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Effect of Diesel Fuel Composition on Sealing Materials

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<p>Through several already concluded tests it is known that fuel compositions have an effect on how sealing materials react when exposed, but the results are not always easy to understand or comparable.</p> <p>This thesis provides Neste Corporation with research material on the effects of fuel composition on sealing materials at the research and development unit. The tests included in this thesis were carried out in the engine laboratory of the research and development unit in Kilpilahti, Porvoo.</p> <p>In this thesis fuels and sealing materials, and their compatibility, especially in automotive fuel systems, are studied. In the experimental part, sealing materials were tested by two different standards, ASTM D471 and ASTM D395, which define the tests that simulate the underlying conditions during vehicle usage such as temperature and mechanical compression.</p> <p>Materials which are not fully compatible with fuels were also chosen to undergo the tests. Experimenting these materials is important because it eases the visualization of extreme reactions, which then helps to understand the results.</p> <p>After the tests were successfully carried out, the differences between sealing materials could be seen. Results pointed, that materials such as fluorocarbon and nitrile rubbers, which are widely used in automotive fuel systems, showed minimal alteration. Instead, materials, such as butyl and ethylene propylene diene rubbers, which are not knowingly used in applications with imminent fuel contact, showed extreme reactions, which would be fatal for the designed functionality of automotive fuel system applications.</p>	
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<p>Useiden jo suoritettujen testien kautta tiedetään, että polttoainekoostumuksilla on vaikutus siihen, kuinka tiivistemateriaalit reagoivat altistuttuaan, mutta tutkimustulokset eivät ole aina helposti ymmärrettäviä tai vertailukelpoisia.</p> <p>Tässä insinööriyössä laadittiin Neste Oyj:lle tutkimus polttoainekoostumuksien vaikutuksista tiivistemateriaaleihin. Insinööriyöhön sisältyvät testit suoritettiin tutkimus- ja kehitysosaston moottorilaboratoriossa Porvoon Kilpilahdessa.</p> <p>Insinööriyössä tarkastellaan polttoaineita ja tiivistemateriaaleja sekä niiden yhteensopivuuksia erityisesti ajoneuvojen polttoainejärjestelmissä. Kokeellisessa osuudessa tiivistemateriaaleja koestettiin kahden eri standardin, ASTM D471 sekä ASTM D395, määrittämällä testeillä, joissa simuloidaan ajoneuvokäytön aikaisia olosuhteita kuten lämpötilaa ja mekaanista puristusta.</p> <p>Kokeisiin valikoitiin myös materiaaleja, jotka eivät täysin sovellu yhteiskäyttöön polttoaineiden kanssa. Näiden materiaalien kokeilu on tärkeää, koska silloin voidaan visualisoida äärimmäiset reaktiot, joiden kautta tulosten ymmärtäminen helpottuu.</p> <p>Kokeiden suorittamisen jälkeen voitiin havaita tiivistemateriaalien väliset erot. Tulokset osoittivat, että materiaalit kuten fluori- ja nitrilikumit, joita laajalti käytetään ajoneuvojen polttoainejärjestelmissä, suoriutuivat testeistä minimaalisin vaihteluin. Sen sijaan materiaalit kuten butyyli- ja eteeni-propeenikumit, joita ei tietoisesti käytetä sovelluksissa, joissa on välitön polttoainekontakti, reagoivat erittäin voimakkaasti, mikä olisi kohtalokasta ajoneuvojen polttoainejärjestelmäsovellusten suunnitellulle toiminnalle.</p>	
Avainsanat	tiiviste, polttoainekoostumus, koejärjestely

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List of Abbreviations

AEM	Ethylene acrylate rubber.
AFV	Alternative-Fuel Vehicle. AFV is a vehicle equipped with an internal combustion engine that operates with any other fuel than conventional fuels, e.g. gasoline or diesel. An example would be a vehicle capable of running only with fuel with high ethanol content
ASTM	American Society for Testing and Materials. ASTM is an international standardization organization
AU	Polyester urethane.
EPDM	Ethylene propylene diene rubber.
FFV	Flex-Fuel Vehicle. FFV is a vehicle equipped with an internal combustion engine that can operate with more than one fuel, which usually is gasoline with or without any content of ethanol
FAME	Fatty Acid Methyl Ester. FAME, also known as biodiesel, is a type of fuel produced from animal fats or vegetable oils through a process known as esterification
FKM	Fluorocarbon rubber.
FVMQ	Fluorosilicone rubber.
HNBR	Hydrogenated acrylonitrile-butadiene rubber.
HVO	Hydrotreated Vegetable Oil. HVO is fuel produced from animal fats or vegetable oils through a process of hydrotreating
IIR	Butyl rubber.
NBR	Acrylonitrile-butadiene rubber (nitrile rubber).

OEM	Original Equipment Manufacturer. Manufacturer which manufactures the original parts or equipment of a certain product
Ppm	Parts per million. Ppm is a percent- and permille-like relative unit that indicates how many parts of a million something is
PTFE	Polytetrafluoroethylene.
R&D	Research & Development. R&D refers to innovative activities in developing new or improving existing services and products
VMQ	Silicone rubber.

1 Introduction

The vast amount of different types and mixtures of petroleum and biofuels set high demands for sealant manufacturers to find solutions that can withstand the effects of different fuel compositions. Excellent chemical resistances are crucial for the required functionality of sealants. There is not one sealant material that meets the requirements of all applications in the automotive industry, and therefore, multiple solutions must be available for a variety of needs. Even though researches and tests are carried out to find the best sealant material that suits most automotive applications – the product development does not stop.

In this thesis, several different types of OEM sealant materials used by the automotive industry, especially in the automotive fuel systems, were tested and compared. The sealants were experimented and differentiated by properties on how the different fuel compositions affected them. Sealants tested were made from elastomeric materials, except for PTFE which is a thermoplastic polymer. These materials can be found in vehicle applications all around the world.

This thesis was assigned by Neste Corporation as a research project at the engine laboratory located in Kilpilahti, Porvoo. Neste Corporation is a Finnish refining and marketing company of high quality fuels, lubricants and chemicals, a pioneer in sustainable development and a global market leader of renewable diesel [1]. Neste invests highly in R&D in the field of renewable fuels which requires active suitability testing with current technologies and materials – for example sealants, which this thesis investigates.

The tests were conducted by designing an experimental setup for the safe immersion of sealant materials in fuels. A key factor during the tests was to simulate the conditions such as temperature and mechanical pressure in which the sealants are used in vehicles to get genuine results. During and after these test cycles analyzing, reporting and creating visual data for further use played a major role for the commissioner of this thesis, Neste Corporation.

This thesis is divided into parts where theory leads to practice. First the background of the thesis is explained; after that the experiments are conducted and the results are analyzed.

2 Use of Sealants

Sealants are used to develop a static seal between two separate members of a mechanical assembly and to maintain that seal under operating conditions, which may differ because of changes in pressure, temperature or a variety of chemical exposures. If two surfaces could be connected perfectly, and if it was possible to maintain the intimate contact under extreme conditions, a sealant would not be needed. However, since this is not possible, sealants must be used because of the following reasons:

- size of the edges that require sealing in the application,
- difficulties in manufacturing a connecting surface so smooth that it would not require sealing,
- corrosion, erosion and other materialistic wear and tear on the surface of the edges,
- the amount of sealable connections in a typical mechanical application.

A sealant provides a seal by utilizing external forces that compress the sealant material between the connecting surfaces. The connection of the surfaces would be imperfect without a sealant, and because of that, for a functioning sealant closure, three major aspects must be considered for a sufficient seal to be achieved.

- enough force must be applied to the connection so that the sealant between it squeezes into the surface structures and seals the connection,
- force must be sufficient, but not excessive, so that the sealant can maintain its capabilities under operating conditions,
- sealant material must be chosen correctly for the desired application so that it can withstand the effects, such as temperature in its whole range, pressure exerted to the connection and exposure to the present chemicals. [2, p. 4.]

2.1 Automotive Applications

In automotive applications, sealants are used for blocking the passage of oils, fuels and other liquids of chemical nature through the surface, joints or openings in the engine compartment, fuel systems and other mechanical applications which require sealing.

Varying temperatures, pressures and chemical exposures, particularly in applications in the engine compartment of a vehicle, set high requirements for the durability, performance and resistivity of the sealants. A sealant that meets these requirements, should also be lightweight, efficient and recyclable to lower the overall costs. [3, p. 3; 4.]

Especially in fuel systems, different fuel compositions can cause insidious effects and serious damage to sealants. This requires high amounts of suitability research to find the correct material because of the large selection of fuel types and blends available on the market.

There are many affected components (figure 1) in a typical vehicle and all of these require a variety of sealants to function as designed. Components and the sealants affected by fuel can be listed in the following order from the filling station to combustion in cylinders:

- fuel filler and cap,
- fuel tank,
- fuel filters and fuel valves,
- fuel pumps,
- fuel lines,
- fuel line connectors,
- fuel rails,
- regulators and dampers,
- fuel injectors.



Figure 1. Affected components in fuel systems [4].

As the demand for better technologies increases in the automotive industry, the sealant solutions must keep up with it. Constant testing and development of new materials and products is required to meet the ever-changing needs. [3, p. 3.]

2.2 Adverse Effects of Fuel Composition

Fuels are known to influence certain types of elastomers, natural rubbers and plastics used as sealants in automotive fuel systems [5, p. 26; 6, p. 121; 7; 8, p. 103]. Common ways for the damage to occur is during longer periods of fuel storage. Fuels being vulnerable to oxygen causes fuels to oxidize and to form hydroperoxides and carboxylic acids, which then causes damage to the immersed sealants. Oxidizing of fuels is more of a problem with biofuels (especially FAME) than with fuels derived from petroleum. [9, p. 25–26, 49.]

Variations in temperature and contamination of the fuel are known to accelerate the adverse effects of chemical degradation. For example, FAME with even the smallest percentage of water can have a significant effect on the adverse reaction. [4.]

There are many alternatives on how sealant materials react when exposed to a chemical for which it does not have good resistance to. Usually, the negative reactions have harmful effects related to functionality, such as swelling (figure 2), which may cause the material to soften, which can then lead to loss of sealing force and cause possible leaks from the system. Other possible disadvantages are hardening and shrinkage of the material, which usually leads to the material drying and losing its elasticity which then leads to an eventual failure. [6, p. 121; 7.]



Figure 2. Example of volumetric swell on an elastomeric O-ring before and after immersion to an inappropriate chemical [10, p. 33].

The degradation is not always as obvious as in figures 2, 3, 4 and 5, so other means of damage identification must be conducted. There are various standardized tests to find out the changes in the properties of elastomers.



Figure 3. Visible chemical degradation on an elastomeric O-ring [10, p. 34].

Adverse effects, visible and nonvisible, caused by chemical degradation, even by the slightest margin, are irreversible, and therefore, it is important to perform a full environmental check on the material selection [10, p. 34].



Figure 4. Visible chemical degradation on an elastomeric O-ring [10, p. 34].

Structural changes in elastomers posed by chemical degradation may promote the damage caused by compression (figure 5), in applications where the sealant is exposed to constant or momentary mechanical pressure. This effect, however, is usually quite rare because of the high elastic properties of elastomeric substances. [10, p. 34.]



Figure 5. Fracturing of an elastomeric O-ring caused by over-compression [10, p. 34].

3 Presentation of the Experiments

The features of various fuels are known to have an influence of different results on sealing materials when they are in direct contact for longer periods of time. These tests are conducted extensively and the results are somewhat publicly released but the data available is not always clearly understandable or comparable.

The experiments in this thesis were carried out to provide Neste Corporation with test results of the effects of fuel composition on sealing materials executed in their own facilities. Experiments are divided into two major parts; one part being the standardized tests ASTM D471 and ASTM D395 to sealant materials, and the other part being the analysis of each material's success and comparison of all the results.

3.1 Materials

Sealants are in most cases made from substances of rubber, known as elastomers, which are sometimes combined with a strengthening part such as carbon, graphite, metal or thermoplastics, such as PTFE [3, p. 7, 13; 2, p.15].

3.1.1 Elastomers

Elastomers are based on polymers which have the property of elasticity. Elastomers are made up of long chains of carbon, hydrogen and oxygen atoms, which are cross-linked with the neighboring chains. These cross-linking bonds pull the elastomer back in to shape when the force causing the deforming is removed.

Elastomers are by far one of the most versatile engineering materials available. The extraordinary property of being able to deform and recover under load makes them very different from plastics and metals.

Though unique properties such as elasticity and resiliency apply to almost all variations of elastomers, research on choosing the most suitable material for the desired application must be conducted. Exposures to harsh chemicals, temperature extremes and changes in pressure can exclude some materials for the intended application because of complete incompatibility. [10, p. 4–5.]

The elastomeric materials for the tests were received from Trelleborg Sealing Solutions Germany GmbH (table 1).

Table 1. List of elastomers received from Trelleborg Sealing Solutions Germany GmbH.

Material	Category	Supplier
AEM, ethylene acrylate rubber	Elastomer	Trelleborg Sealing Solutions Germany GmbH
EPDM, ethylene propylene diene rubber	Elastomer	Trelleborg Sealing Solutions Germany GmbH
FKM, fluorocarbon rubber	Elastomer	Trelleborg Sealing Solutions Germany GmbH
FKM, fluorocarbon rubber with higher fluorine content	Elastomer	Trelleborg Sealing Solutions Germany GmbH
FVMQ, fluorosilicone rubber	Elastomer	Trelleborg Sealing Solutions Germany GmbH
HNBR, hydrogenated acrylonitrile-butadiene rubber	Elastomer	Trelleborg Sealing Solutions Germany GmbH
IIR, butyl rubber	Elastomer	Trelleborg Sealing Solutions Germany GmbH
NBR, acrylonitrile-butadiene rubber (nitrile rubber)	Elastomer	Trelleborg Sealing Solutions Germany GmbH
AU, polyester urethane	Elastomer	Trelleborg Sealing Solutions Germany GmbH
VMQ, silicone rubber	Elastomer	Trelleborg Sealing Solutions Germany GmbH

Materials for the tests were chosen with anticipation of the fact that some might not be suitable for applications with a possibility of fuel exposure. It is of high importance to conduct tests also to these materials, so the results are much easier to compare, visualize and understand.

Received materials were not directly mentioned by the material. Trelleborg Sealing Solutions uses their own codes to recognize the materials. Some of the materials are even dyed to specific colors for easier identification. Material codes and colors can be identified as seen in table 2.

Table 2. Trelleborg Sealing Solutions material codes and colors.

Material	Material code	Colour
AEM, ethylene acrylate rubber	ACT70	Black
EPDM, ethylene propylene diene rubber	E7T70	Black
FKM, fluorocarbon rubber	V7T30	Black
FKM, fluorocarbon rubber with higher fluorine content	VCT7B	Green
FVMQ, fluorosilicone rubber	FCT30	Yellow
HNBR, hydrogenated acrylonitrile-butadiene rubber	H7T32	Black
IIR, butyl rubber	I7I03	Black
NBR, acrylonitrile-butadiene rubber (nitrile rubber)	N7T30	Black
AU, polyester urethane	Z20	Turquoise
VMQ, silicone rubber	S7T30	Red

AEM, Ethylene Acrylate Rubber

Typical applications for AEM are all kinds of static seals in vicinity of oils as they occur in gearboxes, oil pumps, cam covers and other similar applications. Operating temperatures for AEM materials range from $-40\text{ }^{\circ}\text{C}$ to $+160\text{ }^{\circ}\text{C}$ and momentarily up to $+190\text{ }^{\circ}\text{C}$.

AEM has excellent resistances to most oils and greases (even with aggressive additives), heat and ozone. It also shows good properties in colder climates. Special formulations of AEM can be manufactured to have an increased resistance to chemicals. [11.]

