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MTI MINETA TRANSPORTATION INSTITUTE

Evaluation of Polymer Binder Technisoil G5® in Concrete Mixture

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CSUTC California State University Transportation Consortium

CALIFORNIA STATE UNIVERSITY LONG BEACH

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16. Abstract

Plastic is everywhere, and with its increasing use in so many everyday materials, the production and demand of plastic has skyrocketed. Unfortunately, this has resulted in the accumulation of a mammoth amount of plastic waste and adverse effects on the environment. To optimize the huge amount of materials required by the pavement industry each year and reuse recycled plastics, the use of reclaimed asphalt pavement (RAP) has been common practice. This research studied the use of a binder completely made from recycled waste plastic named Technisoil G5® and compared it with performance grade PG 70-22 mix containing virgin aggregates and RAP aggregate. The study compared the mechanical properties, including fracture resistance and rutting resistance, and performed IDEAL Cracking Test (IDEAL CT) to evaluate the fracture resistance of samples. Results included that the fracture cracking resistance of Technisoil G5® samples is significantly lower than the PG 70-22 samples. Meanwhile, the peak load of Technisoil G5® samples is higher than PG 70-22 and can take a higher load before failure. Further testing is needed, but these and other results of this study are first steps toward testing and implementing sustainable development to conserve the environment.

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Executive Summary

The use of plastic for personal and industrial use has increased rapidly, creating a massive demand for plastics all around the globe. As a result, the production of plastics has increased rapidly. However, the non-biodegradable property of plastic creates a massive accumulation of waste plastic. These waste plastics pollute the environment. Many innovative ideas are being tested to reuse waste plastics.

Plastic is a type of polymer and also a petroleum-based product. These properties open a new door for the study of recycled waste plastic in road pavements. A high amount of energy is required to prepare hot mix asphalt (HMA). A binder prepared with recycled waste plastic that can be mixed at room temperature could reuse the waste plastics, conserve a lot of energy, reduce greenhouse gas emissions, and also help to reduce the waste plastic management problem. RAP is one inseparable component of the pursuit of sustainability in the pavement industry. Currently, reclaimed asphalt pavement, or RAP, is highly used, and its use is encouraged by many transportation agencies.

This study uses a binder completely prepared with recycled plastics which can be mixed and compacted at room temperature. This binder is manufactured by Technisoil Industries and is commercially known as Technisoil G5®. The mechanical properties of the G5 mix are compared with those of the PG 70-22 conventional mix. Apart from this, virgin aggregate and aggregate with 20% RAP were incorporated in the G5 and PG 70-22 mixes. For PG 70-22 mix, a binder content of 5.4% was used in the virgin aggregate mix and 4.9% for aggregate with RAP mix. Similarly, 5.3% binder content by total mix weight was used in the G5 mix. A Superpave Gyratory Compactor was used to prepare the compacted samples with a diameter of 150 mm and a height of 60 mm. The test methods used for fatigue and rutting resistance of compacted samples specified that the air void of compacted samples should fall within the 7% ± 0.5% range as directed by ASTM D8225 and AASHTO T324. Twenty-eight compacted samples with air voids within the 7% ± 0.5% range were prepared.

The fatigue cracking resistance of compacted samples at intermediate temperature was tested using the IDEAL Cracking Test. Cutting, drilling, notching, or gluing of compacted samples are not required in this test method. The test results suggested a significant decrease in fatigue cracking resistance while using a G5 binder instead of a conventional PG 70-22 binder. However, there was no significant difference in fatigue cracking resistance between virgin aggregate and aggregate with 20% of RAP for the G5 and PG 70-22 mixes.

The Hamburg Wheel Tracking test is a popular test method used to examine the rutting resistance of compacted samples. Twenty thousand passes and 12.5 mm of maximum rut depth were selected according to AASHTO T324. The G5 samples showed very high rut resistance properties compared to PG 70-22 samples. The compacted samples with RAP showed a slightly lower rut

depth than samples with virgin aggregates. More future studies are required to ahieve the fatigue resistance similar to conventional HMA mix.

1. Introduction

Environmental degradation is among the major problems of the modern world. Plastic pollution and greenhouse gases are considered significant factors contributing to the degradation of the environment. However, the use of plastics for personal and industrial uses is increasing each year. As a result, the amount of waste plastics ending up in landfill sites and oceans also increases each year. These plastic wastes are non-biodegradable and can remain there without degrading for many years, affecting soil quality and aquatic ecosystems. Recycling and reusing plastic is one of the effective ways to manage plastic waste. However, to reuse a huge quantity of plastic, an industry requiring a massive quantity of materials is required.

The pavement industry is always in need of more materials. Over a billion tons of hot mix asphalt (HMA) is produced worldwide each year.[1] One of the important components of asphalt concrete is a binder that binds the aggregates together and provides strength to the mix. Plastic is a kind of polymer and also a petroleum-based product (like asphalt binder). Recycled waste plastics show the potential to be used as a substitute for asphalt binder in asphalt concrete. If recycled waste plastics can be successfully used as a binder, a significant volume of waste plastics can be used as a pavement material.

A massive amount of energy is required to prepare HMA. The mixing and compacting temperature of conventional HMA is more than 100°C. Thus, HMA plants produce a large amount of greenhouse gases. Greenhouse gases are responsible for global warming. Cold mix asphalt (CMA) can be used, which doesn't require heating before application. However, cold mix asphalt doesn't provide strength like HMA, and it can only be used for temporary repair of the pavement. A mix that can be prepared like CMA but provide the strength like HMA could play a huge role in reducing greenhouse gases from pavement industries. Enter Technisoil G5®, a binder that is completely prepared with recycled waste plastics and that can be mixed and compacted at room temperature.

Reclaimed asphalt pavement (RAP) refers to removed or reprocessed pavement materials containing asphalt and aggregates. The use of RAP as a partial substitute of aggregates up to a certain percentage doesn't affect the performance of the pavement[2]. The use of RAP in constructing a new pavement surface and repairing existing pavement reuses a lot of RAP that may end up in landfill sites and also helps to save a lot of material resources. Due to the environmental benefits and performance of pavement with RAP, many states' Departments of Transportation have encouraged the use of RAP and published guidelines regarding its use. Furthermore, some counties such as Los Angeles make the use of RAP compulsory.

The performance of the new mix should be similar or superior to the conventional HMA mix to be successfully used in the field. Among many other properties, fatigue cracking resistance and rutting resistance are essential properties that must be considered to examine the feasibility of the mix. The IDEAL Cracking Test (IDEAL CT) is a test to calculate the fatigue resistance of the mix. This method doesn't require cutting, drilling, gluing, or notching of the compacted sample. The Hamburg Wheel Tracking (HWT) test is a test method used to examine the rutting resistance of the mix. It is a popular and efficient rutting resistance test. In the following chapters, conventional PG 70-22 mix and Technisoil G5® mix are tested according to the IDEAL CT and HWT methods, and conclusions are drawn from the results.

2. Literature Review

Global warming and solid waste management are the most significant environmental challenge of the modern world. Plastics waste has created a significant problem for solid waste management. The dependency on plastics is increasing each year, resulting in increased production of plastics. Global production of plastics increased from two million tons in 1950 to 368 million tons in 2019.[3] Such a massive amount of plastics and the non-biodegradable nature of plastics make it harder to manage waste plastic. As a result, a huge quantity of waste plastics end up in the ocean, creating a disturbance in the aquatic ecosystem.[4] One of the effective ways to manage waste plastic is by reducing, reusing, and recycling waste plastics. With the goal of reusing waste plastics, the pavement industry has been trying to use waste plastic in paving work for a long time. Plastics-modified asphalt commercially known as Novophalt, Ditescpesa, and Polyphat have been used since the 1980s.[5] However, plastics and asphalt binder are generally incompatible when blended, which results in the phase separation (see below) between asphalt binder and plastics. Thus, plastic-modified HMA is not extensively used in commercial applications.

Plastics are added to HMA by two different methods: the dry method and the wet method. In the dry method, plastics are added as a substitute for aggregates. Plastiphalt is an example of a mix using the dry method where recycled waste plastics partially replaced the aggregate.[6] In the dry method, plastics are added to the hot aggregate/asphalt mix. Thus, only the performance of the final HMA mix can be measured. However, in the wet method, plastics are added to the binder as a substitute for the binder. This allows an examination of the change in performance of both the binder and the HMA mix when plastics are added. Thus, better quality control is available for the wet method, and the wet method is preferred over the dry method.

