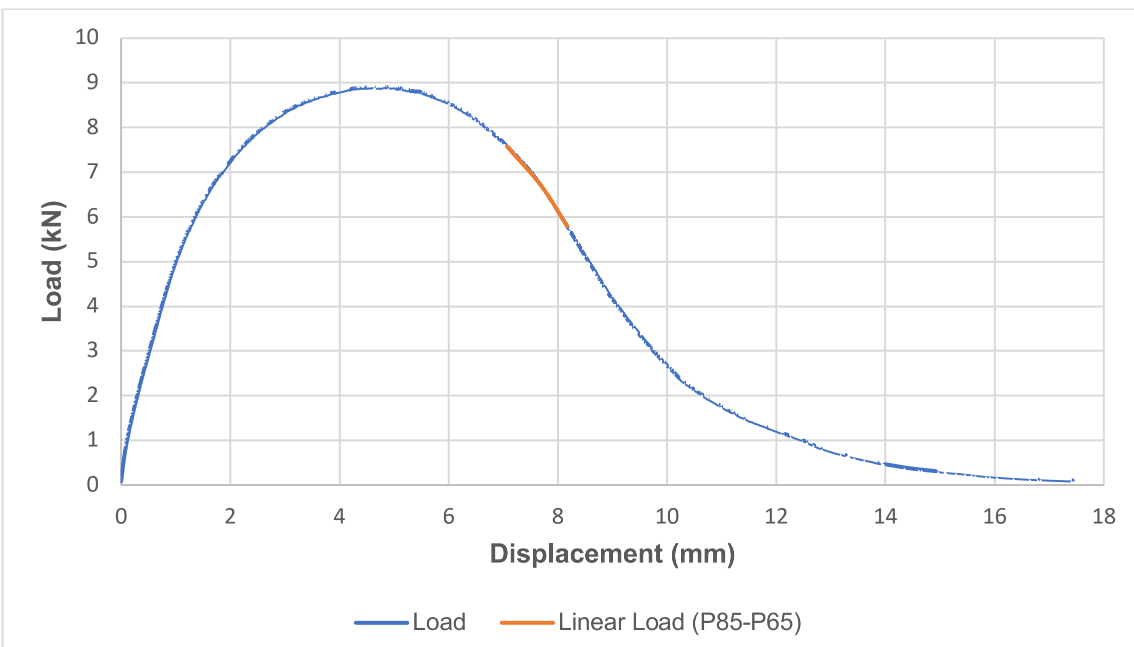


Figure 9. Load vs. Displacement Curve for VCM1

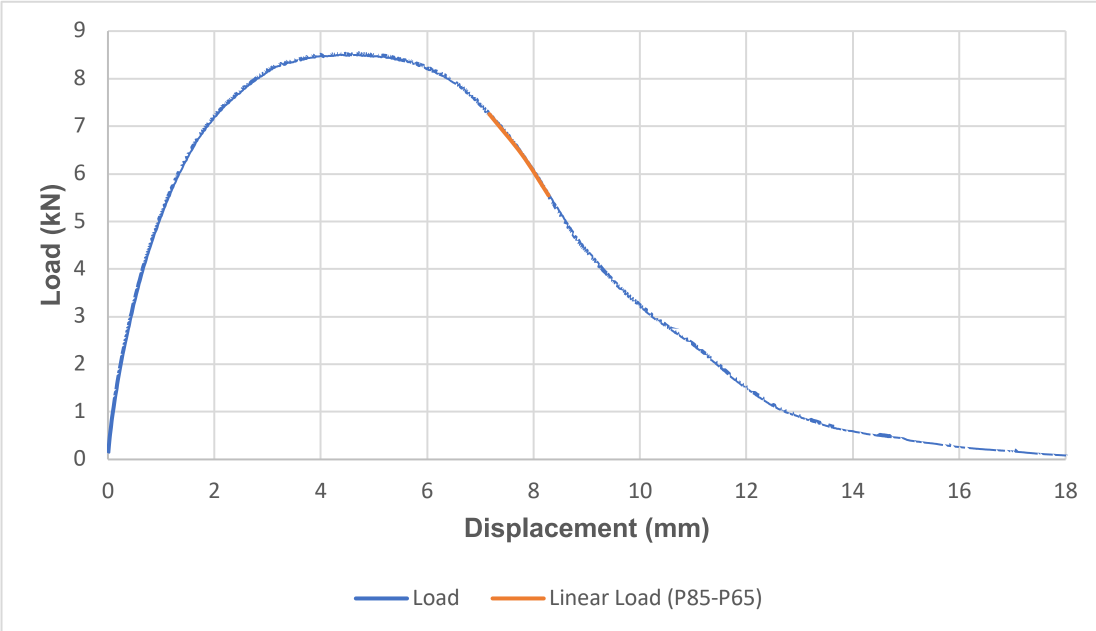


Figure 10. Load vs. Displacement Curve for VCM2

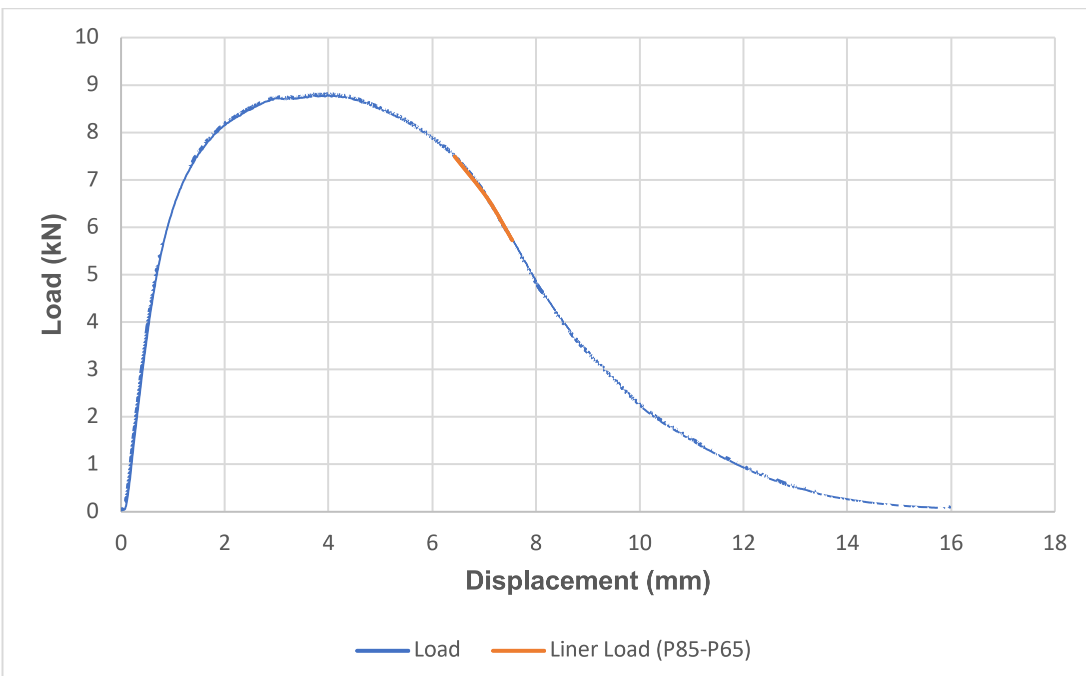


Figure 11. Load vs. Displacement Curve for VCM3

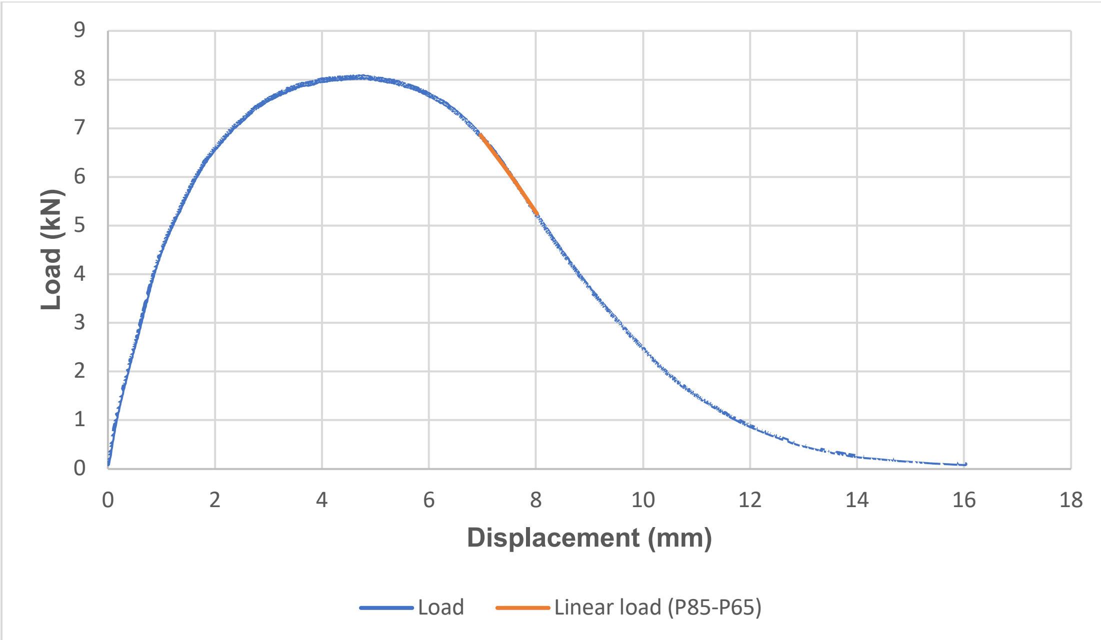


Figure 12. Load vs. Displacement Curve for VPM1

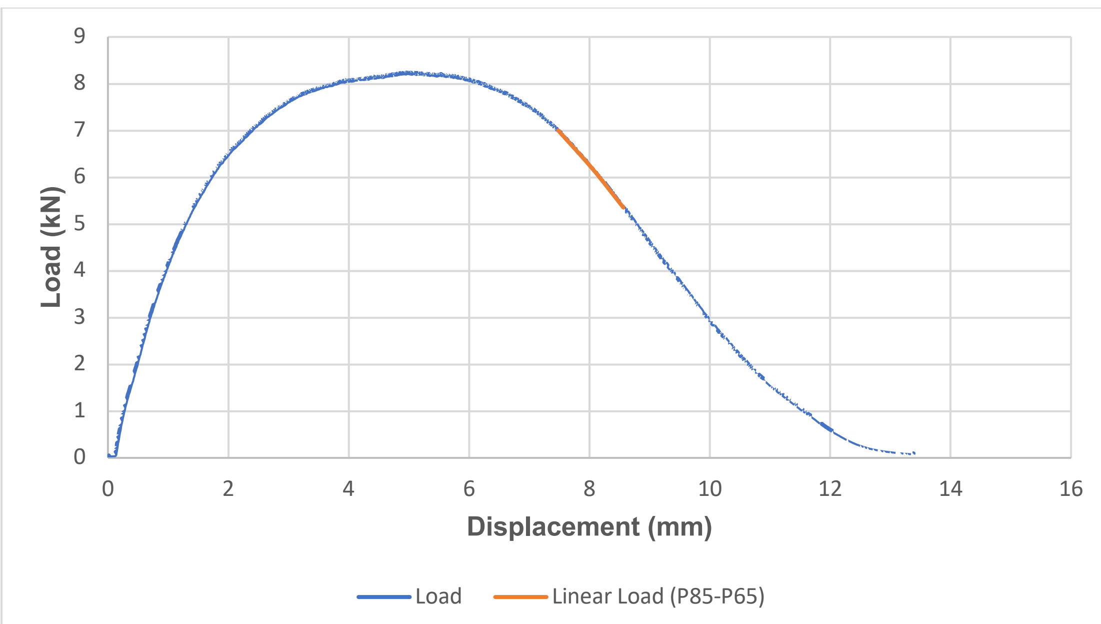