EPDM, Ethylene Propylene Diene Rubber

Applications where glycol based brake fluids and hot water are used, are often sealed using EPDM sealants. Temperature range for EPDM material operation is from $-45\text{ }^{\circ}\text{C}$ to $+150\text{ }^{\circ}\text{C}$ and for a short period of time up to $+175\text{ }^{\circ}\text{C}$. EPDM sealants vulcanized with sulfur have a lowered temperature operation area of $-45\text{ }^{\circ}\text{C}$ to $+130\text{ }^{\circ}\text{C}$ (momentarily up to $+150\text{ }^{\circ}\text{C}$.)

EPDM sealants have good resistances to heat, ozone and aging. A high level of elasticity, good behavior in lower temperatures as well as good insulation are also some of the properties of EPDM. [12, p. 6.]

FKM, Fluorocarbon Rubber

FKM material is particularly known for its non-flammability, low gas permeability and excellent resistances to ozone, weathering and aging. Temperature range for FKM material begin from $-20\text{ }^{\circ}\text{C}$ to $+200\text{ }^{\circ}\text{C}$ and $+230\text{ }^{\circ}\text{C}$ for a limited amount of time. Special formulations of FKM material can function in temperatures as low as $-35\text{ }^{\circ}\text{C}$. Common uses of FKM materials are applications where direct contact with mineral based oil or grease is certain at higher temperatures. [12, p. 7.]

Different structure and fluorine content can greatly influence the chemical resistance of FKM [4.] For this reason, two types of FKM were received for the tests; one with so-called standard properties and the second one with higher fluorine content, which increases its resistance to chemicals.

FVMQ, Fluorosilicone Rubber

Good heat resistance, very good flexibility in low temperatures, good electrical properties and excellent resistances to weather, ozone and UV rays are some of the features of FVMQ materials. Compared to a standard silicone material, FVMQ has better chemical resistance especially to hydrocarbons, aromatic mineral oils, fuels and low molecular aromatic hydrocarbons such as benzene and toluene.

Temperature range for FVMQ materials range from $-50\text{ }^{\circ}\text{C}$ to $+175\text{ }^{\circ}\text{C}$ and temporarily up to $+200\text{ }^{\circ}\text{C}$. [12, p. 7.]

HNBR, Hydrogenated Acrylonitrile-Butadiene Rubber

HNBR material is made from NBR butadiene groups via selective hydrogenation. HNBR material properties are dependent on the ACN (acrylonitrile) content, ranging from 18 % to 50 %, as well as the materials degree of saturation. Operating temperatures for HNBR material range between $-30\text{ }^{\circ}\text{C}$ to $+140\text{ }^{\circ}\text{C}$ with time limited extensions of up to $+160\text{ }^{\circ}\text{C}$. Special types of HNBR can be used in temperatures as low as $-40\text{ }^{\circ}\text{C}$.

HNBR materials show good mechanical properties and functions well with mineral oils and greases. [12, p. 7.]

IIR, Butyl Rubber

IIR has a very low permeability for gas and moisture. On top of that, the material shows good resistance to many organic and inorganic chemicals, ozone, weathering and aging. The electrical insulating properties of IIR are also excellent.

Range of temperature where IIR materials function, ranges from $-40\text{ }^{\circ}\text{C}$ to $+110\text{ }^{\circ}\text{C}$ and momentarily up to $+120\text{ }^{\circ}\text{C}$. [12, p. 7.]

NBR, Acrylonitrile-Butadiene Rubber (Nitrile Rubber)

NBR material properties are highly dependent on the ACN content ranging from 18 % to 50 %. Suitable formulations of NBR have good mechanical properties and they work well with mineral based oils and greases.

Temperature range for NBR starts from $-30\text{ }^{\circ}\text{C}$ to $+100\text{ }^{\circ}\text{C}$ (momentarily up to $+120\text{ }^{\circ}\text{C}$.) Specially formulated NBR can be used in temperatures as low as $-60\text{ }^{\circ}\text{C}$. [12, p. 7.]

AU, Polyester Urethane/EU, Polyether Urethane

In general polyurethanes are an exceptionally complex group of elastomeric materials. Typically, polyurethanes are individually designed for the intended purpose of application, and because of this it is hard to unify any of its unique properties.

Temperature range for polyurethanes starts from $-50\text{ }^{\circ}\text{C}$ to $+110\text{ }^{\circ}\text{C}$, with feasibility to go even higher. [12, p. 7.]

In automotive fuel systems, the chosen polyurethane should be polyester because it is more resistant to oils, fuels, fuel vapors and solvents. [13.]

VMQ, Silicone Rubber

VMQ has excellent heat resistance, cold flexibility and dielectric properties as well as good resistance to weather, ozone and UV rays. Special formulations of VMQ work well with aliphatic engine and gear oils, high temperature water and high-molecular chlorinated hydrocarbons.

Operating temperature for VMQ materials is between $-50\text{ }^{\circ}\text{C}$ to $+175\text{ }^{\circ}\text{C}$, and for a short period up to $+230\text{ }^{\circ}\text{C}$. [12, p. 7.]

Operating temperature ranges of different elastomers are shown in the figure (figure 6) in a more comparable and reader-friendly manner.

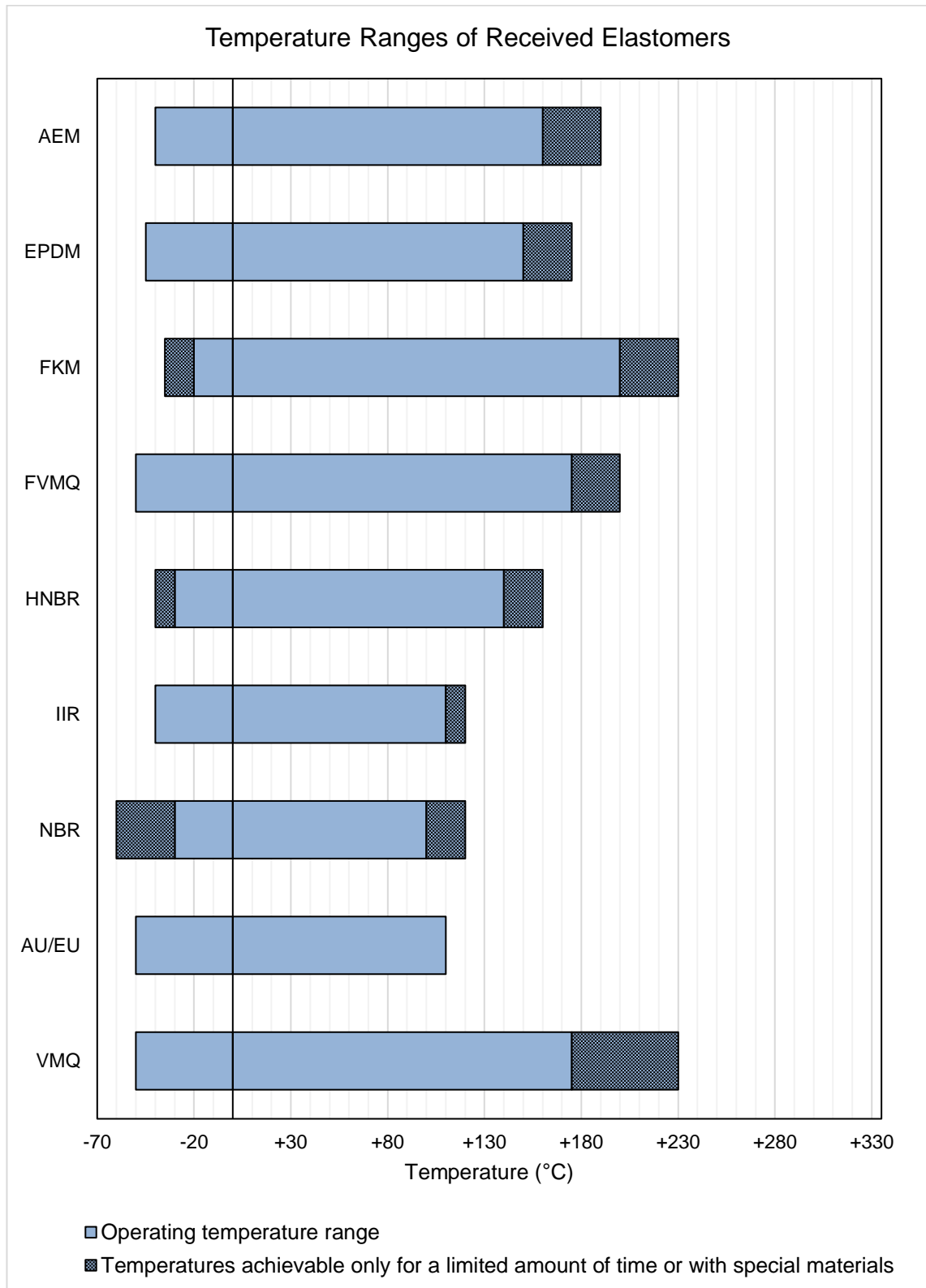


Figure 6. Temperature ranges of different elastomers used in automotive applications.

3.1.2 Thermoplastics

A thermoplastic polymer consists of long, unlinked polymer molecules generally with a high molecular weight. Thermoplastics form a crystalline structure under cooler temperatures, resulting in a smooth surface and significant structural strength. As the temperature rises, thermoplastics gradually soften and gain some elastic properties until they eventually melt.

Seals fabricated or strengthened with thermoplastics are used in applications where sealing materials such as elastomers fail to meet the required temperature range, chemical resistance or friction and wear requirements. Strengthening sealants means covering it with the thermoplastic to give it some of the extraordinary properties (figure 7).

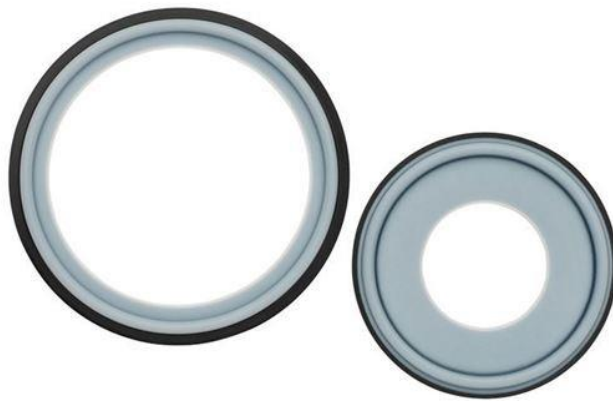


Figure 7. PTFE strengthened elastomer O-ring and gasket.

PTFE, Polytetrafluoroethylene

Pure PTFE is a white waxy solid which has remarkable properties because of its unique molecular structure. PTFE has a wide temperature range of $-270\text{ }^{\circ}\text{C}$ to $+260\text{ }^{\circ}\text{C}$ with a melting point of $+342\text{ }^{\circ}\text{C}$, excellent resistivity for degradation and heat-aging, and shows no alteration in physical properties during temperature cycling. It has one of the lowest friction coefficients in solid materials and exceptional dry running ability because of its self-lubricating capabilities. PTFE also precludes reactions, for example decomposition under pressure and swelling when exposed to chemicals with virtually all industrial applications – even at elevated conditions. [14, p. 7.]

In automotive applications, PTFE has emerged as one of the most common type of thermoplastic polymer for sealants.

PTFE materials for the tests were received from Trelleborg Sealing Solutions Finland Oy (table 3).

Table 3. List of compounded PTFEs received from Trelleborg Sealing Solutions Finland Oy.

Material	Category	Supplier
Virgin PTFE compounded with Turcon® additive	Thermoplastic	Trelleborg Sealing Solutions Finland Oy
Virgin PTFE compounded with carbon and graphite	Thermoplastic	Trelleborg Sealing Solutions Finland Oy

Thermoplastic materials which were obtained from Trelleborg Sealing Solutions Finland Oy, were not pure PTFE because of their availability and rather infrequent usage due to their softness.

As the received elastomers, PTFE materials also have their own codes and colors with which they are identified from. Material codes and colors can be seen in table 4.

Table 4. Trelleborg Sealing Solutions material codes and colors.

Material	Material code	Colour
Virgin PTFE compounded with Turcon® additive	T51	Turquoise
Virgin PTFE compounded with carbon and graphite	T05	Black

The compounded materials which were received are commonly used in automotive applications [15].

3.2 Fuels

The reason why some fuels cause vigorous reactions and others do not, is because fuels differ from each other in many ways. The main differences are the base material which they are processed from, renewability, processing method, chemical composition and the characteristics of performance. [5; 6.]

This chapter comprehensively investigates fuels and their differences from a general point of view. During the execution of the tests in chapter 4, the fuels used are presented more specifically.

Concepts

Flash point is the lowest temperature where vapors of the material will ignite, when given an ignition source.

Cetane rating is a diesel fuel rating or a number which indicates the time between the start of the injection and the first identifiable pressure increase during combustion. Higher cetane rating refers to a shorter ignition delay, or in other words, how easily the fuel can be ignited. Good cetane number is required for a diesel to properly start and warm-up with an even combustion in low temperatures. [6, p. 119; 16, p. 83.] In Europe, diesel is required by the standard EN 590 to have a cetane rating of at least 51 [17, p. 17].

Pour point is the temperature below which the liquid comes semi-solid and loses its flowing characteristics [6, p. 119; 16, p. 83]. Pour point, however, is not regulated in Europe [18].

Cloud point refers to a temperature below that causes the waxes in diesel fuel to form a cloudy appearance which thickens the oil and clogs filters and injectors. Fuel suppliers distribute fuels with cloud point for the climate conditions of the area. [6, p. 119; 16, p. 83.]

Sulfur content influences the life cycle of engines. Sulfur in fuel creates sulfuric acid during combustion process, which can damage the engine and cause piston ring wear. Regulations and standards have limited the sulfur content amount to less than 10 ppm because high sulfur content also contributes to acid rain. [16, p. 83; 17, p. 17.]

Octane rating indicates the level of compression a fuel can withstand before igniting. Lower octane ratings may lead to engine knock which can be harmful to the engine. [16, p. 54.]

Reid vapor pressure is the pressure of the vapor above the fuel when the fuel is at 38 °C. High vapor pressure eases the starting of an engine in cold weather since gasoline will not burn without air. [16, p. 51.]

3.2.1 Petroleum Products

Petroleum or crude oil formed from the remains of tiny sea plants and animals that passed away millions of years ago and sank to the depths of the oceans [6, p. 3.] This makes petroleum products nonrenewable, because their rate of renewability is not sufficient enough for a sustainable economic extraction in timeframes meaningful to human [6, p. 41].

Petroleum consists of a complex mixture of various hydrocarbons, mostly of alkenes and aromatic compounds [6, p. 3].

Diesel

Petroleum diesel, which is simply referred to as diesel, is composed of drastically varying amounts of saturated and aromatic hydrocarbons [18]. Diesel is sold in various grades of quality which are characterized by the sulfur and aromatic content, ignition quality (cetane rating), properties in cold weather, content of pollutants, viscosity, density and boiling point. Petroleum diesel has a flash point of at least +55 °C which categorizes it as a combustible liquid. [6, p. 125; 17, p. 17.]

Emission wise, untreated diesel fuel contains a high amount of sulfur and because of that desulfurization is required, so that the product can meet the standard requirements. For example, the diesel fuels used in Europe are under the diesel fuel standard EN 590 which requires diesel to have less than 10 ppm of sulfur [5, p. 72; 17, p. 17]. Lowering the sulfur content reduces the lubricity of the fuel which then requires use of lubricating additives. Good-quality diesel fuel contain additives such as detergents, dispersants, rust preventatives, and metal deactivators. [6, p. 125; 16, p. 83.] Oxidation inhibitors are sometimes added as a preservative, but this is not common [18].