Many studies have been conducted to examine the effects of adding plastics to the HMA mix. The addition of recycled polyethylene (PE) showed more thermally stable behavior than when a virgin binder was used. Similarly, the addition of PE increased softening point and viscosity, and it decreased penetration and ductility.[7] The high-temperature performance grade (PG) is raised by one level for every 2% increment in PE content by the weight of the binder.[8] The use of chemical additives such as MA-g-PE and GMA-g-PE positively affected low-temperature properties, increased penetration and ductility, and enhanced high-temperature stability and compatibility between the polymer and binder.[9] Increased elasticity, cohesive strength, heat resistance, and improved low-temperature behavior are observed by the addition of SBS-type polymer additives.[10] The addition of 1.5% of linear low-density polyethylene by the total weight of the binder doesn’t show any adverse effects in the mechanical performance of HMA.[11]

There are some problems associated with the addition of plastics to asphalt binders. Phase separation and storage stability are reasons to avoid the extensive use of plastic-modified binders in pavement. The polymer’s separation from the binder during polymer modified bitumen (PMB) transport and storage is called phase separation. Phase separation depends on the difference in molecular structure, density, and molecular weight between the composite components. A higher percentage of plastics in asphalt binder means the mix will be more prone to phase separation. The use of 4 wt% of waste high-density polyethylene (HDPE) pipe showed no phase separation for a longer time.[12] The addition of 7% of recycled waste polymers showed incompatible behavior.[13] A PE concentration of more than 5% is not recommended for a binder for paving operations.[14]

In our study, storage stability refers to the tendency of recycled waste plastic to separate from the binder. Novophalt produced with 7% by the weight of PE content didn't demonstrate storage stability.[15] Higher storage stability is observed in PE modified binder with 2% low-density polyethylene than 4% by the weight of binder.[16] One way to eliminate the problem of phase separation and storage stability is to completely substitute the asphalt binder with recycled waste plastic in the pavement. Dalhat et al. conducted a study in 2016 using recycled plastic bounded concrete containing zero asphalt binders and Portland cement. The results showed that the compressive strength of recycled HDPE bound concrete is similar to asphalt concrete, and recycled polypropylene (PP) showed similar strength to Portland Cement Concrete (PCC).[17]

Hot mix asphalt (HMA) requires the heating of aggregates and asphalt binder at high temperatures. On the other hand, cold mix asphalt (CMA) is a low-carbon manufacturing approach for producing flexible pavement material that is very promising, both economically and ecologically. This technique allows mixtures to be manufactured at ambient temperature without heating a large amount of aggregates and asphalt binder. However, the presence of water within CMA makes this mix highly sensitive to traffic and environmental stresses.[18] The binder, which is completely prepared with recycled waste plastics with application temperature like CMA and performance similar to HMA, can be the most environmentally friendly pavement material. Technisoil G5® polymer is entirely made with recycled waste plastic and is in a liquid state at room temperature. The commercial use of Technisoil G5® can be a huge step towards energy conservation, waste plastic management, and future sustainability. A pilot study results showed superior performance of G5 binder at high and intermediate temperatures when 100% RAP aggregate was used, suggesting a good performance in the field when used for a surface course.[19]

Reclaimed asphalt pavement (RAP) helps to conserve resources and plays a crucial role towards future sustainability.[20] RAPs are highly used these days in HMAs. Higher percentage of RAP decrease the fatigue resistance of pavement. Thus, many transportation state agencies allow the use of RAP up to 29%.[21] The mix design becomes complex when more than 25% of RAP is used because of the asphalt binder's properties in the RAP.[22] HMA with 20% RAP shows better rutting resistance than HMA with virgin agrregates.[23]

A limited number of studies have been conducted regarding the performance of the G5 mix. More studies should be done to explore the properties of the G5 mixture.

3. Objectives

The objective of this study is to compare the mechanical properties of PG 70-22 asphalt concrete with Technisoil G5® concrete. This study aims to compare the mechanical properties of concrete mixes prepared with the virgin and 20% RAP aggregates. Fatigue cracking and rutting resistance will be examined using, respectively, the IDEAL Cracking Test and the Hamburg Wheel Tracking test. Table 1 shows the factorial to be used in the study.

Table 1. Testing Factorial

Conventional Binder	G5 Binder
Virgin Aggregate Conventional PG 70-22 Mix (VCM)	Virgin Aggregate G5 Mix (VGM)
Aggregate with RAP Conventional PG 70-22 Mix (RCM)	Aggregate with RAP G5 Mix (RGM)

4. Materials

Aggregate, binder, and air voids are the major constituents of concrete mix. Aggregate occupies about 90 to 95% of the mix's total weight and is responsible for stability. Another constituent, 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 a mix during compaction. Air voids play a vital role in the mix design and performance of the mix.

Aggregates

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").

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

Binder

The main function of the binder is to bind the aggregates together and provide strength to the mix. Binder mixes with mineral filler to form mastic, which binds aggregates with each other. Conventional binders of PG 70-22 and Technisoil G5® binders are used in this study. PG 70-22 asphalt binders for this study are provided by Asphalt Martin Company. The conventional binder consists of 1.3% of ELVALOY™ RET EP 1177 and 0.26% of polyphosphoric acid (PPA) by weight. Technisoil G5® binders are provided by Technisoil Industrial.

Table 3 shows the properties of the conventional PG 70-22 binder.

Table 3. Asphalt Binder Properties

Property	Conventional Binder PG (70-22)	Test Methods
Rotational Viscosity (Pa-s)	0.74	AASHTO T316
Elastic Recovery (%)	62.5	AASHTO T301
Dynamic Shear Rheometer Original at 70°C	1.11	AASHTO T315
Dynamic Shear Rheometer RTFO at 70°C	3.03	AASHTO T240 and T315
Dynamic Shear Rheometer PAV at 25°C	3090	AASHTO R28 and T315
BBR Stiffness S at -12°C	173	AASHTO T313
BBR Slope m-value at -12°C	0.313	AASHTO T313
Softening Point, °F	129	AASHTO T53
Penetration, dmm	70	AASHTO T49

The Technisoil G5® binder is entirely made from recycled waste plastics. The composition of binder is listed below

- Isocyanic acid, polymethylenepolyphenylene ester, polymer with alpha.-hydro.-.omega.-hydroxypoly[oxy(methyl-1,2-ethanediyl)] cover 40-50%
- 4,4'-Methylenediphenyl diisocyanate cover 20-30%

- Soyabean covers 5-10%
- Methylene diphenyl diisocyanate mixed isomers also covers 5-10%
- Polyester polyol from recycled PET occupies less than 20%

G5 binder are in a liquid state at room temperature and can be mixed and subsequently compacted at room temperature. This reduces energy consumption and carbon emissions. Furthermore, using the binder prepared by reusing recycled waste plastic may decrease the material cost. These factors may decrease the overall cost for manufacturing the mix.

5. Methodology

A series of steps are carried out to prepare the compacted samples to the required specifications before conducting the tests. These steps include mixing materials, short-term aging of the mix, compaction, and fabrication of samples.

Mixing

Aggregates were batched to meet the target gradation for the mix. Two different procedures are followed to prepare the PG 70-22 mix and G5 mix. For the PG 70-22 virgin aggregate HMA mix, a binder content of 5.4% by total weight of HMA mix was used. Similarly, for the PG 70-22 RAP mix, a binder content of 4.9% by total weight of HMA mix was used.

While preparing the PG 70-22 mix, the 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 of the aggregates and the asphalt binder. After that, the aggregates were poured into the mixing bucket and weighed on the scale. For virgin aggregate and RAP-containing aggregate, 5.4% or 4.9% of asphalt binder by the total mix weight was added, respectively. After that, the mixing bucket was placed at the mobile bucket mixer, and mixing was initiated. The aggregates start to get coated with asphalt binder. The mixing was continued until a homogenous mix formed wherein aggregates were entirely coated by asphalt binder. Once a homogeneous mix was obtained, the mixing was stopped, and the HMA mix was transferred to a tray, where it was spread to an even thickness of 1 to 2 inches.

(a) (b)

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

For the G5 mix, the aggregates and binder were mixed at room temperature 25°C (77°F) and with the mobile bucket mixture. The optimum binder content is based on the total surface area of the aggregate and the film thickness around the surface area of aggregates. A low percentage of the mineral fillers requires a low percentage of binder content and vice versa. Based on the mineral filler content of the aggregates gradation used in the study, 5.3% binder content by the total weight of the mix was found to be optimum binder content. Aggregates were mixed with a binder in the mobile bucket for about two to three minutes until a homogeneous mix was obtained.

The G5 binder cures by reacting with atmospheric moisture after it is mixed with aggregates. In PG 70-22, the mix gains strength once the mix starts to cool down, whereas the G5 mix takes about 24 hours. Thus, the G5 mix showed higher workability than PG 70-22.

Aging

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

AASHTO R30 test method was implemented for short-term aging of PG 70-22 mix. Following this test method, the 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.

For the G5 mix, the mixed materials were spread over the pan, and all large conglomerates of material larger than 6.35 mm (0.25") were separated and materials smaller than 6.35 mm were cured at room temperature for 24 hours. Then, a theoretical maximum specific gravity test was conducted.