Figure 13. Load vs. Displacement Curve for VPM2

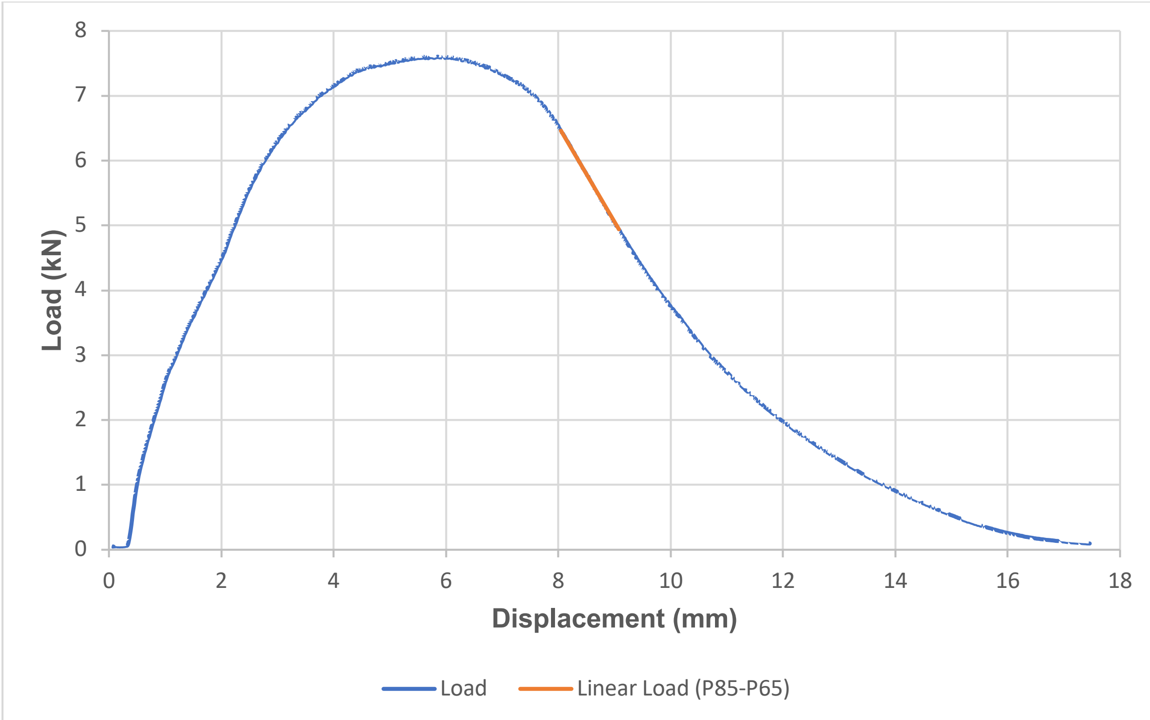


Figure 14. Load vs. Displacement Curve for VPM3

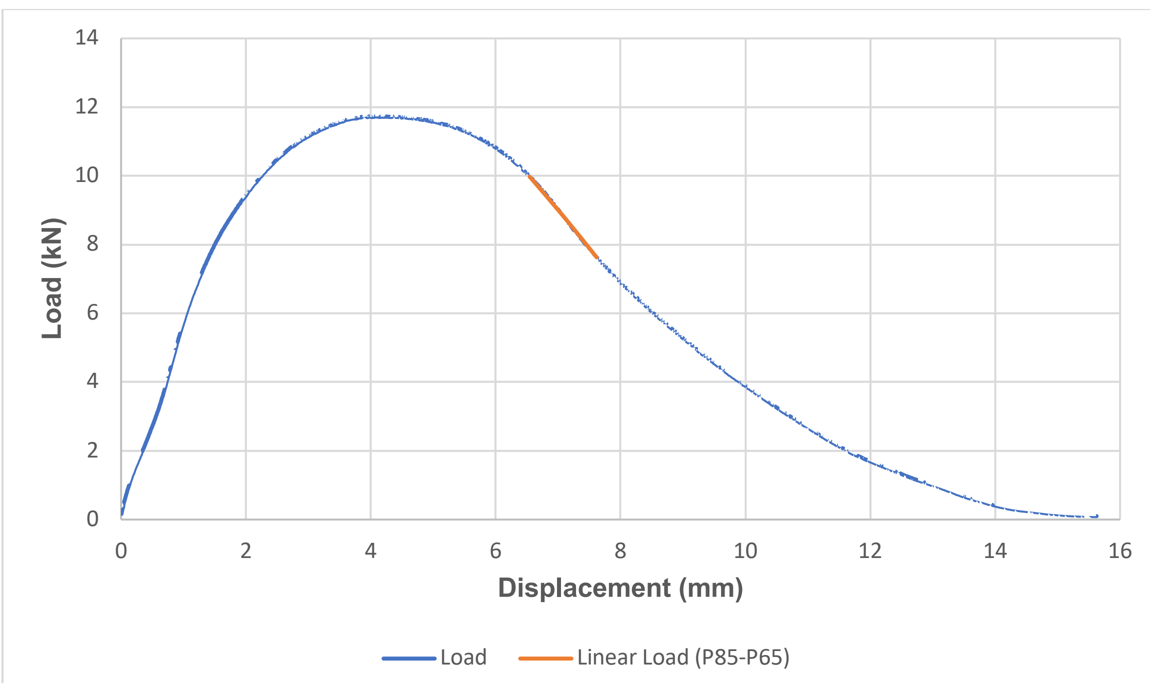


Figure 15. Load vs. Displacement Curve for RCM1

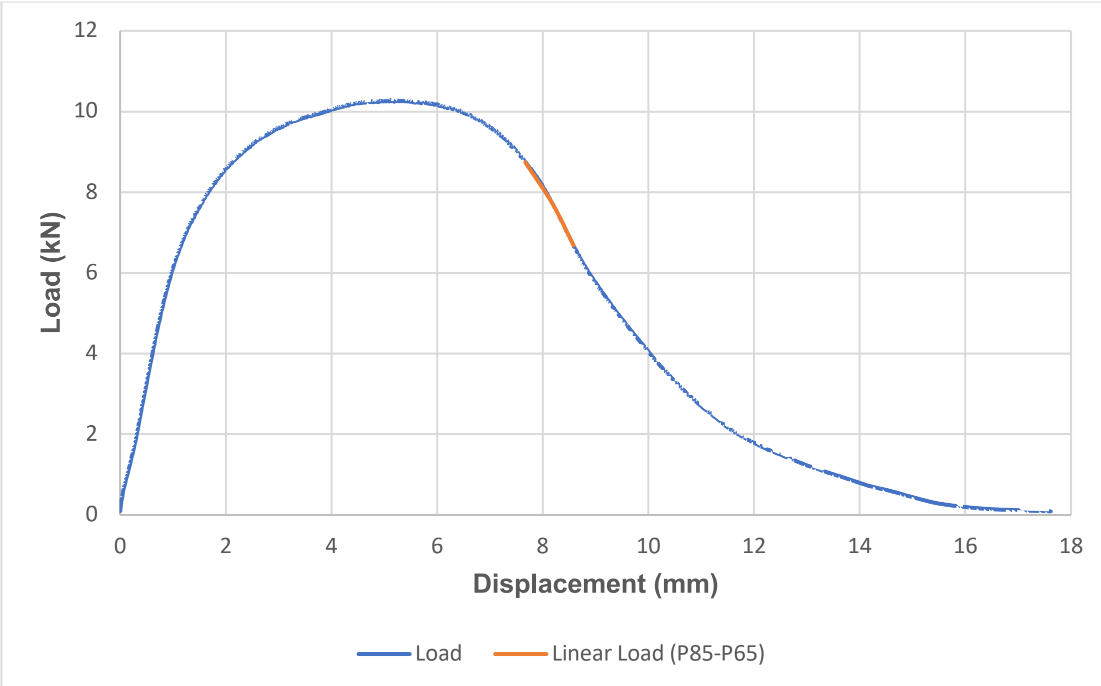


Figure 16. Load vs. Displacement Curve for RCM2

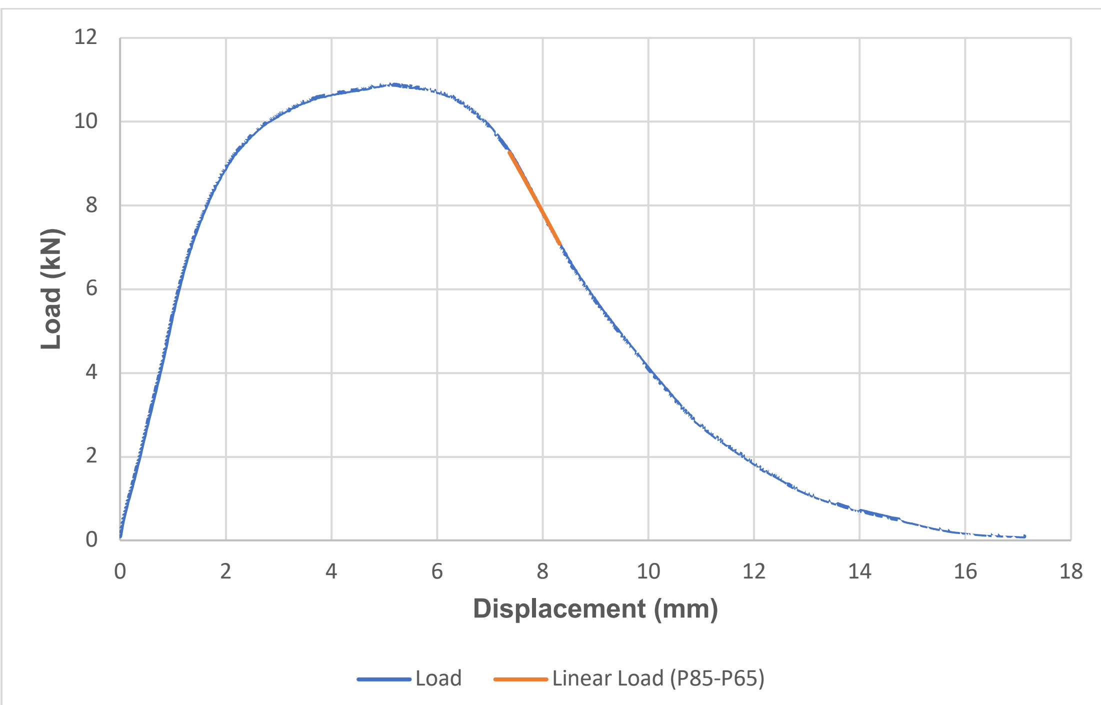


Figure 17. Load vs. Displacement Curve for RCM3

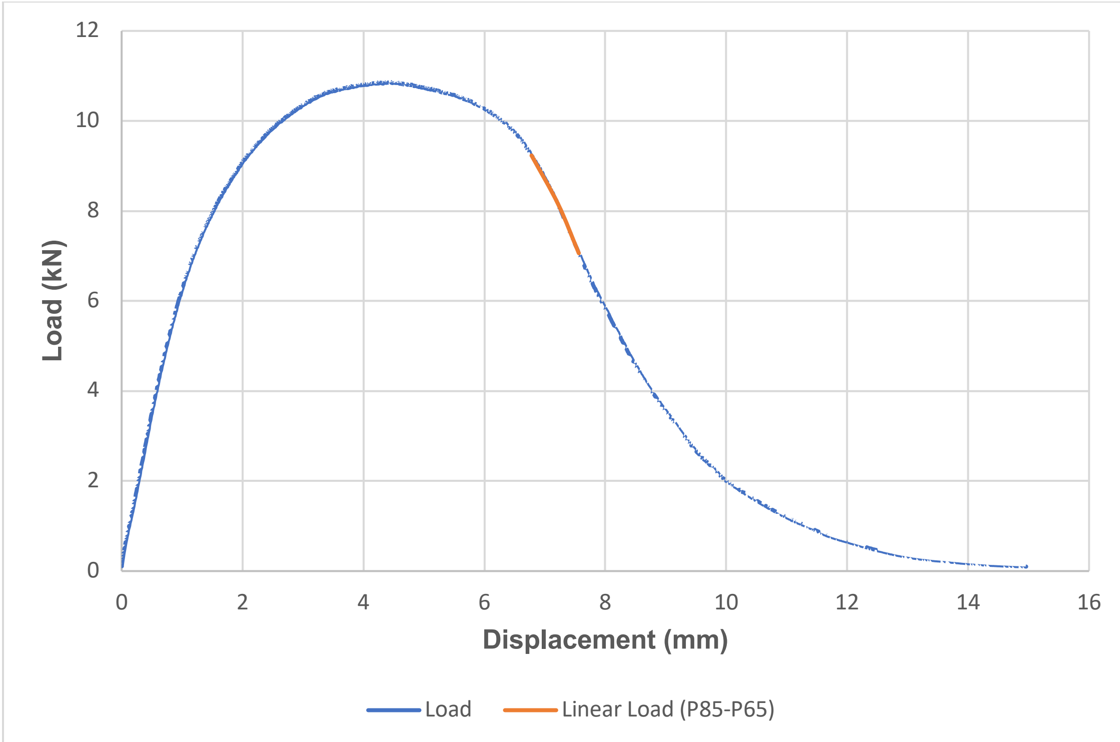