Gasoline

Gasoline is motor fuel derived from petroleum with high energy amount and a high octane number [8, p. 42]. Gasoline consists of hydrocarbons and several additives which are added to enhance its properties. Since the regulations and standards have declined the use of lead in gasoline, other components have been introduced to help maintain the antiknock properties of gasoline. These octane improvers can be grouped into two broad categories: aromatic hydrocarbons and alcohols such as ethanol. [16, p. 53; 18.]

Because of the high octane rating, gasoline cannot be used in diesel engines. High octane rating means low cetane rating which then means that gasoline would not ignite, or would ignite at the wrong time. This would cause damage either to the engine or emission control components.

Gasoline properties and trade policies in Europe are defined in the EN 228 standard [19, p. 10].

3.2.2 Biofuels

The share of biofuels in automotive industry have come to stay due to the numerous benefits, such as renewability and cycle of life, reduction of greenhouse emissions, sustainability, regional development, reduction of rural poverty and to increase fuel security. [6, p. 17; 18.]

Biofuels are derived from various sources of renewable material such as carbohydrates which includes grains and sugars, animal fats, vegetable oils and biomasses including wood, stalk and grasses. [6, p. 16.]

Currently, there are three types of liquid biofuels as alternative or replacement for petroleum products: FAME and HVO for petroleum diesel, and ethanol for gasoline. Main differences between biofuels and petroleum fuels is the oxygen content, except for HVO which because of other similarities to petroleum diesel does not contain any oxygen [5, p. 3, 38; 18]. FAME and ethanol have a 10 to 45 % weight content of oxygen, whereas petroleum fuels have essentially none, making the chemical properties very different from the properties of petroleum. [6, p. 17.]

Biodiesel

Biodiesel is a renewable fuel for diesel engines that is comprised of mono-alkyl esters of long-chain fatty acids processed from animal fats or vegetable oils [6, p. 102]. Biodiesel, also known as FAME, has to meet the requirement standard EN 14214 which validates biodiesel manufactured through esterification chemistry, when used as a blending component [5, p. 3, 9; 6, p. 117].

FAME differs from petroleum diesel in many ways. Advantages are higher flash point of +150 °C which makes biodiesel nonflammable and nonexplosive. This leads to safety benefits in situations of an accident. FAME is also biodegradable, nontoxic and it contains virtually no sulfur which significantly reduces toxins and some emissions when burned as a fuel. [6, p. 102].

Disadvantages of biodiesel are that it produces less power and torque because of a 5 to 10 % less energy content which then leads to higher fuel consumption [6, p. 121]. Higher viscosity, higher cloud and pour point, and higher emissions of nitrogen oxides are also downsides of biodiesel. Precautions for cold climate use should also be considered because FAME tends to gel earlier than petroleum diesel upon cooling. [6, p. 102.]

Bioethanol

Ethanol is a renewable fuel for gasoline engines. Majority of the world's ethanol is produced from corn, sugarcane and beet molasses [6, p. 17]. Ethanol consists of 52 % carbon, 13 % hydrogen and 35 % oxygen. It is a colorless and highly flammable liquid with a boiling point of +78 °C and boiling point of -114 °C [6, p. 73].

When put to comparison with gasoline, ethanol has higher octane rating, broader flammability, higher flame speeds and heats of vaporization. These features allow higher compression ratio, faster burn time and leaner engine which results in better level of efficiency. [6, p. 73; 8, p. 101–102.]

Disadvantages when compared to gasoline are lower energy density, corrosiveness and functionality in cold starts because of its low vapor pressure. As well as gasoline, pure ethanol is not suitable for diesel engines because of its high-octane and low cetane rating, and high heat of vaporization that causes problems with self-ignition. [6, p. 73; 8, p. 101–102; 18.]

Exceptions to the compatibility of ethanol in diesel engines are products such as ED95 and RED95. These products are designed for heavy transport usage and they consist of 95 % bioethanol and a small percentage of additives. Additives such as ignition improvers, denaturants, lubricants and anticorrosive additives are added to optimize combustion suitable for operation in modified diesel engines. [18; 20; 21.]

HVO

HVO is also a type of renewable diesel which often is falsely considered to be a similar type of biodiesel as FAME [22]. Unlike FAME, HVO is processed through hydrotreating chemistry, and therefore, it cannot be recognized by the same EN 14214 standard as FAME, because of the differences in the processing method and the chemical composition [5, p. 4, 9].

Though HVO is produced from renewable sources, it still has a lot of similarities as petroleum diesel. Like petroleum diesel, HVO is also fully composed of hydrocarbons [5, p. 6]. HVO is a mixture of straight chain and branched paraffin except for that HVO does not contain significant amounts of aromatics or naphthene, which are not beneficial for a clear combustion [5, p. 4]. As the diesel fuel standard EN 590 does not regulate the raw material used to produce fuels or the processing method, HVO technically meets the requirements, except for minimum density which is below the lower limit [5, p. 6].

For paraffinic diesel fuels, such as HVO, there is a standard EN 15940. Since paraffinic content is practically impossible to measure, the fuels meeting the standard are limited to have basically zero content of aromatics. [5, p. 6.]

Overall, HVO has similar properties as petroleum diesel and does not need any modifications to the engine. Few advantageous exceptions are very high cetane rating ranging from 70 to 95, cleaner combustion (figure 8), and therefore, lower emissions because HVO contains less than 5 ppm of sulfur and no aromatics. [5, p. 4, 7, 17, 47; 22.]



Figure 8. Smoke testing of HVO and petroleum diesel from left to right respectively [23].

HVO can be used as it is or mixed with either bio or petroleum diesel [5, p. 24–25].

3.2.3 Blends

The blends of previously mentioned fuels are commonly used, either to increase the properties of fuel or the usage of renewable sources.

Diesel Blends

Diesels can be blended in many ways. Blends containing petroleum and biodiesel are known as B5, B7, B20 etc. The amount of blending contents the product may contain is standardized, for example the diesel fuel standard EN 590 limits the use of FAME to 7 %, but allows blending of HVO without any limit. Diesel fuel blend using the maximum amount of biodiesel defined in EN 590 standard, would be then known as B7. Other blends are B10, which meets the EN 16734 standard, and B20, and B30 which are defined by the EN 16709 standard. As in EN 590, the standards EN 16734 and EN 16709 does not regulate the amount of blended HVO. [5, p. 7–9.]

Because of its extraordinary properties HVO can be used to increase the quality of the base diesel fuel, such as increasing the cetane rating or lowering the emissions by decreasing the amount of sulfur and aromatics [5, p. 17–19; 18].

E5, E10 and E85

Ethanol can be mixed with gasoline to make blends such as E5, E10 and E85 to increase the use of renewable fuel sources and at the same time some of gasolines properties such as octane rating. The contents of ethanol in gasoline are defined in standard EN 228 and the requirements for ethanol when used as a blending component are defined in the EN 15376 standard. [19, p. 10, 14.]

Blends with lower percentage of ethanol consistency can be used without any engine modifications, but blends such as E85 will function only in alternative (AFV) or flex-fuel vehicles (FFV) [6, p. 18; 19, p. 31].

3.3 Test Standards

Standards used are shortly briefed in the following chapters to give basic information of what to expect from the tests. Requirements could not be followed entirely because of limitations set by the lack of equipment.

How the standards were implemented in the making of this thesis are explained during the execution of the experiments in chapter 4.

3.3.1 ASTM D471

This standard covers the procedures to evaluate the abilities of certain rubbers and rubber-like compositions to withstand the effects of liquids unchanged [24, p. 1.] Though PTFE is not a rubbery substance, same tests will be conducted to it because of its common usage in similar type of applications as elastomers.

One of the main points in ASTM D471 is to simulate the service conditions in the designed use through controlled accelerated testing [24, p. 3.] Comprehensive amounts of possible experiments are defined in the standard to find out the variables in sealants properties after immersion in fuel. These include tests such as elongation, tensile strength and hardness, but because of inadequate equipment to perform most of the them, only the following were covered in this thesis [24, p. 1]:

change in mass (before and after immersion), which was calculated using the following equation [24, p. 9]:

$$\Delta M, \% = \frac{(M_2 - M_1)}{M_1} * 100 \quad (1)$$

where:

ΔM change in mass, %,
 M_1 initial mass of specimen, g,
 M_2 mass of specimen after immersion, g,

change in length, width and thickness (before and after immersion), which were calculated using the following equations [24, p.9]:

$$\Delta L, \% = \frac{(L - L_0)}{L_0} * 100 \quad (2)$$

where:

ΔL change in length, %,
 L_0 initial length of specimen, mm,
 L length of specimen after immersion, mm,

$$\Delta W, \% = \frac{(W - W_0)}{W_0} * 100 \quad (3)$$

where:

ΔW change in width, %,
 W_0 initial width of specimen, mm,
 W width of specimen after immersion, mm,

$$\Delta T, \% = \frac{(T - T_0)}{T_0} * 100 \quad (4)$$

where:

ΔT change in thickness, %,
 T_0 initial thickness of specimen, mm,
 T thickness of specimen after immersion, mm,

and visual inspections (before and after immersion), which were executed with the help of a checklist presented later in chapter 4.1.

Standard defines that the specimens used are to be cut from each material sheet into a rectangular shape, having dimensions of approximately 25 by 50 by 2.0 mm (figure 9). Each specimen must be separately weighed to the closest milligram and measured to be as identical in size as possible. [24, p. 6].

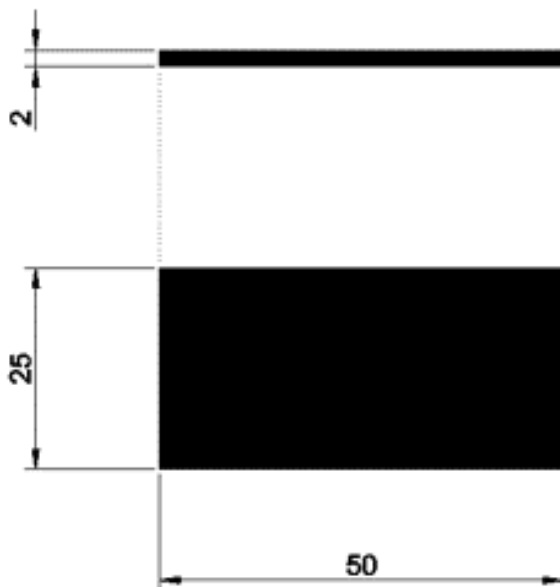


Figure 9. Test specimen proportions.

Materials used to suspend the specimens may not contaminate the test liquid and the setup must be made so that the specimens are not able to touch each other during the immersion period [24, p. 6.]

In actual product testing procedures, temperatures and immersion periods for the tests are picked with anticipation of the designed service conditions or by what was agreed between the customer and supplier. Test temperatures and immersion periods are defined in the standard (table 3 & 4) [24, p. 3–4].

Table 5. Test temperatures [23, p. 3].

Test Temperature °C
-75 ± 2
-50 ± 2
-25 ± 2
-10 ± 2
0 ± 2
+23 ± 2
+50 ± 2
+70 ± 2
+85 ± 2
+100 ± 2
+125 ± 2
+150 ± 2
+175 ± 2
+200 ± 2
+225 ± 2
+250 ± 2

Table 6. Immersion periods [24, p. 4].

Immersion Periods h
22 ± 0,25 (or 1 %)
46 ± 0,25 (or 1 %)
70 ± 0,25 (or 1 %)
166 ± 0,25 (or 1 %)
670 ± 0,25 (or 1 %)
1006 ± 0,25 (or 1 %)
2998 ± 0,25 (or 1 %)
4990 ± 0,25 (or 1 %)

After the immersion period is over, specimens are to be cleaned and lightly blotted dry of lint and excess material with filter paper. After that they are once again to be weighed, measured and inspected as before the immersion. [24, p. 6].

When the tests are completed, the results are to be handled as averages before and after the immersions [24, p. 6.]

3.3.2 ASTM D395

This test method covers the testing of rubber intended for use in applications in which the rubber will be subjected to compressive stresses in air or in liquid media [25, p. 1.]

This test is intended to measure the ability of rubber compounds to retain elastic properties after prolonged action of compressive stresses [25, p. 1.] Standardized test method requires the test specimens to be cut into a cylindrical shape of 29 mm in diameter with a given thickness of 12.5 mm or 13 mm in diameter with 6 mm in thickness [25, p. 2.]

Larger specimen size would have been preferred for easier visualization, but because of availability of certain material thicknesses, this could not be followed and exceptions were made in the sizing of the specimen.

The specimens used in this thesis have dimensions of 30 mm in diameter and 6 mm in thickness (figure 10.) The bigger size required by the standard was imitated to be as close as possible by using two plied specimens of the same material to make the total thickness of the specimen to 12 mm.

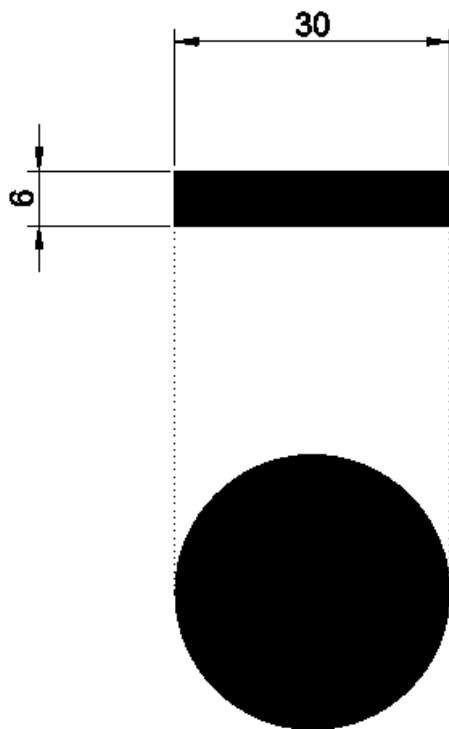


Figure 10. Test specimen proportions.

Standard allows the use of plied specimens but it is to be noted that the results may vary from solid blocks, because of the possibility of trapped air between the specimens. Particular care must be present when assembling the compression set so that the circular faces of the specimens are parallel. [25, p. 2.]

A compression set is used to compress the specimens down to 9.5 mm in thickness, using a similar kind of a setup as in figure 11. Compression set used in this thesis is built in the part 3.3.2.1. Compression process in the standard is suggested to last either 22 or 70 hours in a temperature which can be regulated to be identical for each test [25, p. 6.]

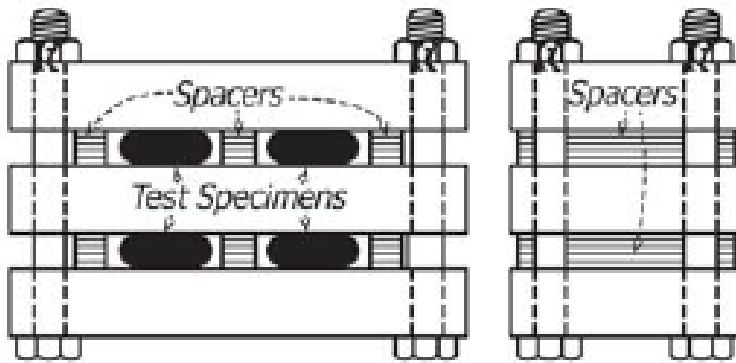


Figure 11. Illustration of the compression process [24, p. 5; 25].

Residual compression is measured using a micrometer from the center of the compressed specimen after opening the compression set and allowing the specimen recover for 30 minutes [25, p. 5; 6.] Figure 12 illustrates the possible effects of prolonged compression.