Compaction and Fabrication

Twenty-eight compacted samples were prepared for the study. Samples were compacted with a Pine Superpave Gyratory Compactor (SGC). Fourteen compacted samples with a conventional PG 70-22 binder and fourteen samples with the Technisoil G5® binder were prepared. For the IDEAL CT, compacted samples should have a diameter of 150 mm and a thickness of 60 mm, as shown in Figure 2. For the HWT test, the procedure given by AASHTO T324 specifies how the 60-mm-thick SGC-compacted samples must be cut. 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. Those volumetric tests are listed below:

- 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

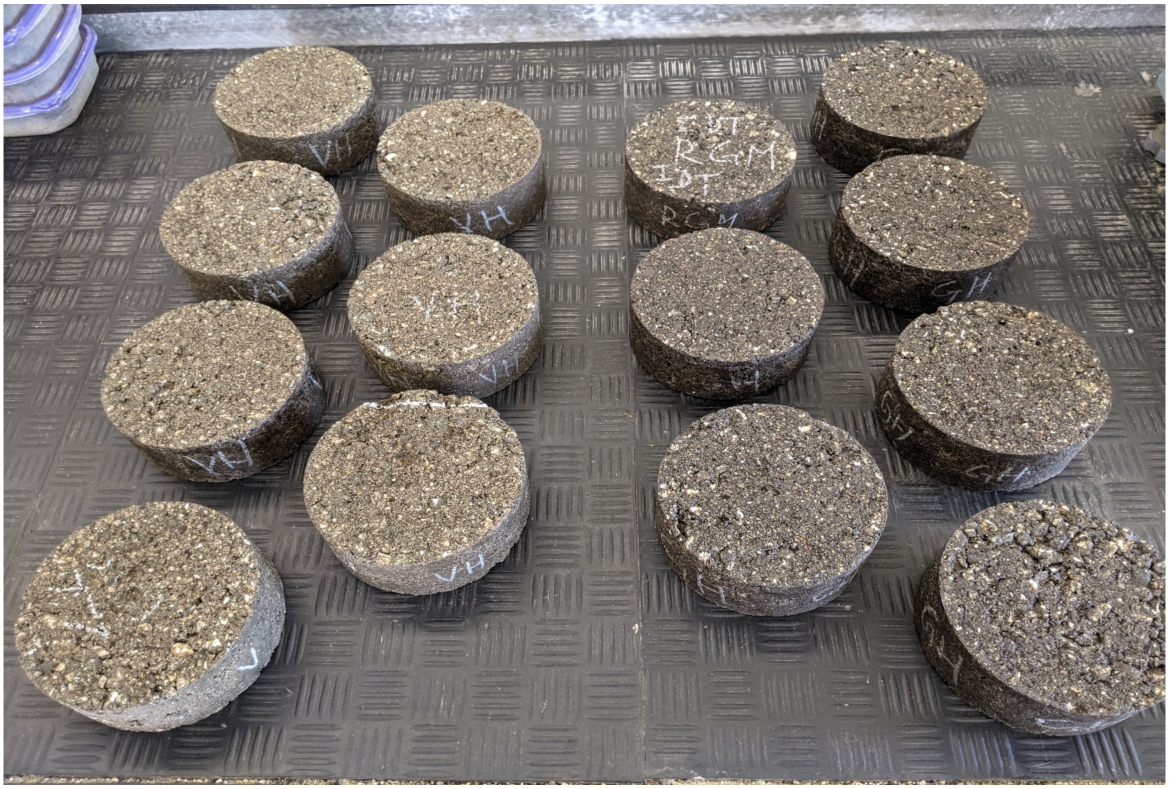

Figure 2. Superpave Gyratory Compacted Samples

The first test includes determining the theoretical maximum specific gravity (G_{mm}) of the mix according to AASHTO T209. The NMAS in this study is 12.5 mm, which require a 1500 gm of short-term aged HMA mix. G_{mm} is measured on the loose mix. Therefore, loose mix is prepared by separating/breaking large particles were by hand. Proper care was taken while separating the particles to ensure particles were separated without fracturing. No significant amount of binder should be stuck to the container or hands; the fine aggregate portion should not be larger than a quarter inch. First, the pycnometer was completely filled with water at 25°C, and the researchers 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 $\pm$ 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 setup for this test is shown in Figure 3. When atmospheric pressure was achieved, the pycnometer was partially filled with water, and the samples were completely filled with water. The researchers measured the mass of the pycnometer and sample. Once all three measurements were taken, equation 1 was used to determine the G_{mm} of the mix:

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

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 includes the compaction of the mix using the SGC to measure the bulk specific gravity of the compacted sample. The Pine Superpave Gyratory Compactor 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 a compaction temperature of 135°C for 30 minutes, as shown in Figure 4. After that, the 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 and an internal angle of 1.16° were applied. 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, and the samples stayed in their place until the rebound period was over. After that, the compacted HMA samples were extracted from the mold and left to cool down to room temperature.

Figure 4. (a) Loose G5 Mix

Figure 4. (b) Pine Superpave Gyratory Compactor Compacting the G5 Sample

The compaction process is different in the case of the G5 mix. The compaction is carried out at room temperature. Once the G5 mix hardens and gains strength, the mix cannot be reheated, like a conventional HMA mix, to make it workable. Thus, the G5 we mixed was prepared such that a batch of mix only had enough material to compact one sample, to prevent aging of mix. Once the mix was prepared, the mix was immediately fed into the compaction mold, and compaction was initiated. The squaring time was set to 15 minutes. G5 samples require a longer time to gain strength. Thus, the compacted sample was left in the mold undisturbed for one hour (±15 minutes) for curing after the squaring time to avoid the distortion of samples. The compacted sample was removed from the mold after curing and left at room temperature for 24 hours before the researchers conducted any test on the compacted sample.

The bulk specific gravity of compacted samples must be determined to calculate the air void in the superpave gyratory compacted sample. AASHTO T166 was used to determine the bulk-specific gravity. According to this test method, recently compacted samples were weighted. Later, the compacted 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:

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

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, we determined the air void in compacted samples according to AASHTO T 269. In order to calculate air voids, G_{mm} and G_{mb} are required. Air voids were calculated using equation 3:

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

V_a = percent air void

G_{mb} = bulk specific gravity

G_{mm} = theoretical maximum specific gravity.

The percent air void of 7% ± 0.5% is mandatory in SGC compacted samples as per AASHTO T324 (HWT test method). 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, we compacted 2400 g of the loose sample and determined the G_{mb} of the compacted sample. Based on the percent air void resulting 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 mix.

Table 4. Volumetric Properties

Mix Type	Total Binder Content (%)	G_{mm}	Air Voids (%)
Virgin Conventional HMA Mix (VCM)	5.4	2.501	7±0.5
RAP Conventional Mix (RCM)	5.4	2.478	7±0.5
Virgin G5 Mix (VGM)	5.3	2.514	7±0.5
RAP G5 Mix (RGM)	5.3	2.489	7±0.5

IDEAL CT sample compaction specification is same as HWT test. After compacting the sample with 7% ± 0.5% air void, the samples were ready for the IDEAL CT. However, for the HWT test, the compacted samples needed 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, and four compacted samples of each mix type were prepared for the HWT test.

Figure 5. Marking of Cut Line of PG 70-22 and G5 Mix for Hamburg Wheel Tracking Test

6. Testing

This study examines the fatigue cracking resistance and rutting resistance of conventional and plastic-modified compacted samples. The methods used to examine the compacted samples were as follows:

- For fatigue cracking, ASTM D8225-19: Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature.
- For rutting resistance, AASHTO T 324: Standard Test Method for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures.

IDEAL Cracking Test

Figure 6. IDEAL CT Testing Machine

The IDEAL CT was conducted first. We 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 Dynamic Testing System (DTS) 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, a sample deformation measurement device, temperature-controlled chambers, and a data control and acquisitions system. This test required a minimum of three SGC-compacted samples , each with a diameter of 150 mm and a thickness of 60 mm. For a sample with a 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 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 the 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 intermediate temperatures. 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 for both the mixes.

Setting the temperature chamber to 28°C was the first step to initialize the test. Once the temperature stabilized at 28°C, the compacted 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 the presence of debris may cause an incorrect measurement. The samples were then placed in an indirect tensile loading frame that was set up inside the DTS testing machine. The sample was centrally placed so as to make uniform contact with 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 for each sample/test. The test will stop once the failure of the compacted sample takes place. The sample is considered to be failed when there is displacement under a load of less than 0.1 kN. The graph is plotted between the load and displacements.

Each test produce load vs. displacement curve. The area under the load vs. displacement curve through the quadrangle rule provide work of failure (W_f), as shown in equation 4.

$$W_f = \sum_{i=1}^{n-1}\left((l_{i+1}-l_i)\times P_i + \frac{1}{2}\times(l_{i+1}-l_i)\times(P_{i+1}-P_i)\right), \text{ where} \tag{4}$$

W_f = work of failure (joules)

P_i = applied load (kN) at the i^{th} load application

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

l_i = LLD (mm) at the i^{th} step

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

Another parameter required to determine CT_{index}, failure energy (G_f), can be calculated with the help of the work of failure (W_f). Failure energy (G_f) can be calculated by dividing W_f by the cross-sectional area of the sample, as shown in equation 5:

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

G_f = failure energy (joules/m²)

W_f = work of failure (joules)

D = sample diameter (mm)

t = sample thickness (mm).

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

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

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 85% of the peak load at the post-peak stage

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

Finally, after calculating these parameters, the CT_{index} can be determined using equation 6:

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

CT_{index} = failure energy (joules/m²)

G_f = failure energy (joules/m²)

D = sample diameter (mm)

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

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

t = sample thickness (mm).

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

Hamburg Wheel tracking Test

The second test conducted was the rutting resistance test. For this test, we 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 samples in a reciprocating rolling-wheel device. SGC-compacted samples were repetitively loaded using a reciprocating steel wheel, and the resultant deformation of the samples caused by the repetitive wheel loading was measured.