Figure 18. Load vs. Displacement Curve for RPM1

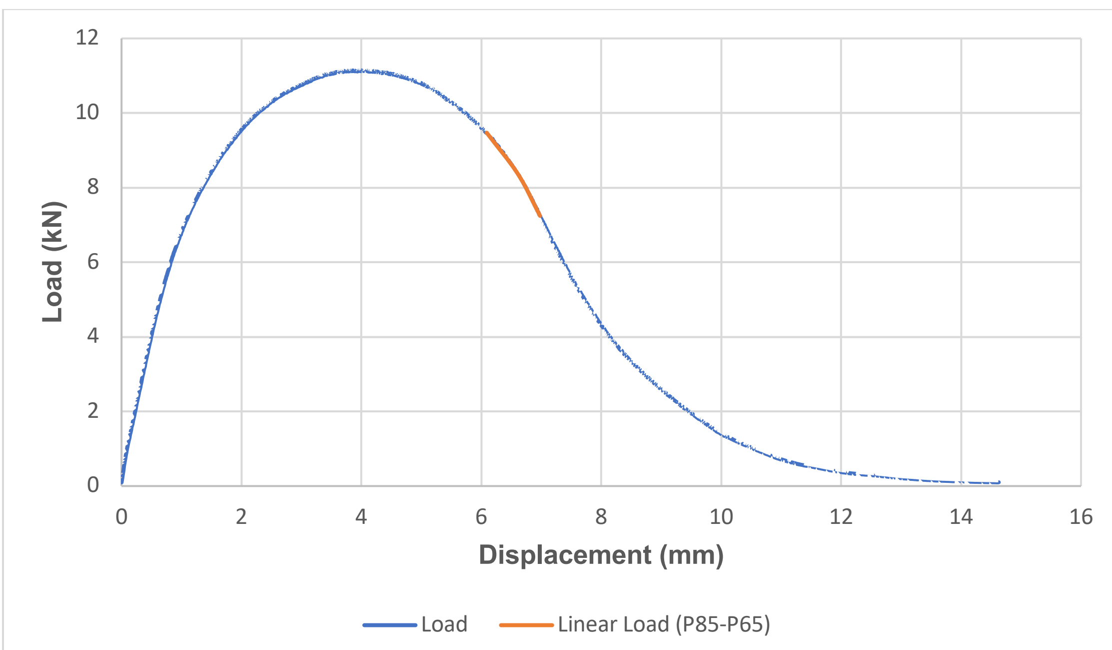


Figure 19. Load vs. Displacement Curve for RPM2

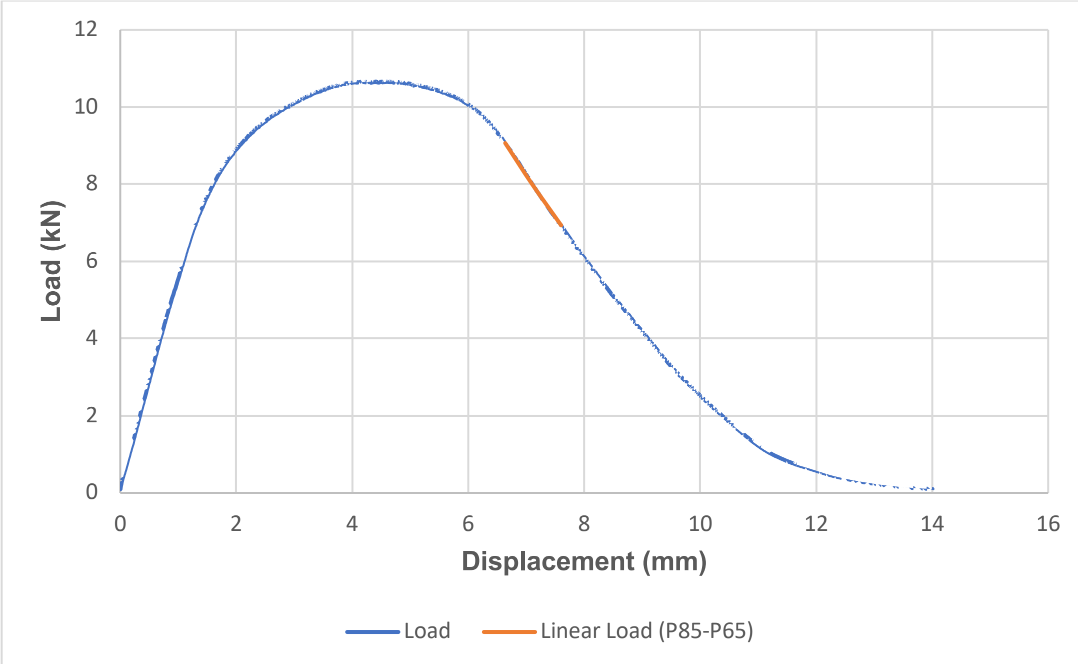


Figure 20. Load vs. Displacement Curve for RPM3

The failure energy (G_f) was determined by dividing the work of failure (obtained from the area covered by the load vs. displacement curve) by the cross-sectional area of samples. Then, CT_{index} was