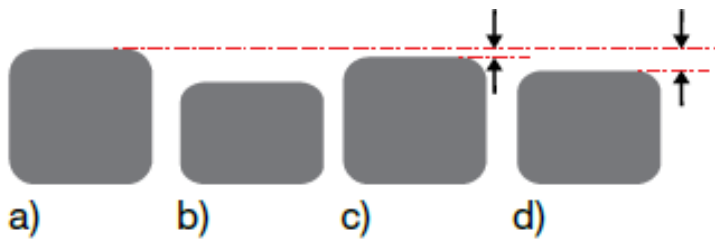


Figure 12. Effect of low and high residual compression on an elastomer

- a) Original unconstrained specimen
- b) Original specimen compressed
- c) Specimen when compressive force has been removed showing low compression
- d) Specimen when compressive force has been removed showing high compression [10, p. 33.]

Residual compression is expressed as a percentage of the compressed material which has not recovered after the recovery period. In practice: 0 percent indicates full recovery and 100 percent indicates no recovery.

Residual compression was calculated using the following equation [25, p. 6]:

$$C = [(t_o - t_f)/(t_o - t_s)] * 100 \quad (5)$$

where:

C	residual compression expressed as percentage,
t_o	original thickness of the specimen, mm,
t_f	final thickness of the specimen, mm,
t_s	spacer bar thickness, mm.

After the results of all the tests have been obtained, comparison can be carried out to spot the effects of different fuel compositions on the material's capability to resist residual compression.

3.3.2.1 Building the Compression Set

Technical drawing (appendix 1) for the compression set was designed with a professional-grade 2D design program DraftSight developed by Dassault Systèmes.

Requirements for the compression set are defined by the Test Method ASTM D395 [25, p. 6.]. Main pieces of the construction are the 20 mm thick steel plates, which when tightened squeeze the rubber specimens placed in between to the 9.5 mm thickness limited by the spacers. Tightening was done by welding nuts with 130 mm long M20 threaded rods to the base plate, which when assembled allowed tightening as seen in figure 13.

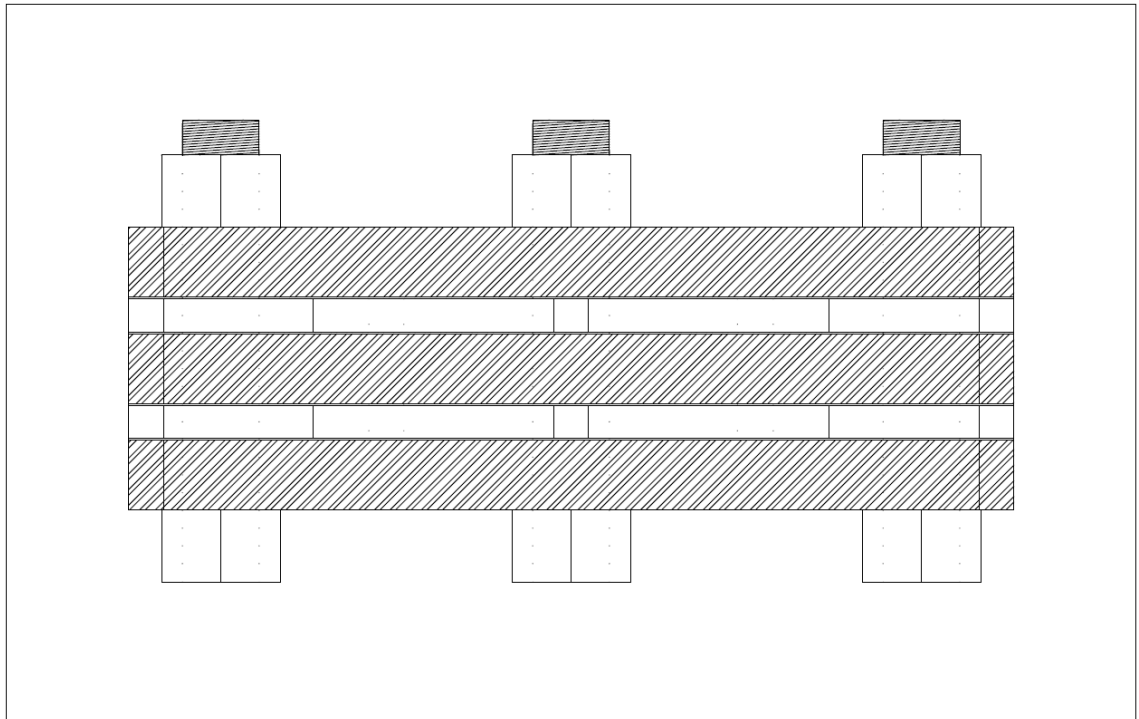


Figure 13. Compression set assembly.

Smooth finish was required on the surfaces which are in direct contact with the specimens [25, p. 5–6.] This was executed with 0.5 mm thick acid-proof metal sheets with the same shape as the 20 mm plates.

Design was fulfilled into reality by a professional metal worker, who through his occupation was able to offer laser cutting services. The technology of laser cutting provides precision, excellent work quality and swiftness beyond human capabilities (figure 14.)



Figure 14. Laser cutting parts for the compression set.

Manufacturing the spacers for the compression set required some changes to the first-hand drawing because of material availability and machining possibilities. Steel plates were not available in 9.5 mm thickness, so either they had to be milled from 10 mm thick steel plates or piled up from different thicknesses. The latter proved to be an easier solution, and the spacers were manufactured from two pieces of 4 mm thick steel plates and one piece of 1.5 mm thick steel plate, to then reach the summarized thickness of 9.5 mm (figure 15). Spacer pieces were slightly welded together for easier usage.



Figure 15. Spacer-build using the layering technique to reach the required thickness.

Results of the build came out to be exactly as planned. Figure 16 shows all the pieces of the set and the set from different angles when it is assembled. The compression chambers where the rubber specimens are placed can be seen in the bottom right corner of the collage.

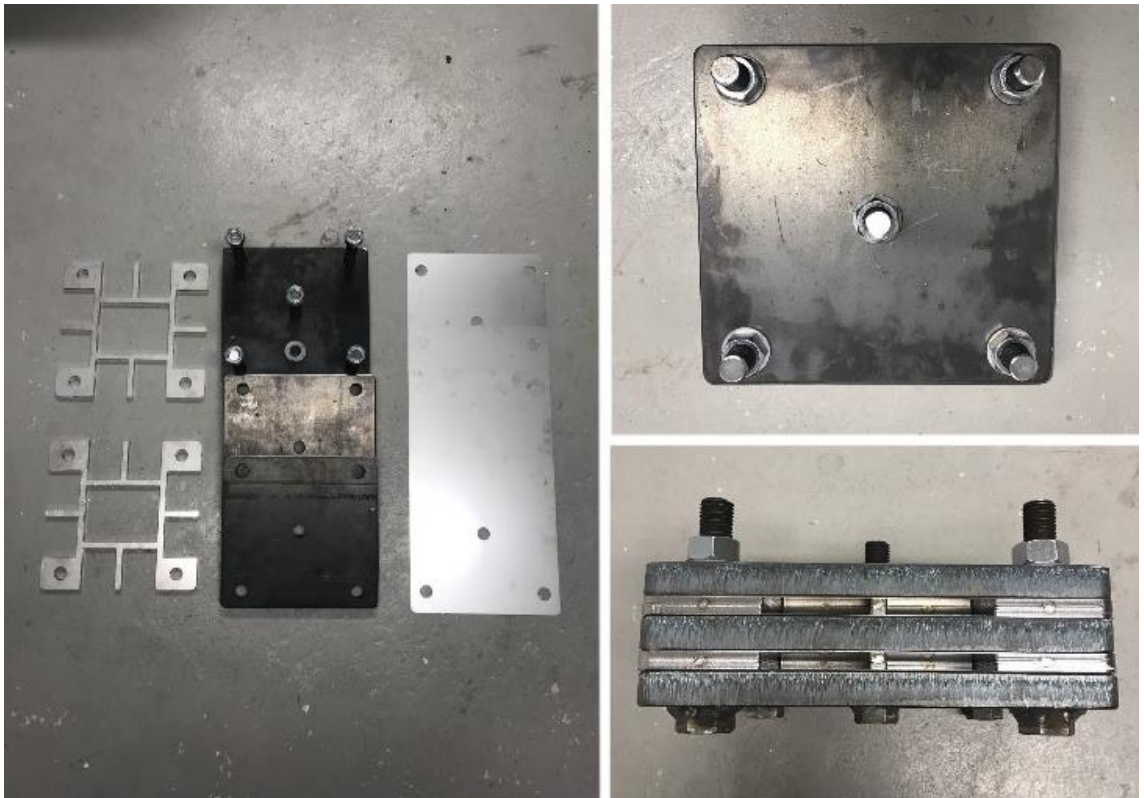


Figure 16. Compression set.

4 Experiments

The main interest in the tests was in fluctuating immersions and residual compressions of sealant materials in petroleum diesel, FAME and HVO. The availability of several grades from which the customer can freely choose when fueling causes unavoidable mixes, which the sealant must withstand by retaining its properties and the required functionality, so that the sealed application may function as designed.

4.1 Immersion Tests with Fluctuating Use of Diesel Fuels

There are strict requirements for the equipment used in the Test Method ASTM D471, but because of limitations set by the lack of equipment, standardized test setup requirements were not the uppermost concern.

The tests began with the preparation of the specimens. Elastomeric materials from Trelleborg Sealing Solutions Germany GmbH (table 1) were received as material sheets with approximate dimensions of 200 mm by 200 mm by 2.0 mm (figure 17).



Figure 17. Test material sheet of VMQ, silicone rubber (S7T30).

Derived from the size of the test sheets, a total of 32 specimen pieces could be cut from one sheet. Since two sheets were received, a total of 64 material specimens of each material were available for the tests conducted in this thesis.

PTFE materials from Trelleborg Sealing Solutions Finland Oy (table 2) were received as approximately 3 mm thick material sheets with uneven dimensions. Regardless of the uneven size, it was possible to cut the required number of specimens for the tests.

Immersion container was chosen to be a metal container with approximately one-liter capacity, which when processed as designed in figure 18, allowed the simultaneous immersion of six specimens. The specimens were suspended using stainless steel wiring. Attaching the specimens on to the lid of the container eased the specimen immersions tremendously.

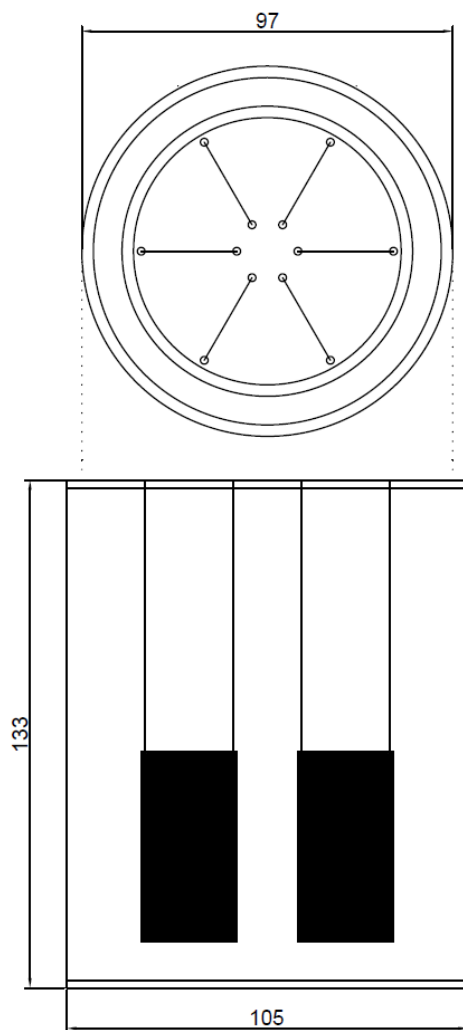


Figure 18. Illustration of the immersion container with the specimen setup.

The idea of the fluctuating immersion test was to immerse the same specimen alternately in petroleum diesel, HVO and again in petroleum diesel, and vice versa in HVO, petroleum diesel and HVO. One immersion path also included the use of FAME, and the immersions path was carried out as FAME, petroleum diesel and HVO.

The way the immersions were designed to be executed, was to immerse three specimens of each sealant material in to each of the diesels, and after a prearranged period of one week or 166 hours (table 6), move all the specimens of each material into a container designed to hold the same material, but with a different grade of diesel. This was repeated until the immersions were conducted as follows (figures 19–21):

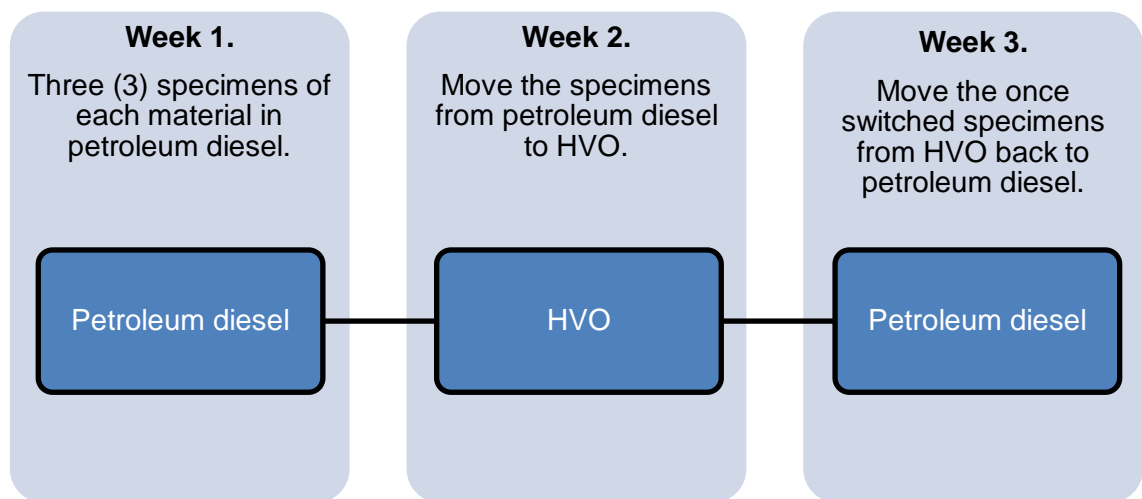


Figure 19. Immersion path of petroleum diesel → HVO → petroleum diesel.

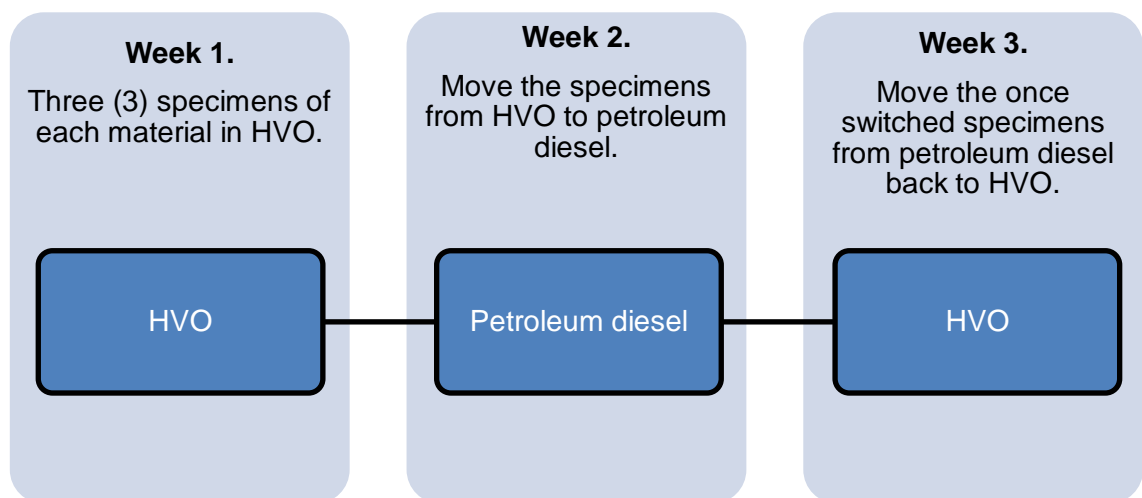


Figure 20. Immersion path of HVO → petroleum diesel → HVO.