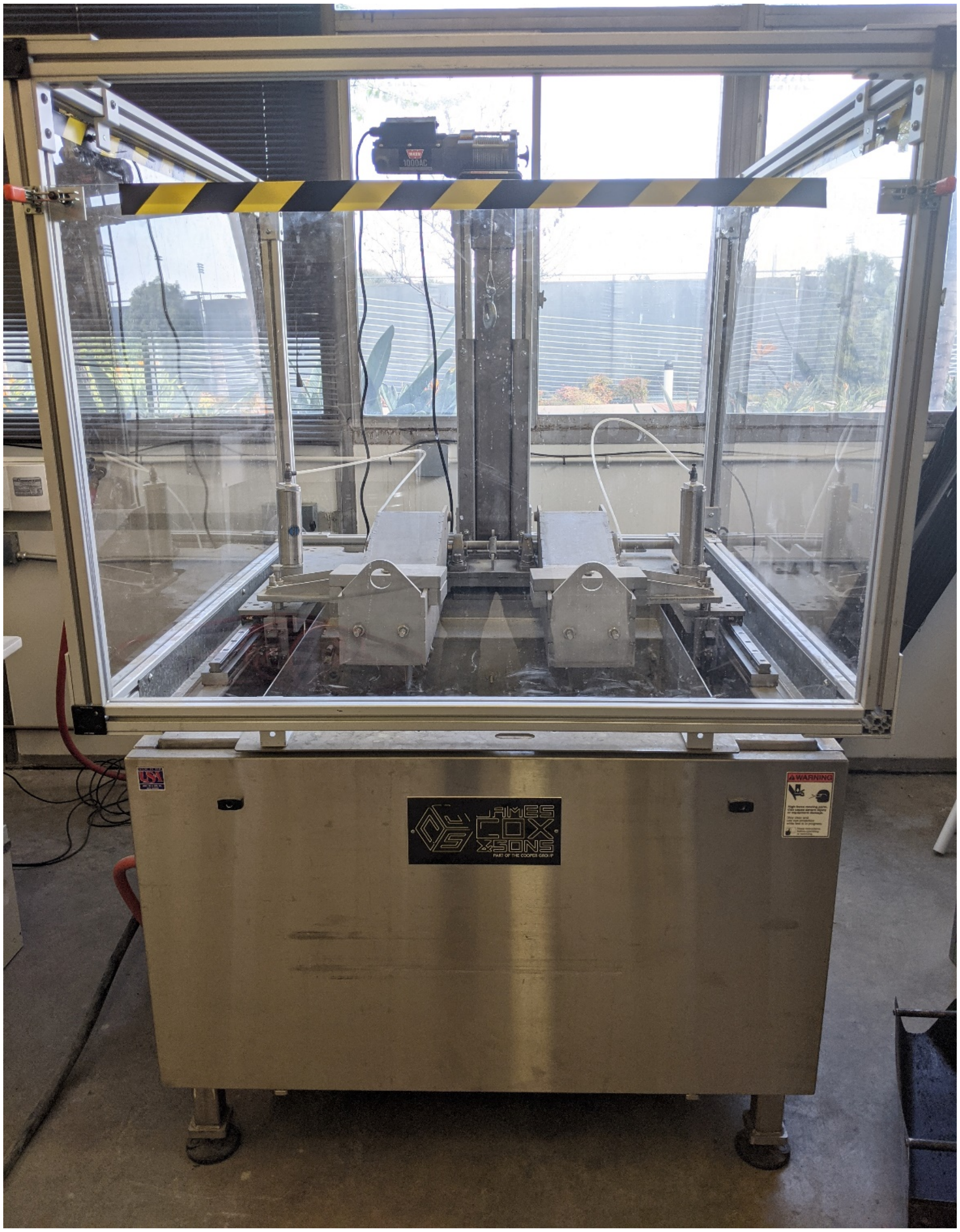

Figure 8. (a) Hamburg Wheel Machine

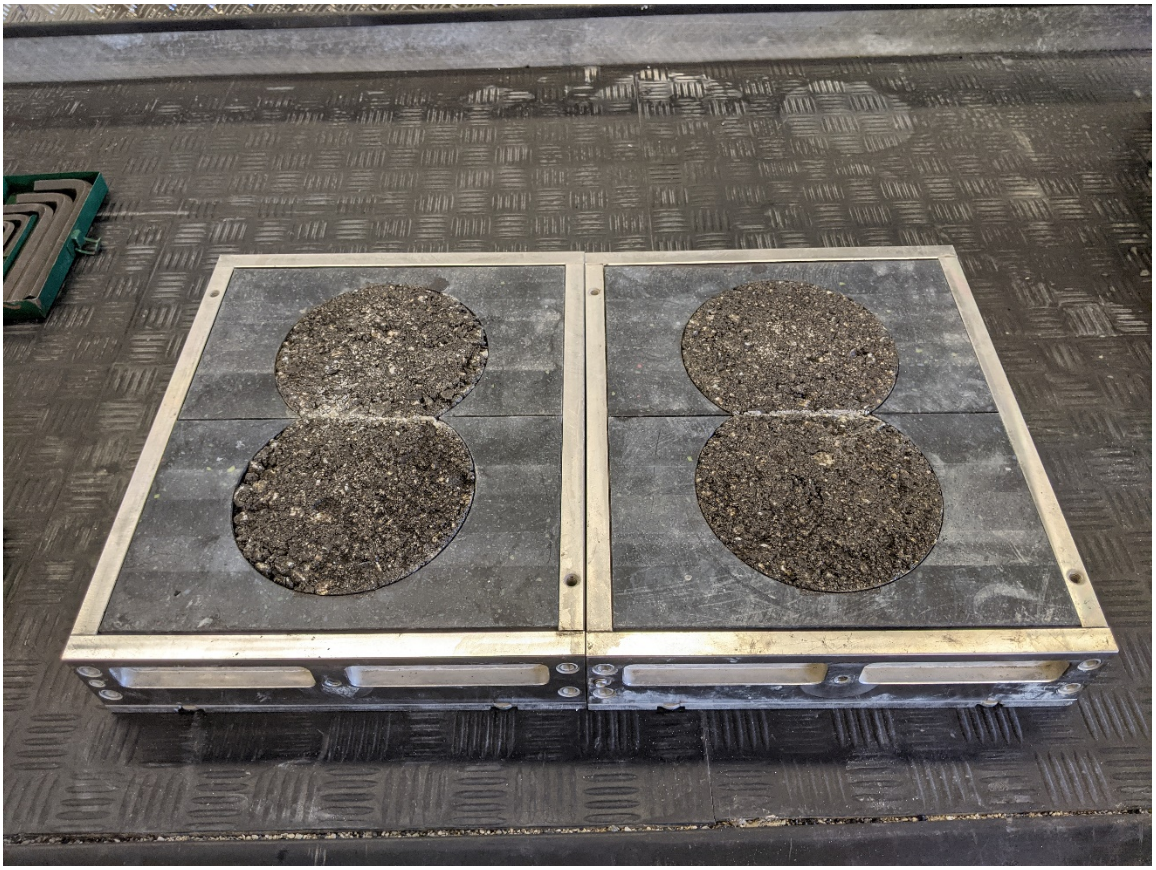

Figure 8. (b) SGC Sample Mounting System

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 8” diameter and a width of 1.85”. 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 sample was placed in the molds and secured properly in the mounting tray. When the target temperature was reached, the compacted samples were placed into the machine by submerging them in the water and conditioning them in that water bath for 45 minutes.

According to the standard, the researchers set a maximum number of 20,000 passes and a maximum rut depth of 12.5 mm in the software. The test ends when one of the cases is met. For each run, once everything was ready, wheels were lowered using a hydraulic mechanism onto the compacted sample’s edge. Proper care was taken to ensure that the wheels applied to the compacted

HMA did not exceed a five-minute period and the samples were not submerged longer than 60 minutes before starting the test.

The test was initiated after all the conditions were satisfied. The software records and plots the rut depth versus the number of passes of wheels on the sample. The test will continue 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. After all samples were tested, the wheels were raised, and samples and mounting trays were removed. The water was drained out, and debris was cleaned with a vacuum cleaner.

7. Results and Analysis

The results obtained from the IDEAL Cracking Test and Hamburg Wheel Tracking test to examine the fatigue and cracking resistance of conventional PG 70-22 binder and G5 binder are discussed below.

IDEAL Cracking Test

The software records the test data—displacement and corresponding loads. The data are then extracted to Microsoft Excel and arranged in a proper format. After that, the load vs. displacement curve was constructed.

Researchers calculated the area under the load vs. displacement curve with the help of the quadrangle rule to obtain work of failure. Similarly, other parameters, such as the absolute value of the post-peak slope and the 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 higher a mix's CT_{index} value, the higher its fatigue resistance, and vice versa. The load vs. displacement curves of different compacted samples are shown in Figures 9 through 20.