calculated. The CT_{index} is shown in Table 5 along with corresponding parameters of each HMA sample.

Table 5. IDEAL-CT Test Results

Sample	l75 (mm)	|m75| (N/m)	Wf(J)	Gf (J/m²)	CTindex
VCM1	7.70	1623731.7	72.89	8099.7	247.87
VCM2	7.78	1533536.6	74.08	8231.7	269.59
VCM3	7.06	1592217.8	69.75	7751.0	221.84
Average VCM					246.43
VPM1	7.51	1530244.1	64.44	7160.8	226.77
VPM2	8.05	1522686.4	66.50	7389.3	252.08
VPM3	8.56	1474016.2	66.17	7352.7	275.55
Average VPM					251.46
RCM1	7.09	2188032.0	91.92	10213.3	213.63
RCM2	8.18	2250056.3	90.10	10011.4	235.00
RCM3	7.85	2297687.5	91.77	10197.7	224.87
Average RCM					224.50
RPM1	7.22	2778263.4	80.65	8961.6	150.25
RPM2	6.61	2506792.5	76.38	8487.2	144.44
RPM3	7.10	2210300.3	79.55	8839.2	183.26
Average RPM					159.31

7.2 Statistical Analysis For IDEAL-CT Samples

Minitab 19 was used as a statistical analysis tool in this study. The CT_{index} of each sample was fed to conduct the statistical analysis. Researchers conducted a t-test to determine the significance of the difference between the two mixes. The analysis was conducted on each mixture, and results were compared with the other mixtures that correlate with it using a t-test. A p-value below 0.05 indicates a significant difference. Table 6 shows the p-values for the results.