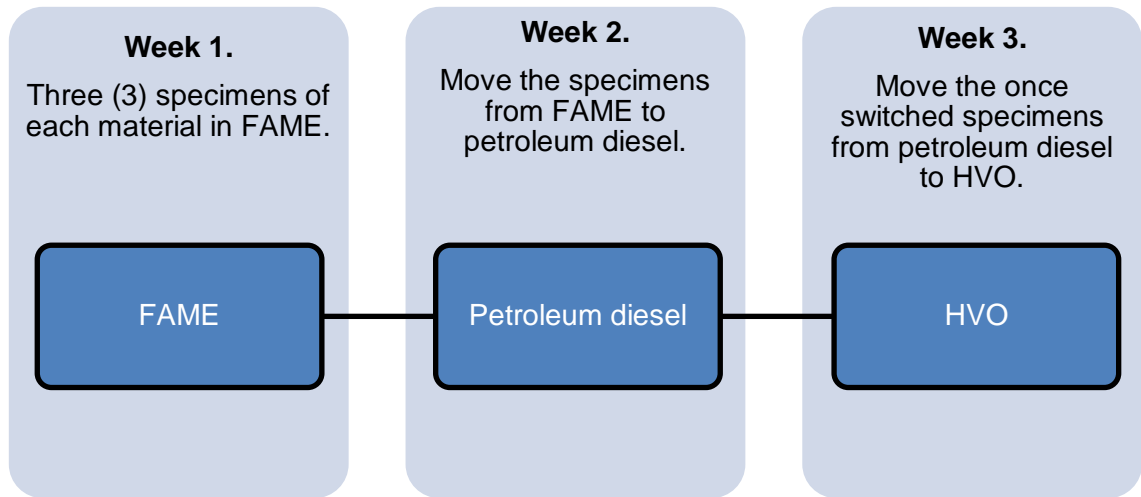


Figure 21. Immersion path of FAME → petroleum diesel → HVO.

During each transfer, the specimens were measured with a caliper, photographed, weighed with GWB Mettler AM100 scale and visually inspected for comparison (figure 22).



Figure 22. Inspection station for the weighing and placing of the specimens on to the lid-specimen contraptions.

The amount of materials and safety regulations prevented the use of individual containers for each material, so two materials had to be placed in the same container. Materials were merged in the same container by the presumed reactions, so the possible dissolved media would not compromise the results of the material which was anticipated to have better success in the tests. Materials were paired as seen in table 7.

Table 7. Material pairings.

Container number	Materials	
1.	AEM, ethylene acrylate rubber	FVMQ, fluorosilicone rubber
2.	EPDM, ethylene propylene diene rubber	IIR, butyl rubber
3.	FKM, fluorocarbon rubber	FKM, fluorocarbon rubber with higher fluorine content
4.	NBR, acrylonitrile-butadiene rubber (nitrile rubber)	HNBR, hydrogenated acrylonitrile-butadiene rubber
5.	AU, polyester urethane	VMQ, silicone rubber
6.	Virgin PTFE compounded with Turcon® additive	Virgin PTFE compounded with carbon and graphite

The metal containers used to immerse the specimens (figure 23) were marked in several ways to avoid the interference of losing track of which container held which material.



Figure 23. Prepared specimen containers.

During the first phase of the tests, which did not include any use of fuel, a simple marker was used to mark, and so, recognize the materials in the containers. The materials were marked with the abbreviations of the material types. The same base material compositions were differentiated with a sequential numbering representing the appearance order in tables 1 and 3.

For the possibility of a fuel spillage soaking the ink or the ink notwithstanding the heat of the oven in the latter phases, the specimens were also marked with steel wiring and different sizes and amounts of washers from the steel wire which suspended the specimens.

Due to any process deviation or confusion, the containers were placed inside the oven according to the immersion paths as follows:

- bottom shelf had the immersion path of petroleum diesel → HVO → petroleum diesel,
- middle shelf had the immersion path of HVO → petroleum diesel → HVO,
- top shelf had the immersion path of FAME → petroleum diesel → HVO.

Container placements on each of the shelves (figure 24) were done so that each of the containers had identical amount of space from the inner surfaces of the oven and from the other containers.

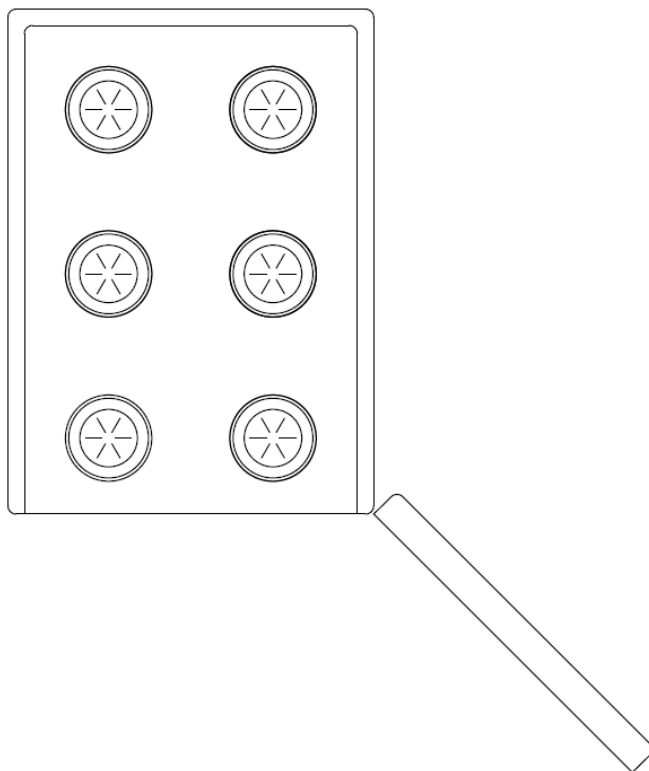


Figure 24. Container placements in the oven.

The tests were executed in an oven (figure 25) with a regulated temperature of $+50 (\pm 2)$ °C, as defined by the standard in table 3. Increased test temperature imitates the genuine conditions of vehicle usage, and at the same time, accelerates the possible adverse reactions [4].



Figure 25. SalvisLab Thermocenter oven used to heat the specimen containers filled with fuels.

For the specimen inspections and switches, a stand was built for easier processing (figure 26). The way the stand was utilized, was by placing the lid-specimen contraption on to it to cool the specimens, and at the same time, free both hands on to inspection of the specimens.

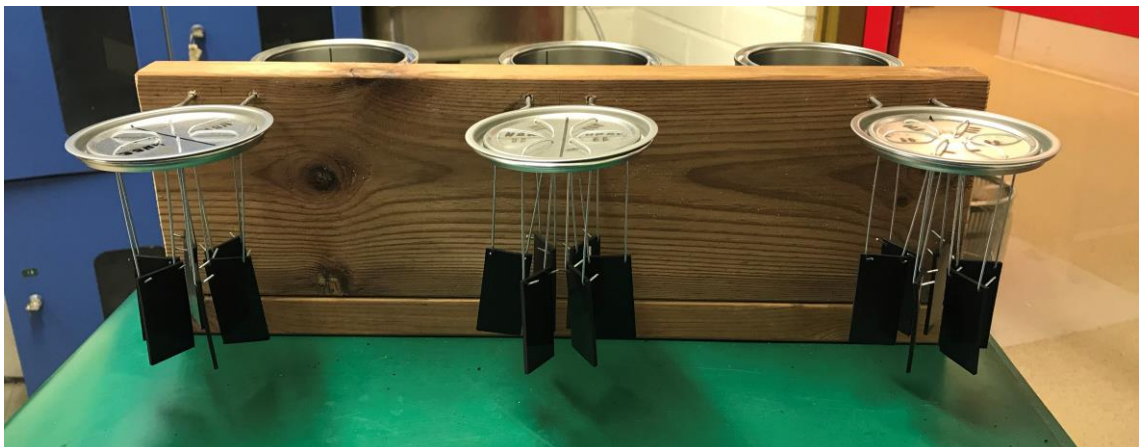


Figure 26. A stand to hold the lid-specimen contraptions for easier processing.

To ease the visual inspections of the specimens an inspection checklist was made to quicken the recording and to keep the descriptions of the results identical, and therefore, easier to compare (table 8).

Table 8. Visual inspection checklist for immersed materials.

<p>The possible adverse effects of chemical degradation are listed. Each of them have unique letter corresponding to the possible effect. Number placed after the letter implies the level of damage. Scale is from 1 to 5, where 1 is minor and 5 is high level of damage. An example on how the checklist works, A2 would indicate medium swelling.</p>	
A	Specimen has visually swollen compared to the original size.
B	Specimen has visually shrunk compared to the original size.
C	Specimen has softened compared to the original state.
D	Specimen has hardened compared to the original state.
E	Visible deformation of the specimen.

Abbreviations of the visual inspection results were then listed, along with the specimen weights and dimensions, after each immersion period to the result lists (appendix 2).

4.1.1 Reports

As an addition to the results, Test Method ASTM D471 requires that all known information of the tested specimens, test conditions, dates, test cycle lengths, equipment used and any process deviations must be precisely reported.

The tests were carried out during a consecutive period of three weeks. Each of the weeks were individually reported. The first report included the most comprehensive amount of the information regarding the specimens, test conditions, dates, test cycle lengths and equipment used, whereas the reports of the following weeks focused on any possible process deviations and remarks, since the conditions did not change during the tests, except for the immersion paths explained in the previous chapter.

Immersion were conducted in accordance with the Test Method D471 to a point which was doable with the available equipment and safety regulations.

Week 1 (Jan 3 – Jan 10, 2018) Report

Descriptions of the samples and their origins (tables 9 & 10):

Table 9. Elastomeric material descriptions.

Elastomers	
Supplier	Trelleborg Sealing Solutions Germany GmbH
Date of vulcanization	27 th of November 2017 (conditions unknown)
Specimens prepared	27 th of December 2017

Table 10. PTFE material descriptions.

PTFE	
Supplier	Trelleborg Sealing Solutions Finland Oy
Date of manufacturing	Unknown
Specimens prepared	9 th of December 2017

- materials were processed and stored in a room temperature of $+23 (\pm 2) ^\circ\text{C}$,
- oven mentioned in the previous chapter was used to heat the fuels to a temperature of $+50 (\pm 2) ^\circ\text{C}$,
- exposure period was set to be $166 \pm 0,25$ (or 1 %) hours,
- tests began on January 3rd of 2018 at 15:45,
- results are shown and deduced in chapters 5 and 6.

As a plausible process deviation, it was noted that the oven used was not able to perform the whole $166 \pm 0,25$ (or 1 %) hours test cycle without rebooting it manually. It was also noted through past experiences that the oven might shut down due to unknown reasons. The consequences of a premature shutdown were minimized by checking up on the oven at the beginning, throughout and at the end of each day.

Notes: During the first week, the oven shutdown by itself on three occasions, totaling about 10 hours of inactive heating. Specimen inspections were started on January 10th of 2018, at 7:14.

Week 2 (Jan 10 – Jan 17, 2018) Report

- Inspections of the first week's immersions were done on January 10th of 2018, between 7:14 and 15:34.
- Specimens were re-immersed in the second fuel grade and the oven was re-started on January 10th of 2018, at 16:15.

Notes: During the second week, the oven shutdown by itself only on one occasion, totaling about 5 hours of inactive heating. Specimen inspections were started on January 17th of 2018, at 7:10.

Week 3 (Jan 17 – Jan 24, 2018) Report

- Inspections of the second week's immersions were done on January 17th of 2018, between 7:10 and 14:05.
- Specimens were re-immersed in the third and final fuel grade and the oven was restarted on January 17th of 2018, at 14:29.

Notes: Specimen inspections were started on January 24th of 2018, at 7:34.

The tests were finished on January 24th of 2018, at 14:15.

4.2 Residual Compression

The residual compression tests were only implemented to elastomeric materials. The reason for this was because PTFE is not a rubbery substance, and therefore, does not show an elastic behavior sufficient enough to provide reliable results in this test method. [4.]

Materials did not need any preparations since they were already processed by the supplier, Trelleborg Sealing Solutions Germany GmbH (figure 27).



Figure 27. Test material buttons of VMQ, silicone rubber (S7T30).

The tests began with the materials being compressed without any effective fuel component to find out the material's own unique resistivity to residual compression (figure 28). The same oven was used as in the immersion tests (figure 30). Compression time was set to be 70 hours in a temperature of $+50 (\pm 2) ^\circ\text{C}$.



Figure 28. Specimens placed into the compression set.

After the first test cycle was completed, the compression set was taken out of the oven and allowed to cool. After cooling, the set was opened and the specimens were removed and allowed to recover for 30 minutes before using a micrometer to measure the final thicknesses of the specimens, which were then recorded in the result list (appendix 3).

After the test without any effective fuel component, the specimens were once again prepared and placed into the compression set. Then, the set was placed into a slightly larger container and filled with fuel, so that the specimens were completely submerged (figure 29).

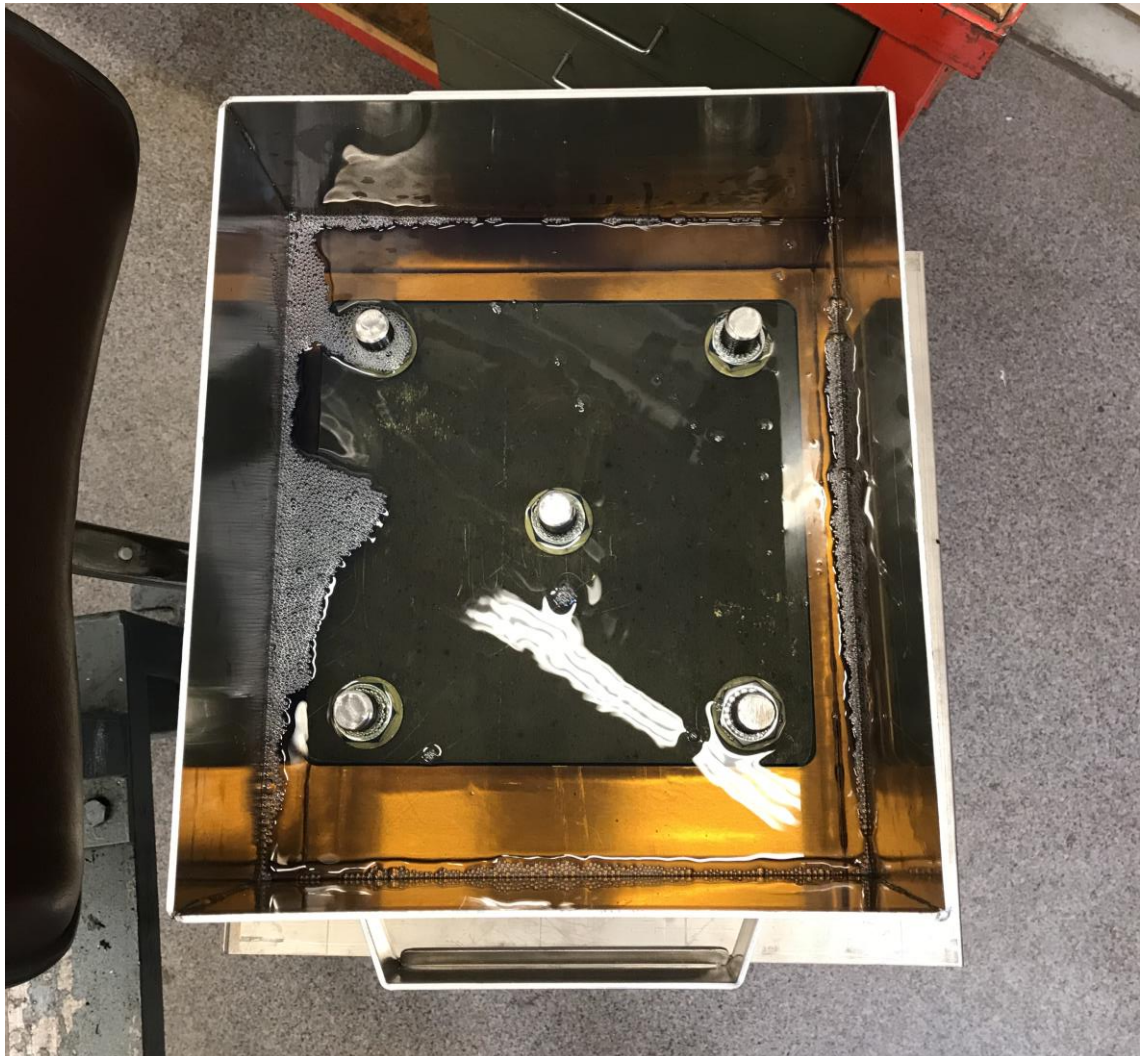


Figure 29. Compression set submerged in petroleum diesel.