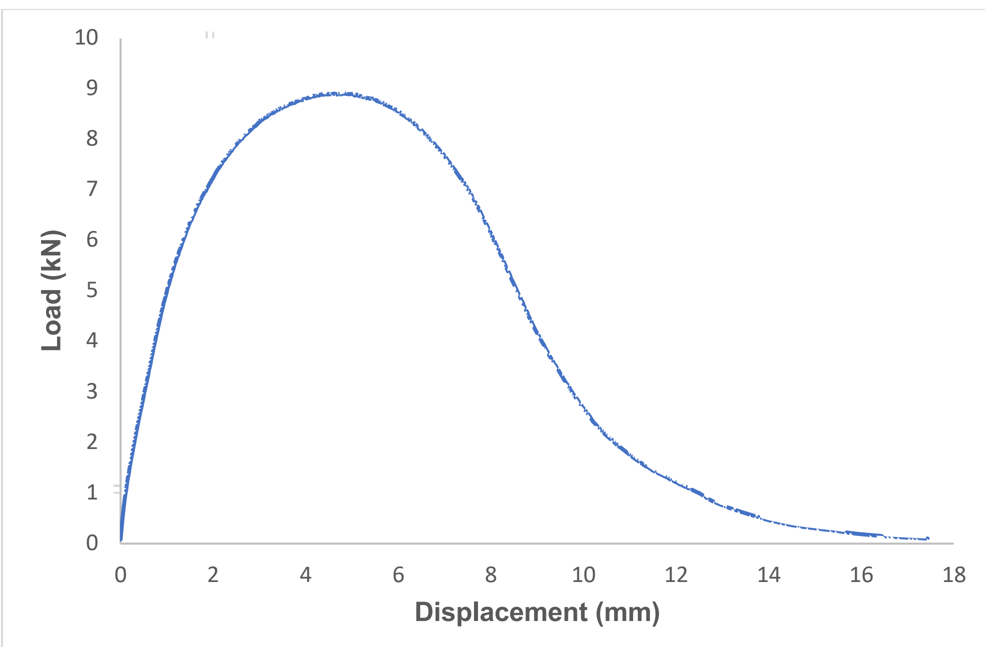

Figure 9. Load vs. Displacement Curve for VCM1

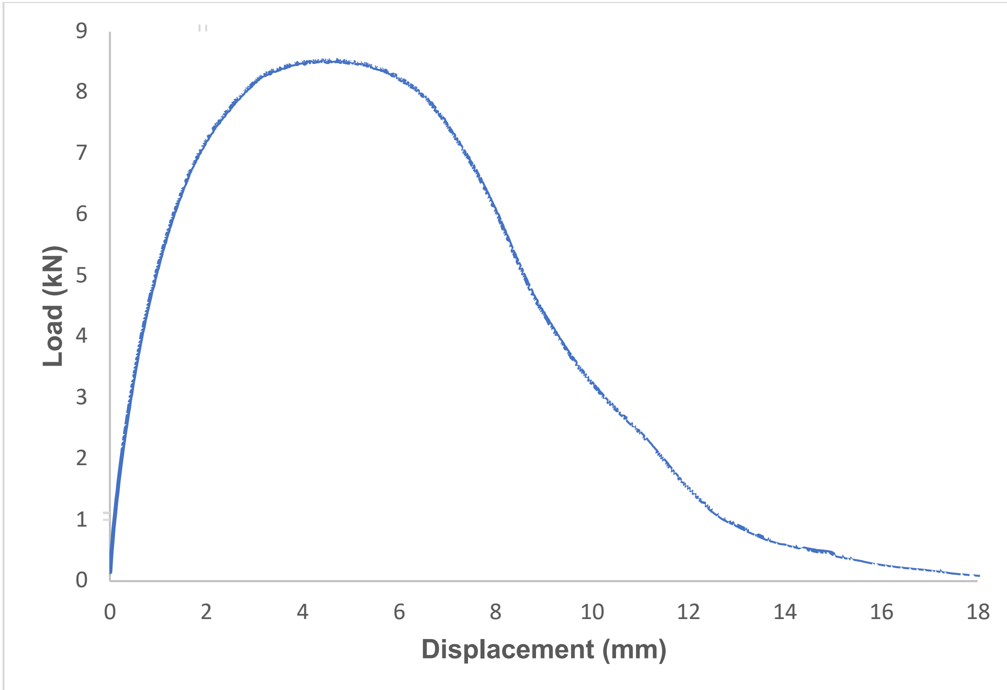

Figure 10. Load vs. Displacement Curve for VCM2

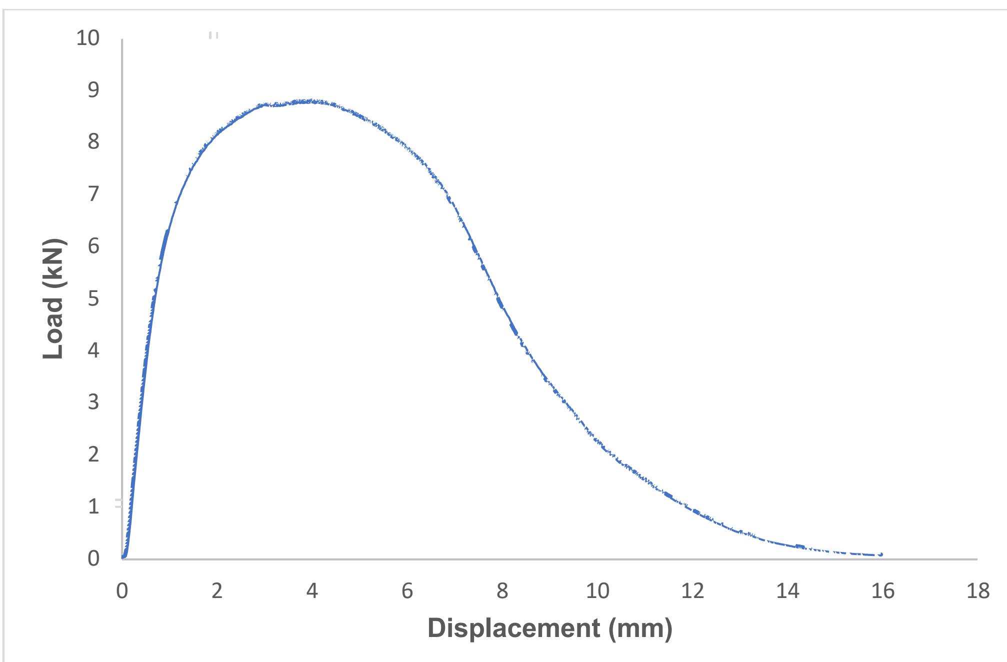

Figure 11. Load vs. Displacement Curve for VCM3

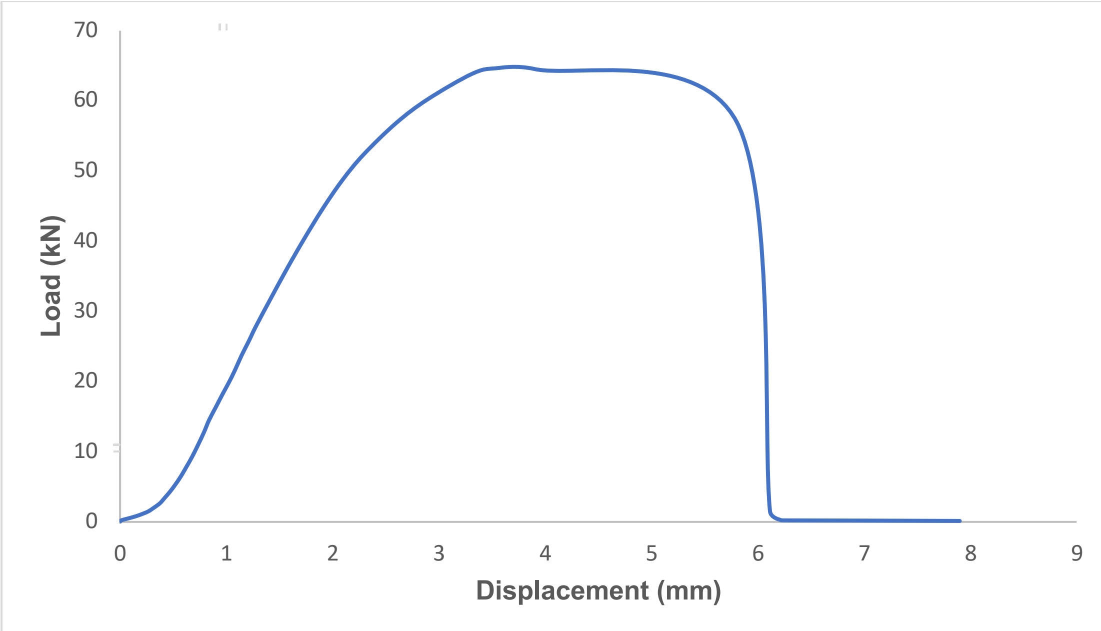

Figure 12. Load vs. Displacement Curve for VGM1

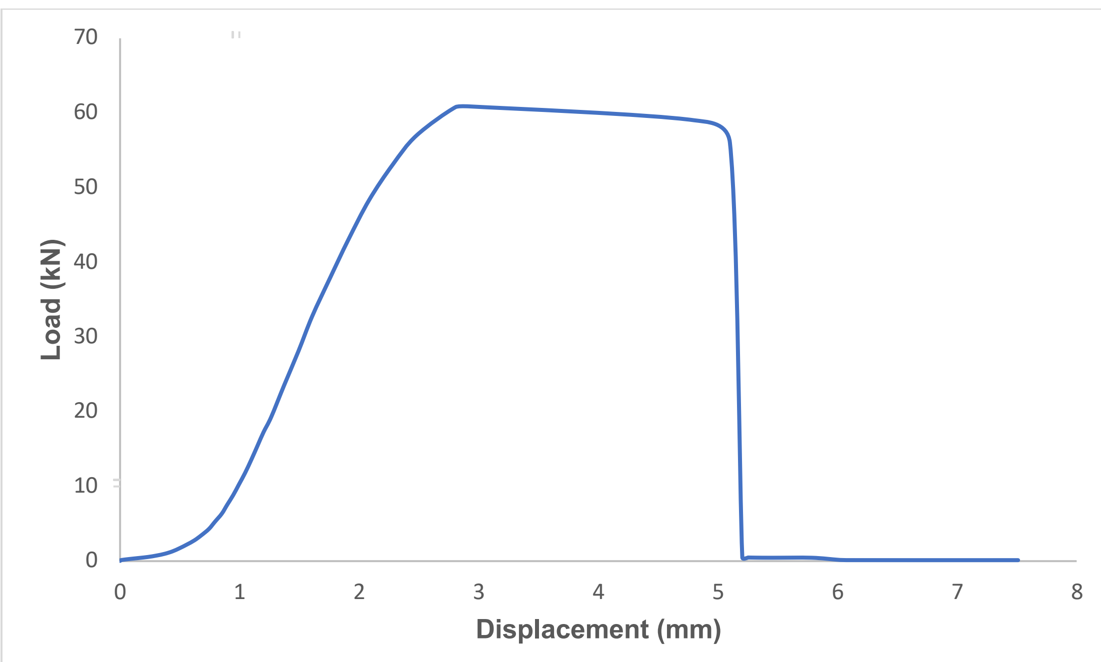

Figure 13. Load vs. Displacement Curve for VGM2

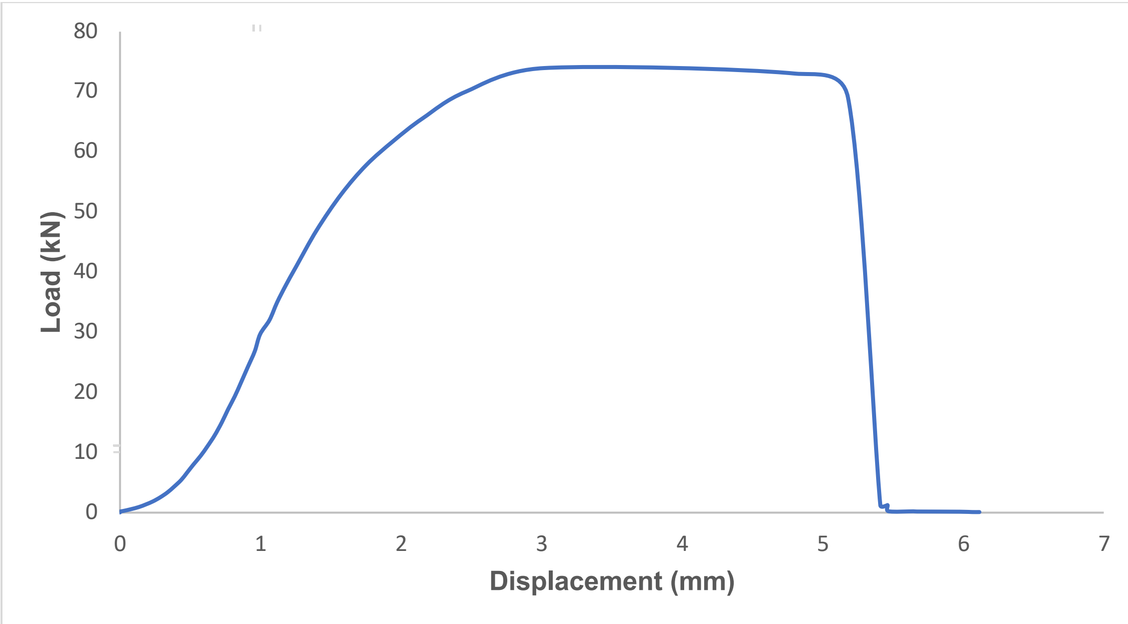

Figure 14. Load vs. Displacement Curve for VGM3

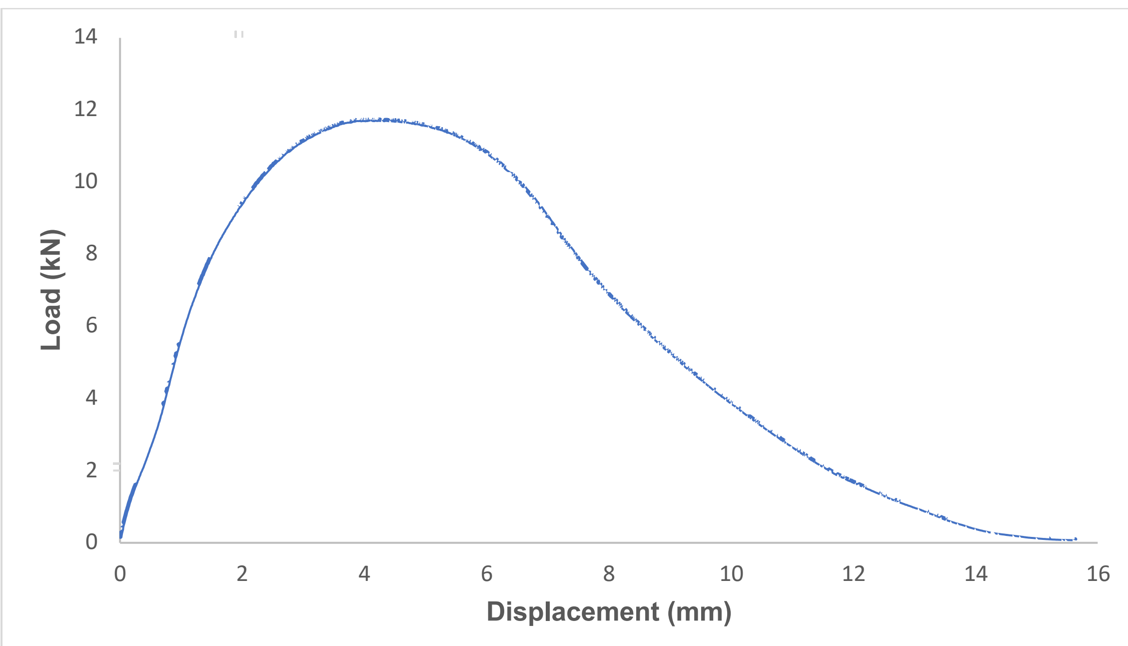

Figure 15. Load vs. Displacement Curve for RCM1

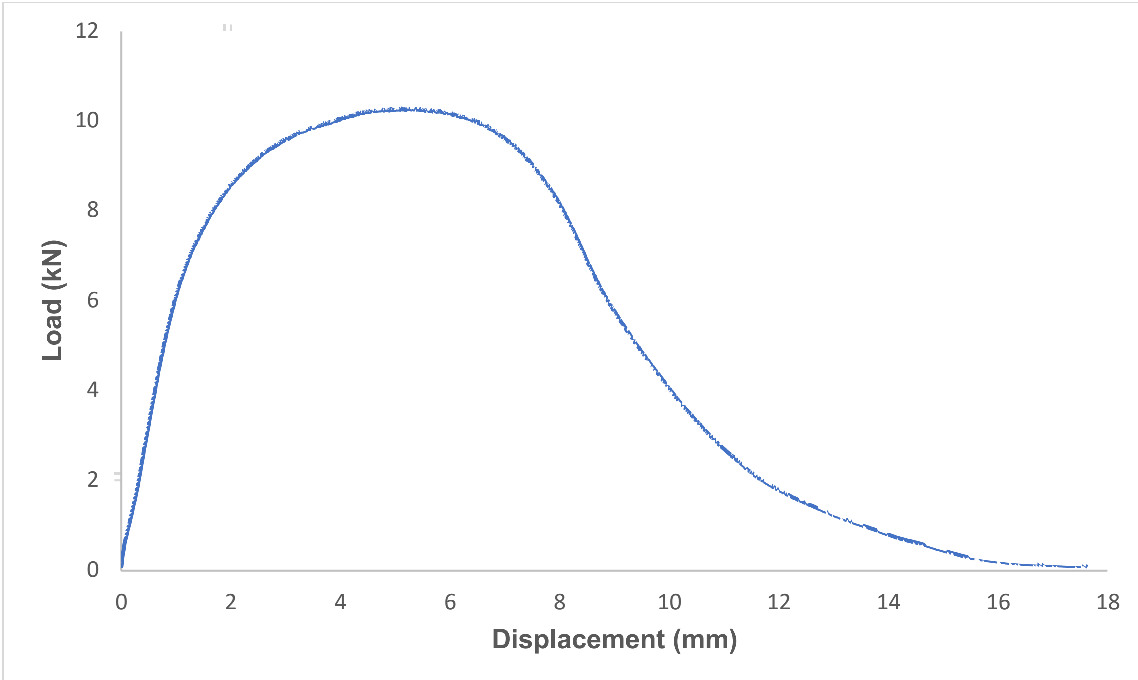

Figure 16. Load vs. Displacement Curve for RCM2