Table 6. Significant Levels Between Mixtures

Comparison Mix1 vs. Mix2	p-value	CTindex Mix1 vs. Mix2
VCM vs RCM	0.221	246.43 vs 224.50
VCM vs VPM	0.855	246.43 vs 251.46
RCM vs RPM	0.044	224.50 vs 159.31
VPM vs RPM	0.009	251.46 vs 159.31

Comparison between Virgin HMA (VCM) and HMA with RAP (RCM)

The CT_{index} of VCM was found to be 246.43. CT_{index} was lesser in the case of RCM. The CT_{index} of RCM was 224.50. The t-test revealed no significant difference between the use of 20% of RAP or virgin aggregates in HMA. These results were similar to those of earlier studies done by other researchers on the performance of HMA with RAP. However, when comparing the CT_{index} of the other HMA mixes, results differed between conventional HMA and plastic modified HMA, depending upon the use of virgin aggregate or aggregate containing RAP.

Comparison between Virgin Conventional HMA (VCM) and Virgin Plastic Modified HMA (VPM)

In the case of the compacted HMA containing virgin aggregate, the use of conventional or recycled waste plastic modified binder showed a similar CT_{index}. The VPM showed a slightly higher CT_{index} value. As for the average CT_{index}, the value was 246.43 for VCM and 251.46 for VPM. The t-test showed no significant difference between these two mixes and the least significant difference between the mixes used in the study.

Comparison between Conventional HMA with RAP (RCM) and Plastic Modified HMA with RAP (RPM)

With the addition of 20% of RAP to HMA and using the plastic modified binder, there was a noticeable decrease in the CT_{index} value as compared to the CT_{index} value of HMA with RAP and conventional binder. The average CT_{index} value was found to be 224.50 and 159.31 for RCM and RPM mix, respectively. The t-test also showed a significant difference in CT_{index} value between the RCM and RPM mix.

Comparison between Virgin Plastic Modified HMA (VCM) and Plastic Modified HMA with RAP (RPM)

There was a large difference between the average CT_{index} value of VCM and RPM. The average CT_{index} of VPM was found to be 251.46, whereas the average CT_{index} value of RPM was 159.31. From the t-test, the p-value between these HMA mixes was 0.009, indicating that there was a significant difference in fatigue cracking resistance between VCM and RPM.

7.3 Hamburg Wheel Tracking Test

The Hamburg Wheel Tracking test was conducted to determine the rutting resistance. VCM, VPM, RCM, and RPM compacted samples were tested. The software records the rut depth for each number of passes automatically for the duration of the test. These data were extracted and the curve between rut depth vs. the number of passes plotted. Table 9 shows the average rut depth of different HMA mix configurations with different numbers of passes. Similarly, Figure 21 shows the rut depth vs. the number of passes.

Table 7. Hamburg Wheel Rut Depth Results

Mix Type	VCM	VPM	RCM	RPM
No. of passes	Rut Depth (mm)			
0	0.00	0.00	0.00	0.00
5,000	-3.32	-4.71	-3.11	-4.07
10,000	-6.42	-8.06	-4.37	-6.98
15,000	-8.18	-8.32	-6.19	-7.47
20,000	-8.26	-8.34	-7.54	-7.89