When filled, the container was placed into the oven having similar conditions as in the previous test cycle (figure 30).



Figure 30. Compression set in the oven without and with an effective fuel component.

(Immersion containers above the compression set in the right figure were not tested as a part of this thesis)

After the test involving the use of fuel was completed, most of the fuel was pumped out to lighten the container. Then it was pulled out and allowed to cool. When the compression set was cooled, it was then lifted to a dry container to avoid any spillage of fuel and opened. The specimens were then removed and allowed to recover for 30 minutes. After the recovery period, the specimens were measured with a micrometer and the results were then recorded in the result list (appendix 3).

After each test which involved the use of fuel, the compression set was cleaned thoroughly to exclude any possibility of specimen contamination in the tests conducted afterwards with different fuel compositions.

After the completion of all the test cycles, the results could be processed and calculated to find out the resistivity for residual compression of the materials in various conditions.

4.2.1 Report

Test Method ASTM D395 also required that the tests had to be precisely reported. The report consisted of information about the tested materials, original dimensions and thicknesses of the specimens, time and temperature of the test, whether or not the surfaces of the specimens were lubricated, final thicknesses of the specimens after removing the specimens from the set and letting them recover for 30 minutes, and which of the methods in ASTM D395 was used to test the specimens.

Compression Set Report

- Sample descriptions and origins were the same as mentioned in table 9.
- Compression set tests were carried out using the test method B of Test Method D395,
- materials were stored in a room temperature of +23 (± 2) °C,
- specimen surfaces were not lubricated in any of the test cycles,
- the same oven used in the Test Method D471 was used to heat specimens to a temperature of +50 (± 2) °C,
- results are shown and deduced in chapters 5 and 6.

Notes: Test without an effective fuel component was started on January 30th of 2018, at 11:47 and finished on February 2nd of 2018, at 11:34.

Test with petroleum diesel was started on February 2nd of 2018, at 12:59 and finished on February 5th of 2018, at 11:34.

Test with HVO was started on February 5th of 2018, at 13:15 and finished on February 8th of 2018, at 11:45.

Test with FAME was started on February 9th of 2018, at 9:59 and finished on February 12th of 2018, at 7:54.

5 Results

In this chapter, the results of the experiments conducted in the previous chapter are presented in both visual and graphical form.

From the results and the deductions in the end of each subchapter, it can be seen which of the materials would function the best in such conditions as simulated in the tests.

The columns in the graphs in the following chapters are colored to represent the effective diesel fuel composition, as follows:

- black stands for petroleum diesel,
- red stands for FAME,
- green stands for HVO.

In the residual compression tests, the column which represents the test cycle which was conducted without an effective diesel fuel composition is colored in blue, which stands for “in air.”

5.1 Fluctuating Immersions in Diesel Fuels

The results of the fluctuating immersion tests are reported separately. Each of the test materials is discussed and reported by the immersion path. Materials are listed in the appearance order as seen in tables 1 and 3.

5.1.1 Petroleum Diesel → HVO → Petroleum Diesel

This chapter presents the results of the immersion path of petroleum diesel → HVO → petroleum diesel (figures 31–54).

The photographs of the specimens were taken immediately after thorough examination, which included weighing of the specimens, measuring of the dimensions of the specimens and visual inspections.

The graphs were created on the basis of the data averages, which were acquired from the recorded data (appendix 2) using the previously mentioned equations in chapter 3.3.1 (equations 1–4).

Average change in size was calculated from the change in length, width and thickness of specimen, as it was expected that the size change was equal in each of the dimensions. The measurement accuracy of the caliper and the scale used was calculated to be approximately $\pm 2\%$.

AEM, Ethylene Acrylate Rubber

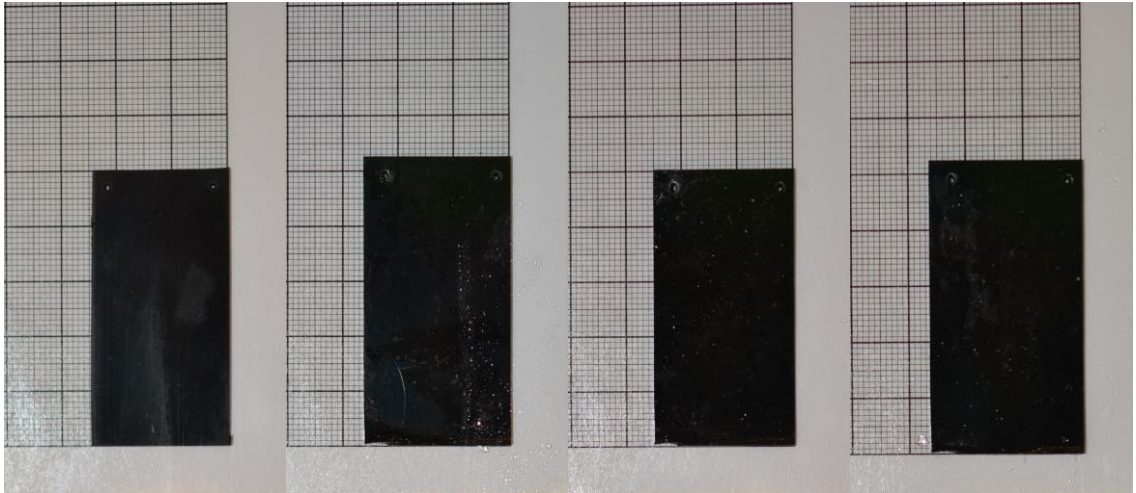


Figure 31. AEM, ethylene acrylate rubber, in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

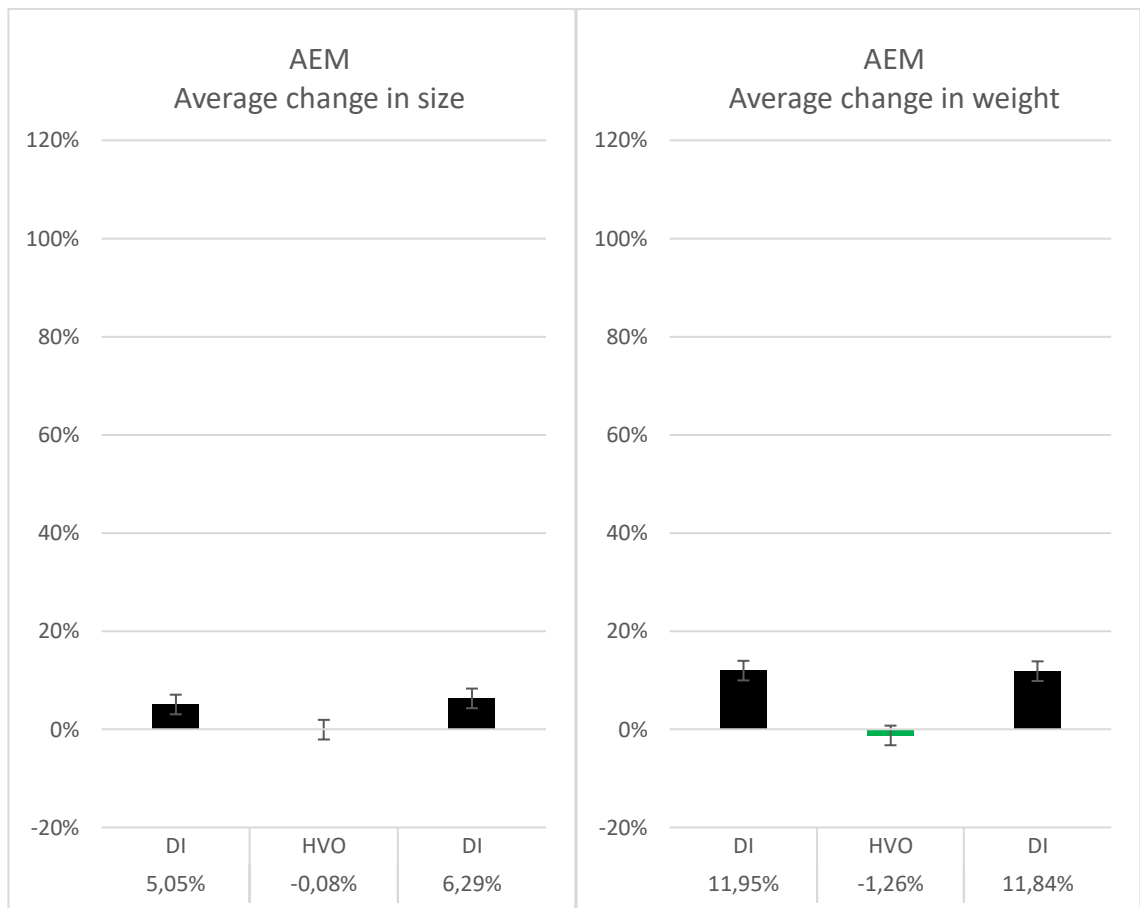


Figure 32. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

EPDM, Ethylene Propylene Diene Rubber

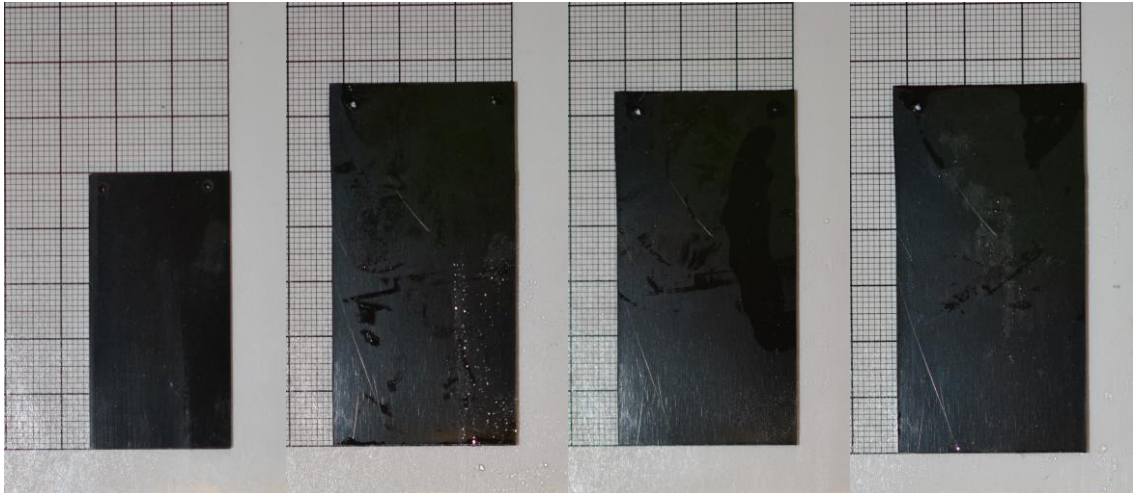


Figure 33. EPDM, ethylene propylene diene rubber, in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

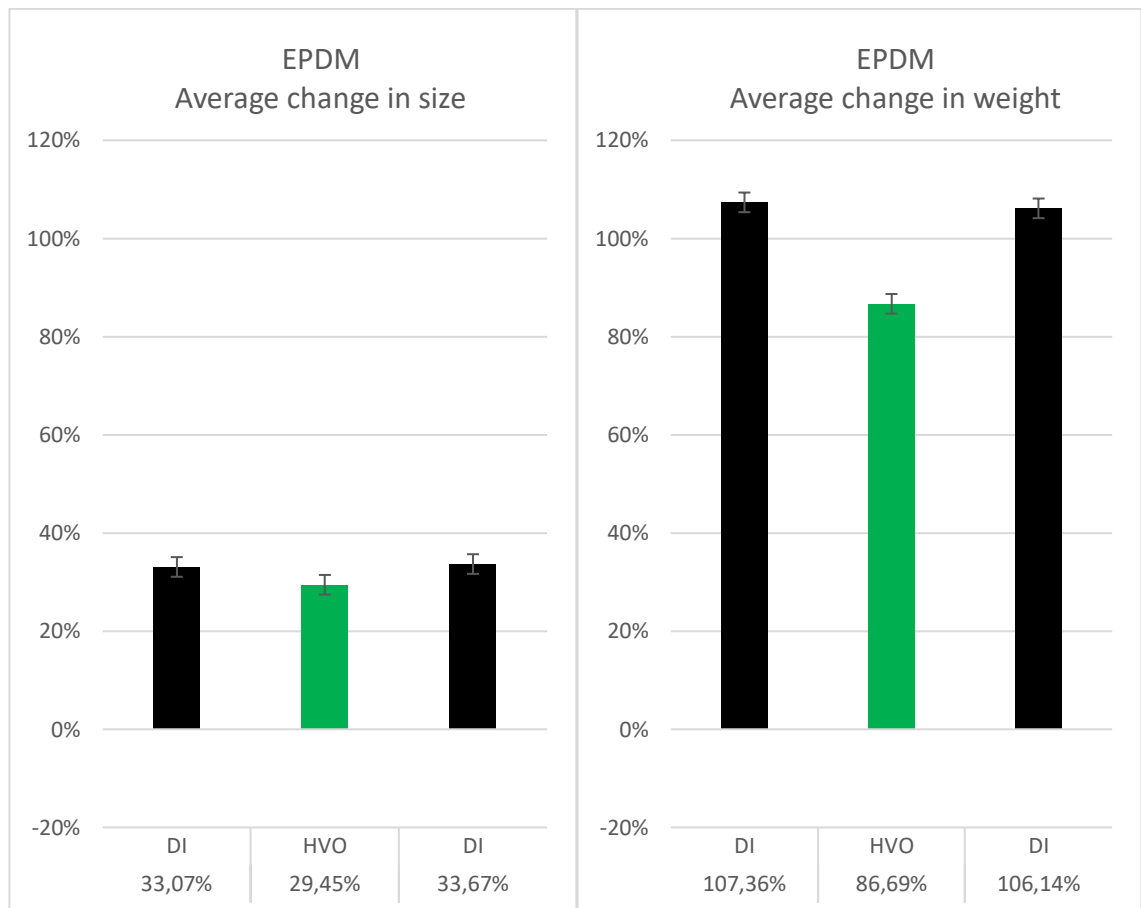


Figure 34. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

FKM, Fluorocarbon Rubber

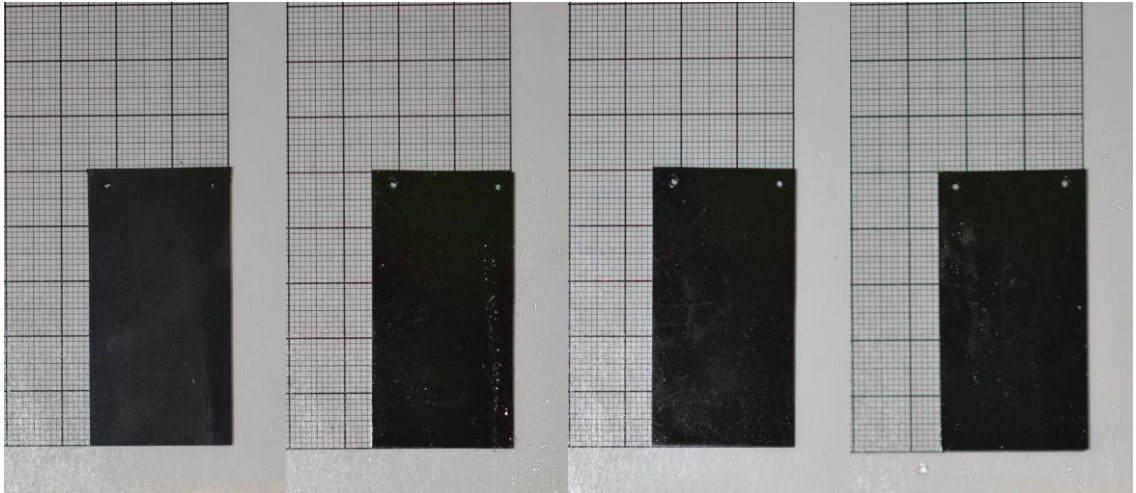


Figure 35. FKM, fluorocarbon rubber, in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