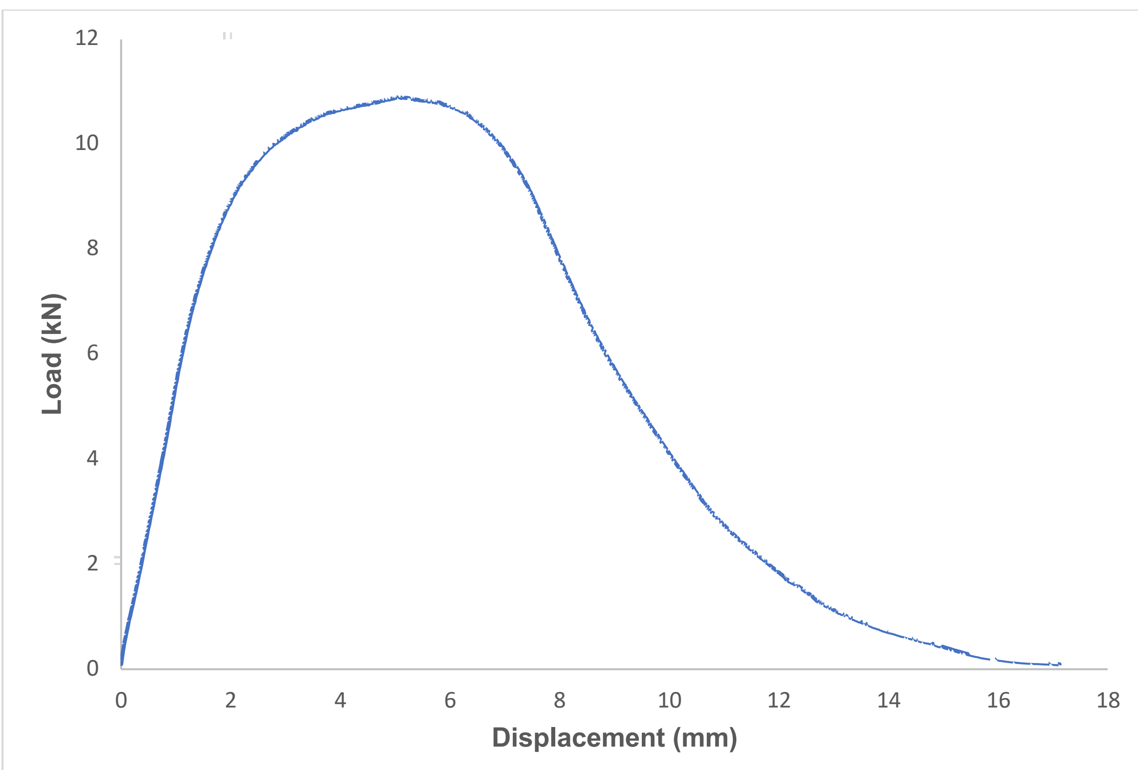

Figure 17. Load vs. Displacement Curve for RCM3

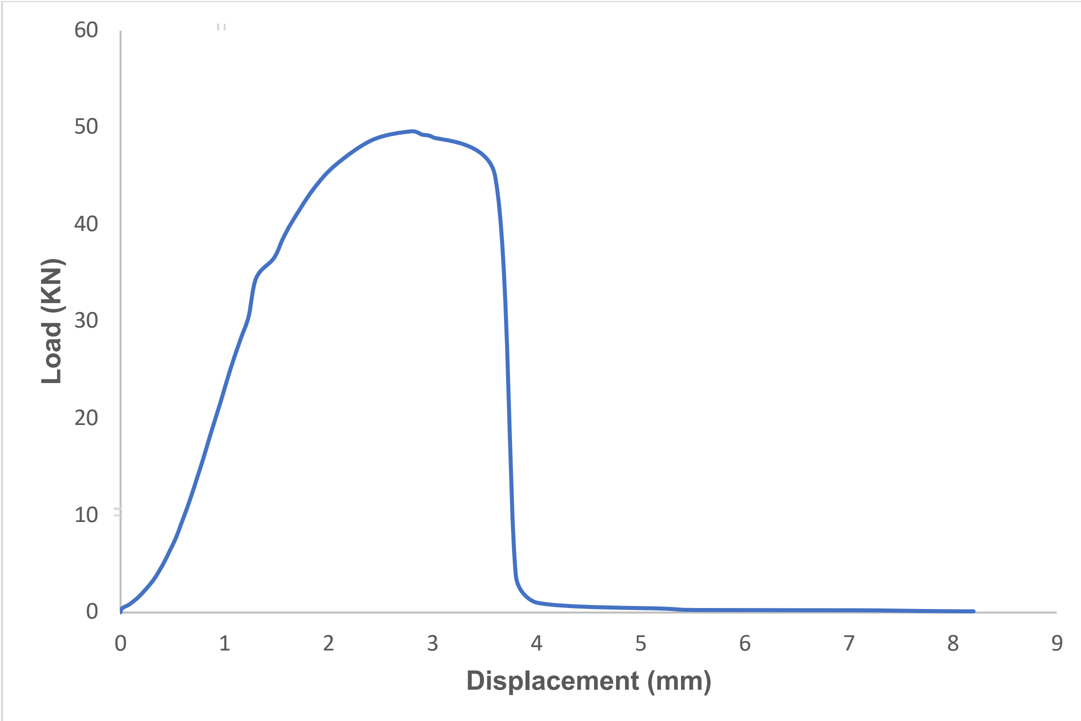

Figure 18. Load vs. Displacement Curve for RGM1

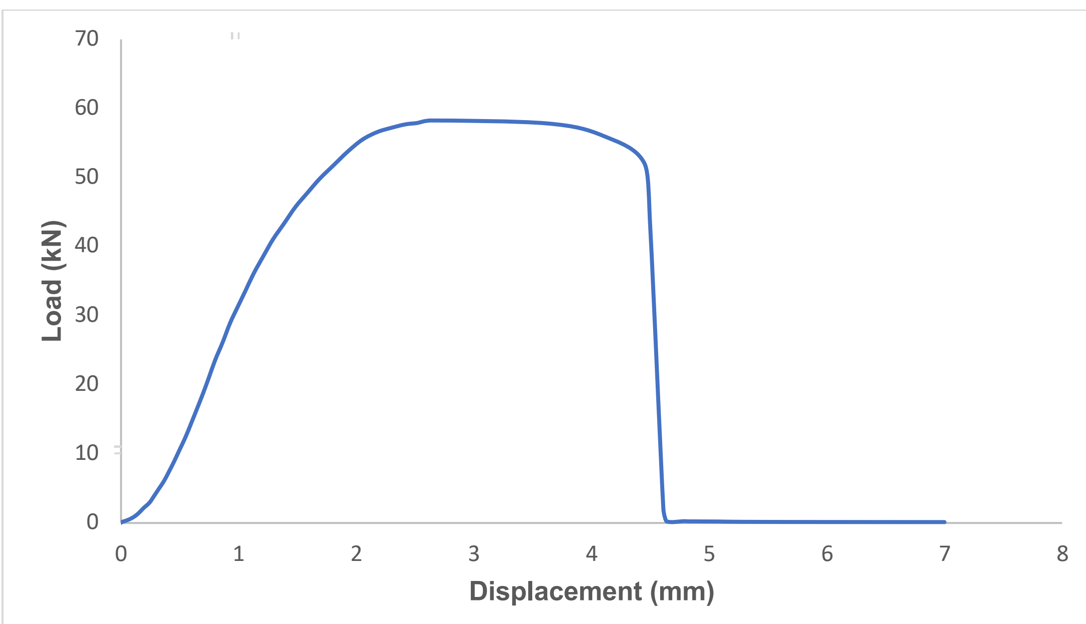

Figure 19. Load vs. Displacement Curve for RGM2

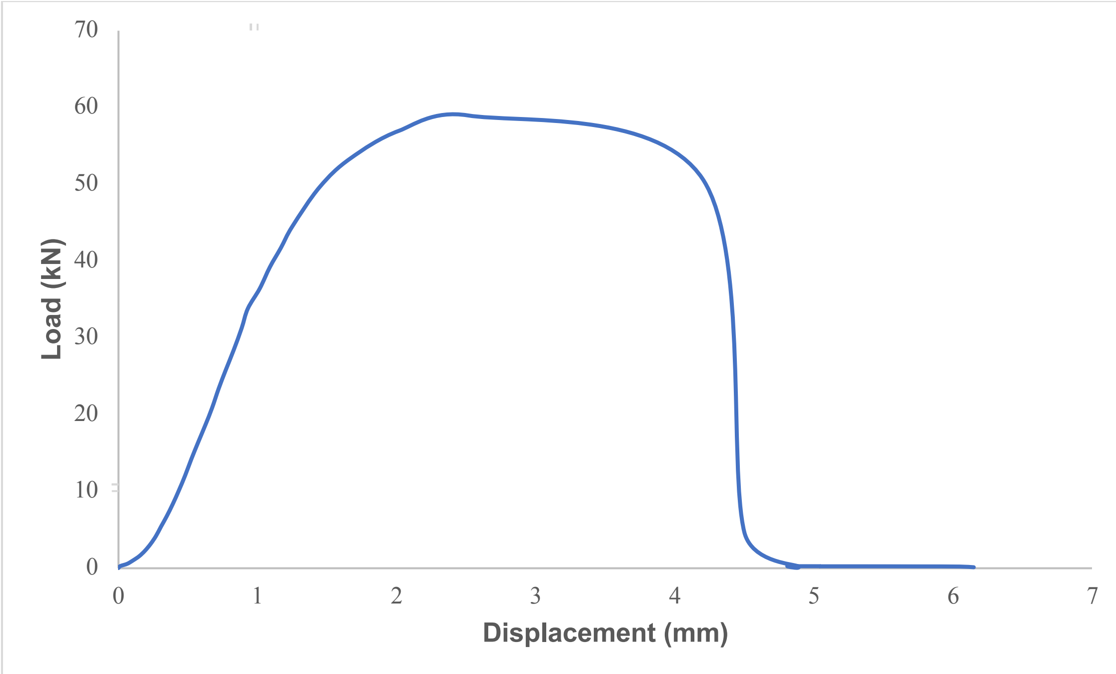

Figure 20. Load vs. Displacement Curve for RGM3

The failure energy (G_f) was determined by dividing the work of failure (obtained from the area covered by the load vs. displacement curve according to equation 4) by the cross-sectional area of samples. After that, CT_{index} was calculated. by using equation 6. Table 5 lists the CT_{index} along with corresponding parameters of each compacted sample are shown in Table 5.

Table 5. IDEAL-CT Test Results

Sample	l75 (mm)	|m75| (N/m)	Wf(J)	Gf (J/m2)	CTindex
VCM1	7.70	1623731.8	72.90	8099.7	247.87
VCM2	7.78	1533536.7	74.09	8231.7	269.59
VCM3	7.06	1592217.8	69.76	7751.1	221.84
Average VCM					246.43
RCM1	7.09	2188032.0	91.92	10213.3	213.63
RCM2	8.19	2250056.3	90.10	10011.4	235.00
RCM3	7.85	2297687.5	91.78	10197.7	224.87
Average RCM					224.50
VGM1	5.83	59644623.3	277.71	30856.7	19.46
VGM2	5.15	50708586.7	215.49	23943.1	15.69
VGM3	5.25	73909279.0	296.23	32913.9	15.08
Average VGM					16.74
RGM1	3.71	57603648.1	128.52	14279.6	5.93
RGM2	4.51	67005372.8	202.31	22478.4	9.76
RGM3	4.31	70842141.8	195.39	21709.5	8.53
Average RGM					8.07

Note: l75 is experimentally observed value.