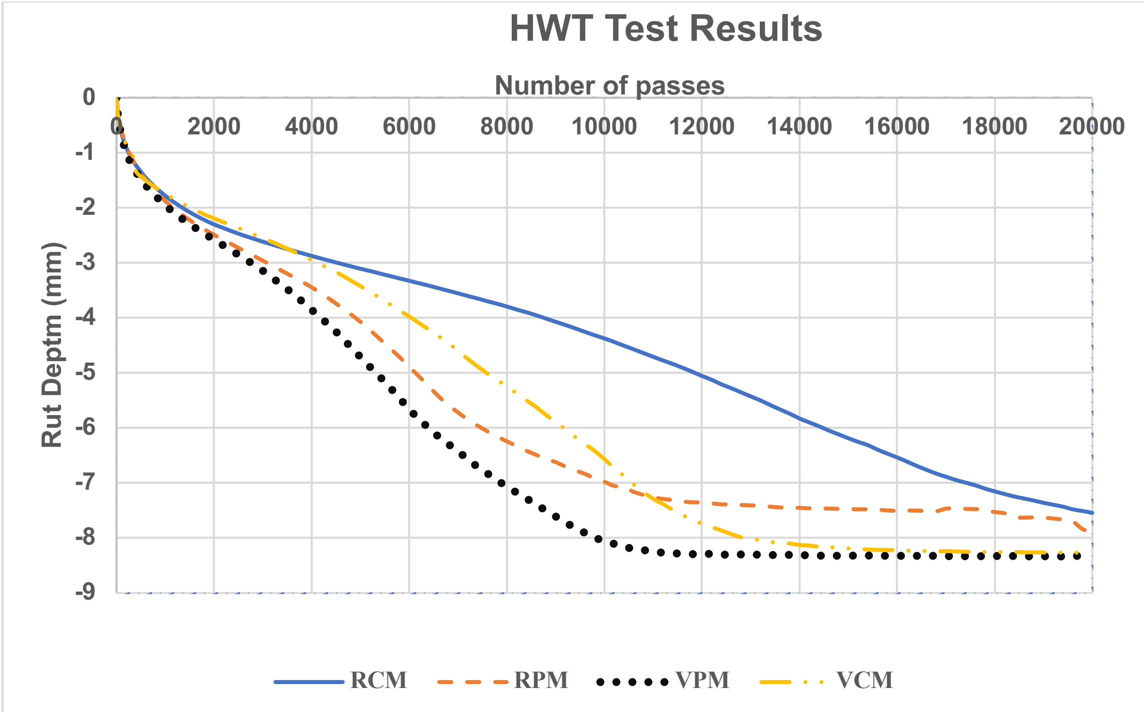


Figure 21. HWT Test Results

A maximum allowable rut depth of 12.5 mm and 20,000 passes were selected based on AASHTO T324. In this study, none of the samples exceeded 12.5 mm of rut depth. Thus, the researchers compared the rut depth of compacted samples with different numbers of passes. This approach will help to analyze the effect of adding recycled waste plastics on the rutting resistance.

At 20,000 passes, the virgin and plastic modified HMA mix showed similar rutting depth. VCM and VPM had a rut depth of 8.26 mm and 8.34 mm, respectively. The HMA with 20% of RAP showed slightly better rutting resistance. RCM had a rut depth of 7.54 mm, and RPM had a rut depth of 7.89 mm. At 10,000 passes, the rut depth of plastic modified HMA was higher than conventional HMA. However, after 10,000 passes, researchers found that the rate of increase in rut depth is higher in conventional HMA. The rut depth of HMA with conventional and plastic modified binder at 20,000 passes was found to be similar.

8. Conclusions

Many studies are being conducted to reuse recycled plastic waste effectively to manage the plastic waste problem. Similarly, the use of RAP in pavement has been a common practice to conserve resources. In this study, recycled waste linear low-density polyethylene (LLDPE) was added to virgin aggregate and aggregate containing 20% of RAP. The mechanical properties of plastic modified HMA containing RAP were tested and compared to conventional HMA. The following conclusions were obtained.

- CT_{index} value for VCM and VPM were similar. This indicates that the fatigue cracking resistance is similar in HMA with conventional and plastic modified binder containing virgin aggregate, suggesting that recycled waste plastic can be used to substitute a certain percentage of binder in HMA having virgin aggregate to produce similar fatigue resistance.
- In the case of HMA with RAP, the fatigue cracking resistance parameter CT_{index} drops when the plastic modified binder was used instead of the conventional binder. This finding indicates that HMA with RAP and plastic modified binder may have reduced fatigue cracking resistance.
- The rut depth of HMA with conventional and plastic modified binder at 20,000 passes was found to be similar.
- The HMA with RAP showed lower fatigue cracking resistance, whereas it showed better rutting resistance compared to HMA with virgin aggregate.
- Recycled waste plastic can be used to partially substitute the binders to produce similar fatigue and cracking resistance.

9. Limitations and Future Work

This study's results are limited to the materials used and are not inclusive of all variations of materials. The authors acknowledge that more extensive testing is required to draw more conclusive results.

The following suggestions can be tested.

- Fatigue cracking resistance can be tested by reducing the RAP aggregate percentage.
- RAP extracted from plastic modified HMA pavement may have different effects on the mechanical performance of HMA than RAP from conventional HMA. The results between conventional RAP and plastic modified HMA RAP can be compared.
- The softer plastic modified binder can be tested to obtain more apparent results on the rutting resistance of the plastic modified HMA.
- Plastic modified HMA with different percentages of recycled waste plastic can be studied to examine the optimum plastic content for better fatigue cracking and rutting resistance.

Abbreviations and Acronyms

CT_{index}	Cracking Tolerance Index
G_{mb}	Theoretical Maximum Specific Gravity
G_{mm}	Bulk Specific Gravity
HDPE	High-Density Polyethylene
HMA	Hot Mix Asphalt
HWT	Hamburg Wheel Test
IDEAL-CT	Ideal Cracking Test
LDPE	Low-Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
NMAS	Nominal Maximum Aggregate Size
PE	Polyethylene
PG	Performance Grade
PMB	Polymer Modified Bitumen
PP	Polypropylene
PPA	Polyphosphoric Acid
RAP	Reclaimed Asphalt Pavement
RCM	RAP Conventional Mix
RET	Reactive Elastomeric Terpolymer
RPM	RAP Plastic Modified Mix
RET	Reactive Elastomeric Terpolymer
HWT	Hamburg Wheel Tracking
SBS	Styrene-Butadiene-Styrene
SGC	Superpave Gyratory Compactor
USDA	United States Department of Agriculture
UV	Ultraviolet
VCM	Virgin Conventional HMA Mix
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate
VPM	Virgin Plastic Modified HMA Mix
WMA	Warm Mix Asphalt

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