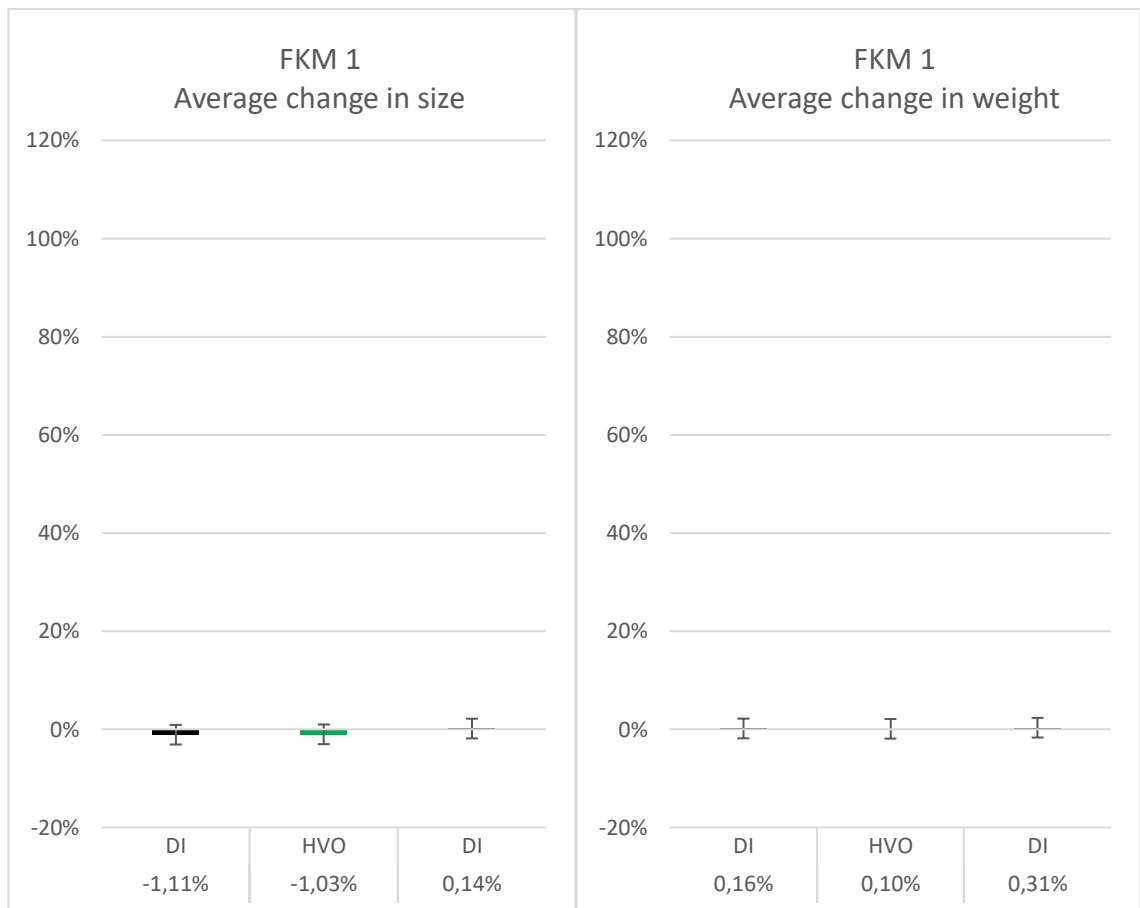


Figure 36. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

FKM, Fluorocarbon Rubber with Higher Fluorine Content

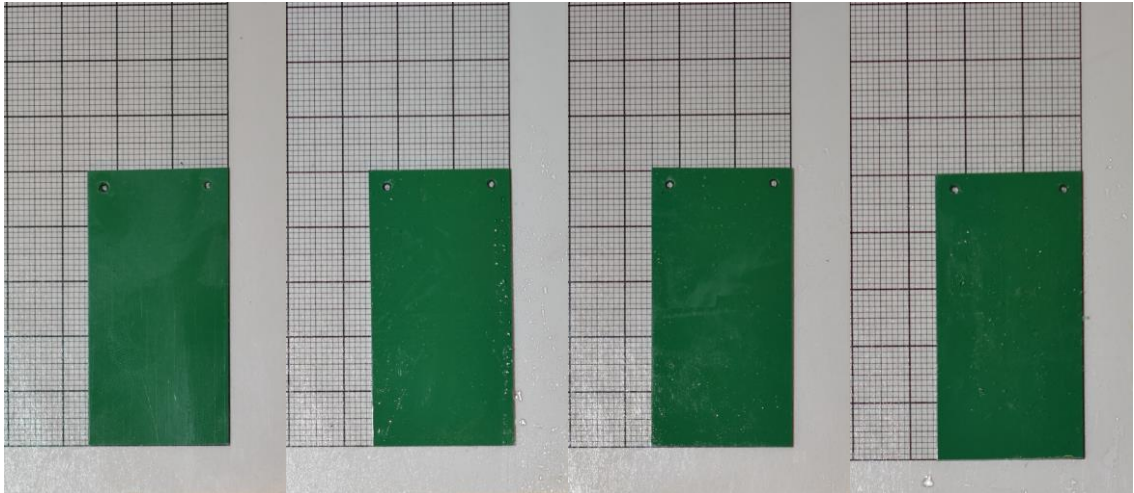


Figure 37. FKM, fluorocarbon rubber with higher fluorine content, in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

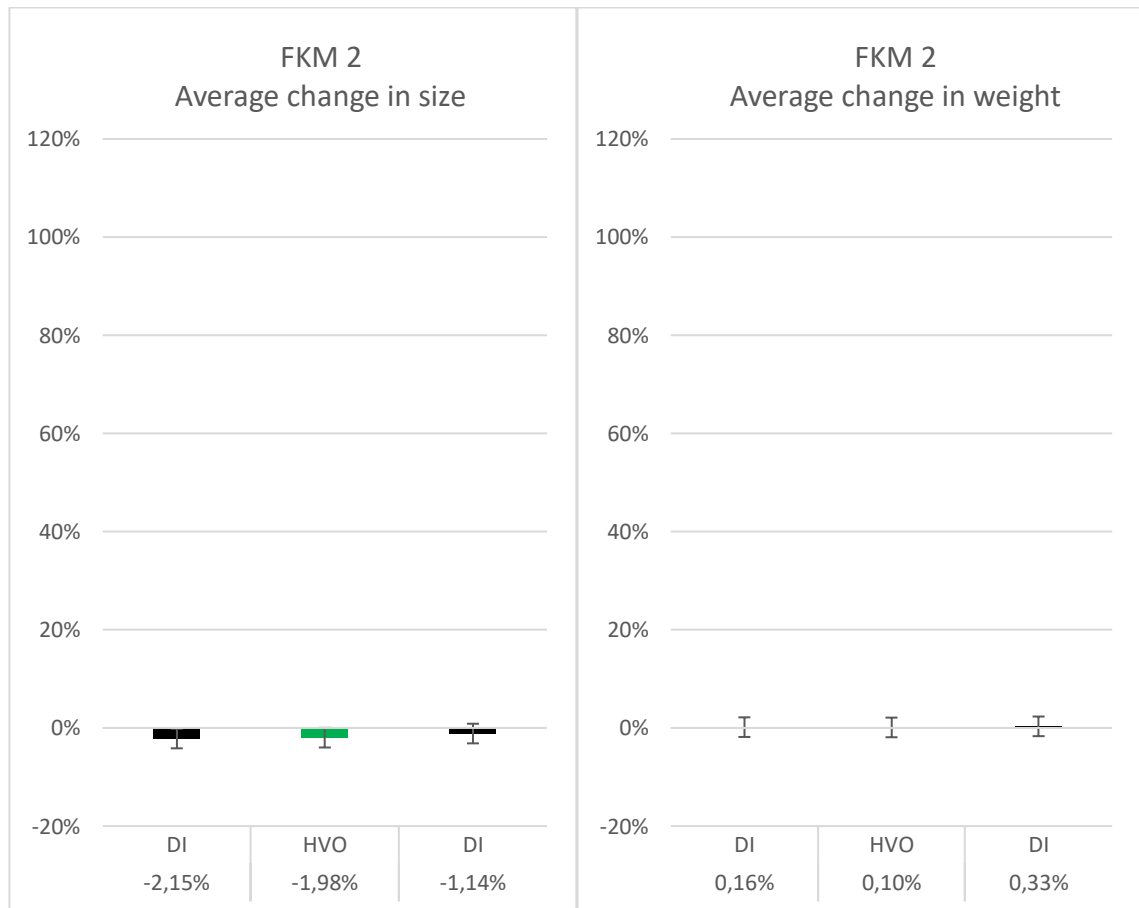


Figure 38. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

FVMQ, Fluorosilicone Rubber

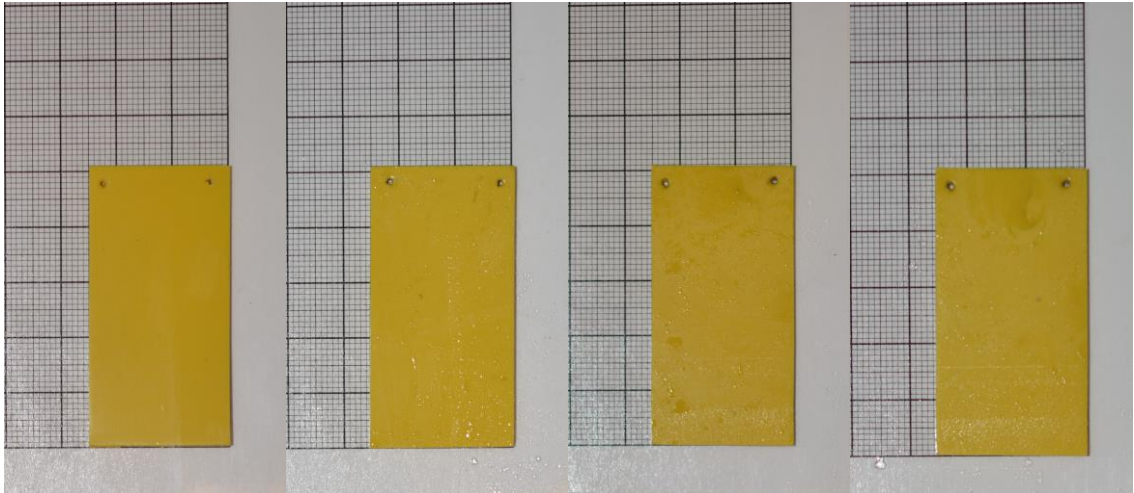


Figure 39. FVMQ, fluorosilicone rubber, in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

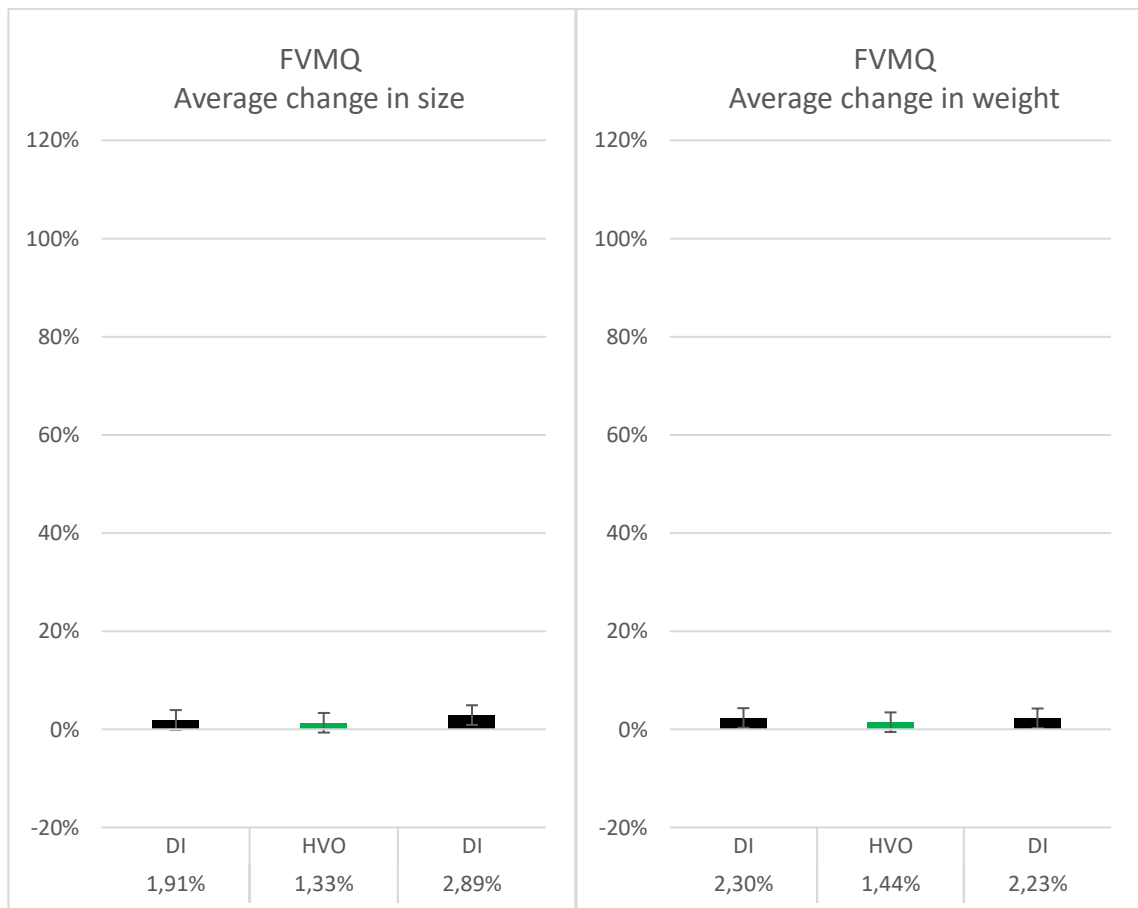


Figure 40. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

HNBR, Hydrogenated Acrylonitrile-Butadiene Rubber

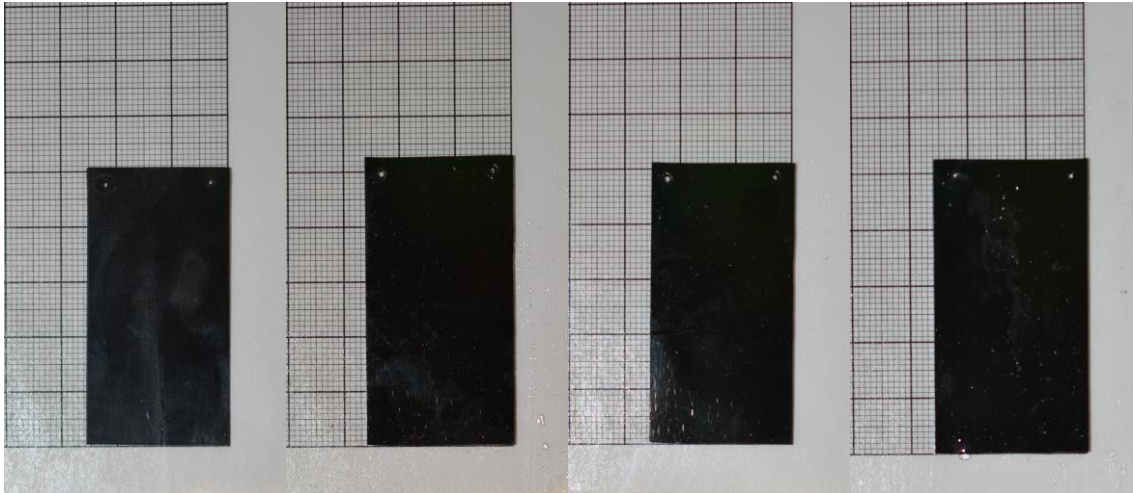


Figure 41. HNBR, hydrogenated acrylonitrile-butadiene rubber, in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