All the G5 compacted samples showed a higher peak load compared to the PG 70-22 samples. However, the G5 samples showed brittle behavior. As a result, the CT_{index} value of all G5 samples is smaller than that of the PG 70-22 samples.

Statistical Analysis of IDEAL CT Samples

There is a difference in CT_{index} value between conventional PG 70-22 samples and G5 samples. However, to determine the significant difference between virgin and RAP mix samples, Minitab 19 was used as a statistical analysis tool. The analysis was conducted on each mixture and compared with the other mixtures. A p-value below 0.05 indicates a significant difference. Table 6 shows the p-values from the analysis.

Table 6. P-value Between Mixtures

Comparison Mix1 vs Mix2	p-value	CT_{index} Mix1 vs Mix2
VCM vs RCM	0.221	246.43 vs 224.54
VCM vs VGM	0.003	246.43 vs 16.74
RCM vs RGM	0.001	224.50 vs 8.07
VGM vs RGM	0.071	16.74 vs 8.07

Comparison between Virgin PG 70-22 (VCM) and PG 70-22 with RAP (RCM)

The average CT_{index} of VCM was found to be 246.43. CT_{index} was smaller in the case of RCM. The average CT_{index} of RCM was 224.50. The t-test showed no significant difference between the use of 20% of RAP or virgin aggregates in HMA. These results showed results similar to those of earlier studies done by other researchers on the performance of HMA with RAP.

Comparison between Virgin PG 70-22 (VCM) and Virgin G5 (VGM)

In the case of the compacted samples containing virgin aggregate, there is a considerable difference between average CT_{index} values for VCM and VGM. The VCM showed an average CT_{index} value of 246.43, and VGM showed an average CT_{index} value of 16.74. The p-value from the t-test is 0.003, which also indicates a significant drop in the fatigue resistance of virgin G5 samples compared to PG 70-22 samples.

Comparison between PG 70-22 with RAP (RCM) and G5 with RAP (RGM)

Similarly, there is a huge difference in CT_{index} values between the RCM and RGM samples. The average CT_{index} values are 224.50 and 8.07 for the RCM and RGM samples, respectively. The t-test showed a p-value of 0.001 between the average CT_{index} values of RCM and RGM, indicating that the difference in average CT_{index} values is very significant. A low CT_{index} adversely affects the fatigue resistance of the RGM mix.

Comparison between Virgin G5 (VGM) and G5 with RAP (RGM)

The difference between the average CT_{index} values of VGM and RGM is not significant. The p-value between those mixes is 0.071, indicating an insignificant difference in fatigue properties. The average CT_{index} value of VGM is 16.74, and for RGM it is 8.07.

Hamburg Wheel Tracking Test

The rutting resistance of the compacted samples was examined with the help of the Hamburg Wheel Tracking Test. VCM, VGM, RCM, and RGM compacted samples were tested. Table 7 shows the average rut depth of different HMA mixes at different numbers of passes. Similarly, Figure 21 shows the curve of rut depth vs. the number of passes.

Table 7. Hamburg Wheel Rut Depth Results

Mix Type	VCM	RCM	VGM	RGM
No. of passes	Rut Depth (mm)			
0	0.00	0.00	0.00	0.00
5,000	-3.32	-3.11	-0.27	-0.20
10,000	-6.42	-4.37	-0.30	-0.22
15,000	-8.18	-6.19	-0.31	-0.24
20,000	-8.26	-7.54	-0.33	-0.25

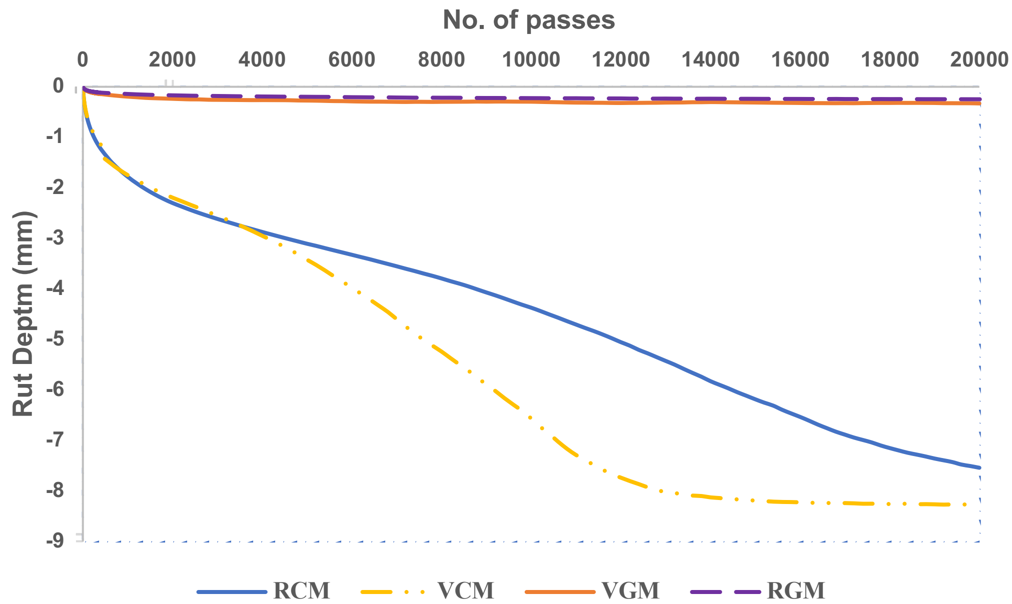

Figure 21. HWT Test Results

All the compacted samples passed the Hamburg Wheel Tracking test, which tested the samples' rutting resistance (see previous chapter for testing details). Thus, it was necessary to compare the rut depth for the different numbers of passes.

The G5 samples showed very high rutting resistance. The rut depth of the virgin and 20% RAP aggregate samples showed less than 1 mm of rut depth at the end of 20,000 passes. The rut depth after 20,000 passes in VGM samples is 0.33 mm, and for RGM samples it is 0.25 mm. The rut depth in PG 70-22 samples is high compared to G5 samples. Both VCM and RCM samples had similar rut depth until 4,000 passes. After 4,000 passes, the rate of rut depth with the number of passes increased in VCM samples more steeply than RCM samples. At the end of 20,000 passes, VCM showed a 8.26-mm rut depth, and RCM showed a 7.54-mm rut depth. In both PG 70-22 and G5 samples, 20% RAP mix showed less rut depth than the virgin aggregate mix.

8. Conclusion

Many ideas are being tested and implemented for sustainable development and environmental conservation. For example, adding RAP has been a common practice in the pavement industry to conserve resources. This study compared G5 binder completely made from recycled waste plastic with conventional PG 70-22 binder. The mechanical properties of Technisoil G5® compacted with virgin aggregate and aggregate containing 20% RAP were tested and compared to conventional PG 70-22 HMA. The following conclusions were obtained after conducting the experiment.

- There was a significant decrease in CT_{index} between the PG 70-22 samples and G5 samples. The CT_{index} value of PG 70-22 is about fifteen times higher than that of the G5 samples. This indicates that the G5 binder samples don't have good fatigue cracking resistance and may be unsuitable to use as a binder in flexible pavement.

- The post-peak curve showed the brittle characteristics of the G5 samples. Brittleness is not a good characteristic for civil engineering materials.

- There was no significant difference in fatigue cracking resistance between using virgin or RAP aggregate with G5 or PG 70-22 binders.

- The IDEAL CT revealed the peak load of G5 samples to be about three times higher than for PG 70-22 samples. G5 may be suitable for pavements that deal with heavy loads, such as airfield runways and port pavements.

- The G5 samples showed very high rut resistance. At 20,000 passes, both VGM and RGM samples have rut depth less than 1 mm. This indicates that the pavement with Technisoil G5® can take a higher repetitive load than PG 70-22 before exhibiting rutting failure.

9. Limitations and Future Work

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

The following suggestions can be tested.

- Testing the fatigue resistance test by increasing the percentage of mineral filler and G5 content in the mix to determine whether the fatigue resistance increase or not.
- Testing whether it is possible to reuse the G5 mix in the form of RAP.
- Comparing the mechanical properties of the G5 mix with the rigid pavement.

Endnotes

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Abbreviations and Acronyms

AASHTO	American Association of State Highway Officials
ASTM	American Society for Testing and Materials
CT_{index}	Cracking Tolerance Index
CMA	Cold Mix Asphalt
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
NMAS	Nominal Maximum Aggregate Size
PCC	Portland Cement Concrete
PE	Polyethylene
PET	Polyethylene Terephthalate
PG	Performance Grade
PMB	Polymer Modified Bitumen
PP	Polypropylene
PPA	Polyphosphoric Acid
RAP	Reclaimed Asphalt Pavement
RCM	RAP Conventional Mix
RET	Reactive Elastomeric Terpolymer
RGM	RAP G5 Mix
HWT	Hamburg Wheel Tracking
SBS	Styrene-Butadiene-Styrene
SGC	Superpave Gyratory Compactor
VCM	Virgin Conventional HMA Mix
VGM	Virgin G5 Mix
WMA	Warm Mix Asphalt

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