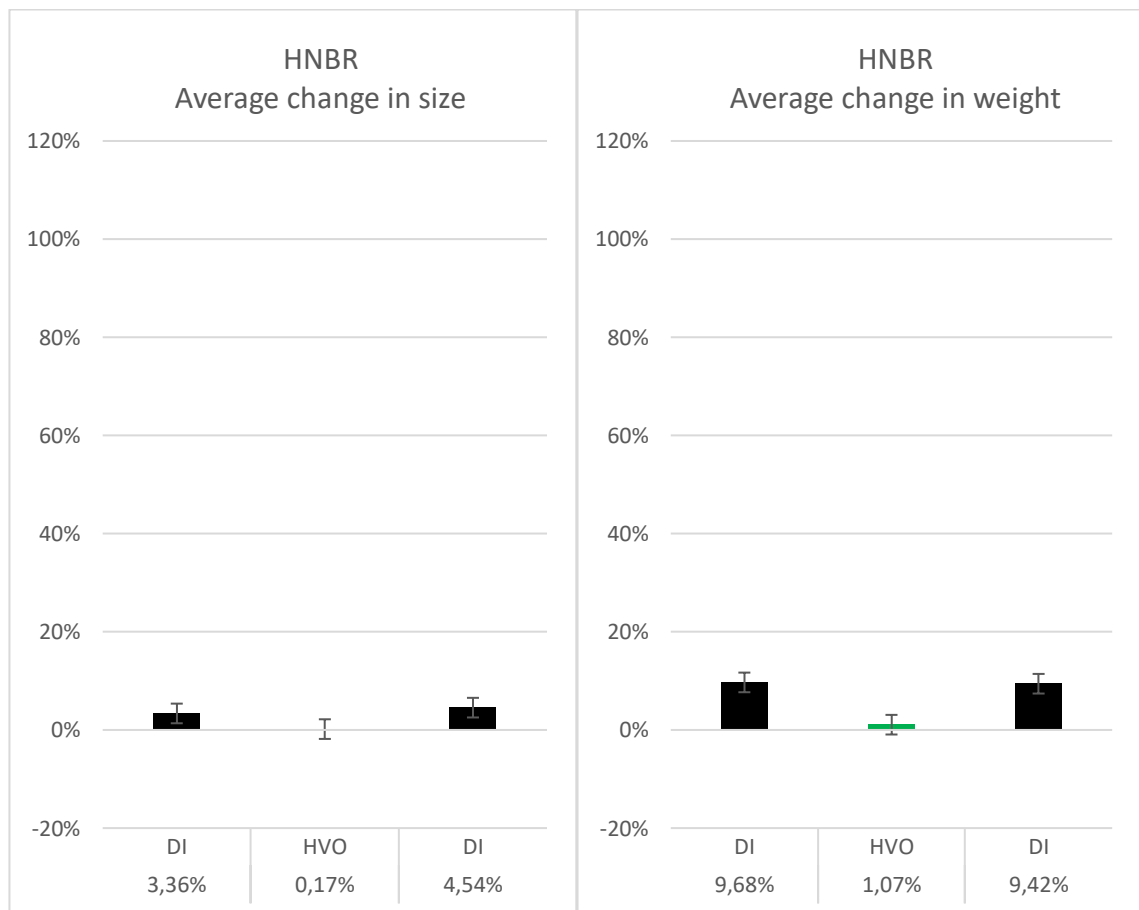


Figure 42. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

IIR, Butyl Rubber

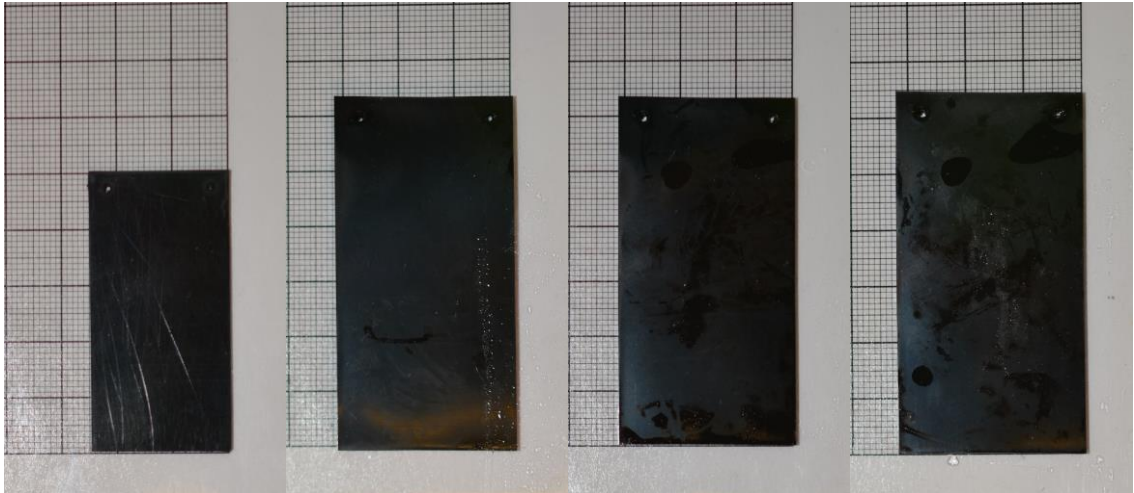


Figure 43. IIR, butyl rubber, in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

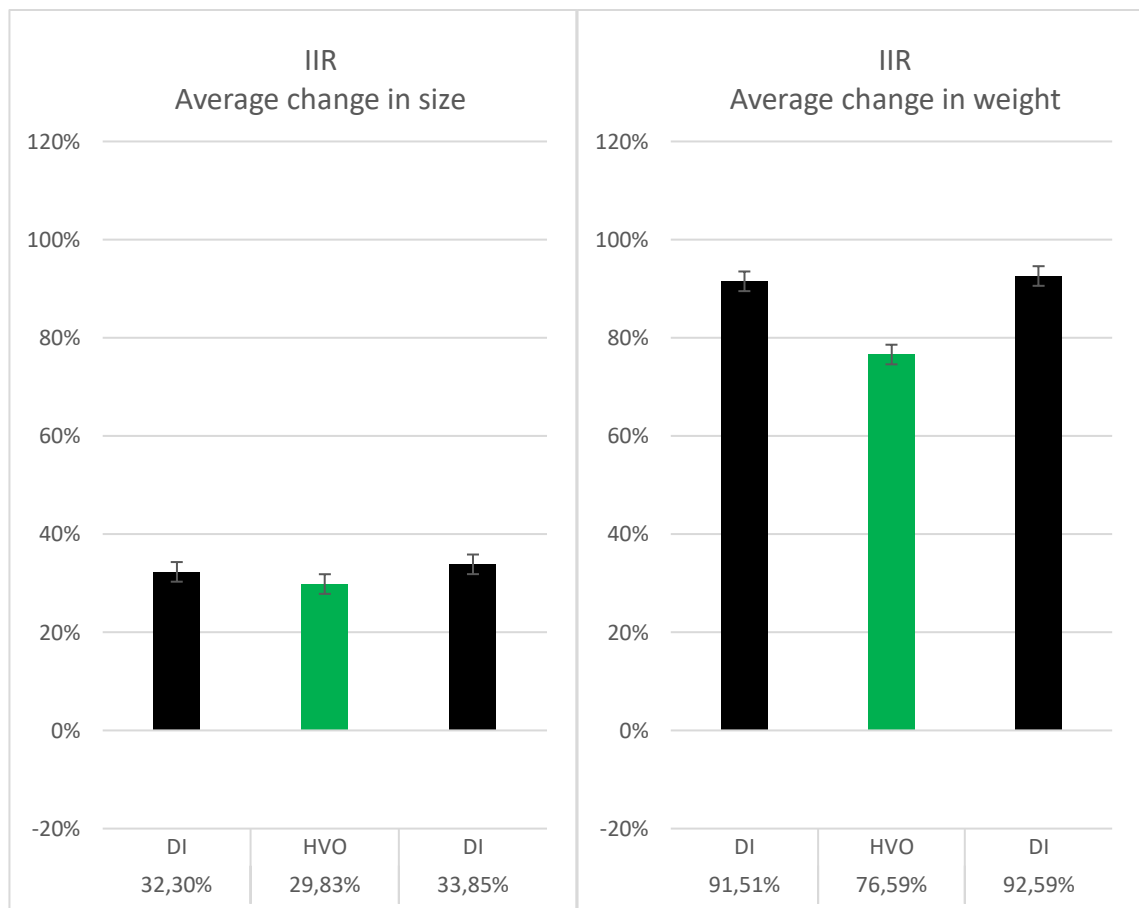


Figure 44. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

NBR, Acrylonitrile-Butadiene Rubber (Nitrile Rubber)

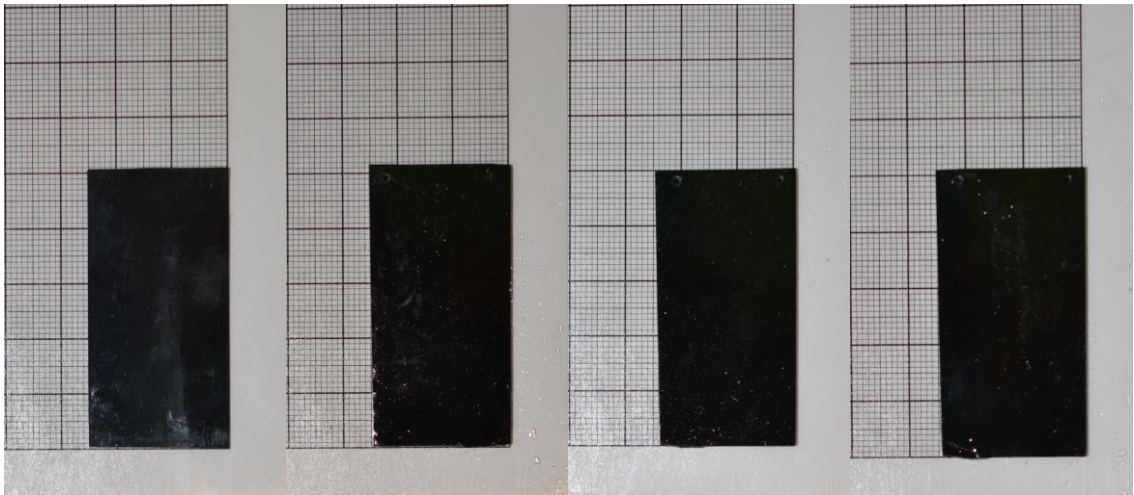


Figure 45. NBR, acrylonitrile-butadiene rubber (nitrile rubber), in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

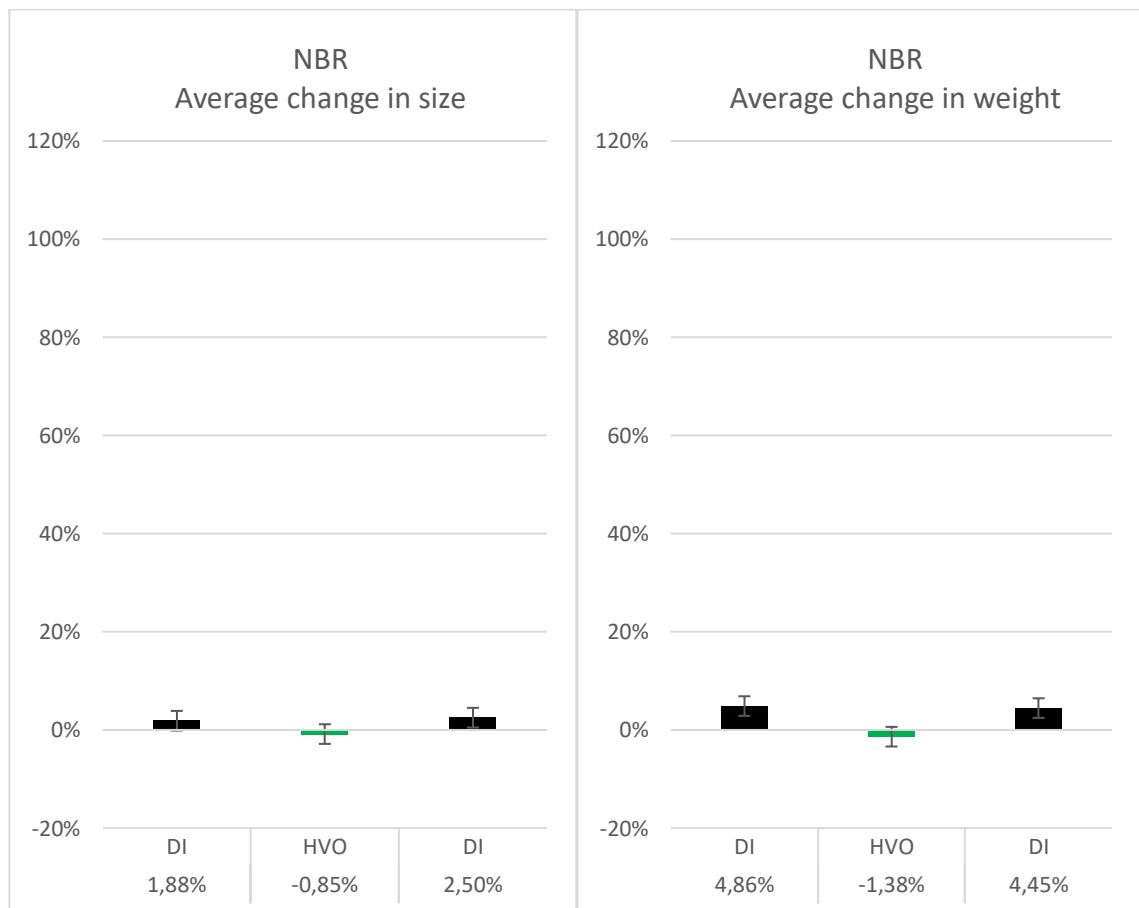


Figure 46. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

AU, Polyester Urethane

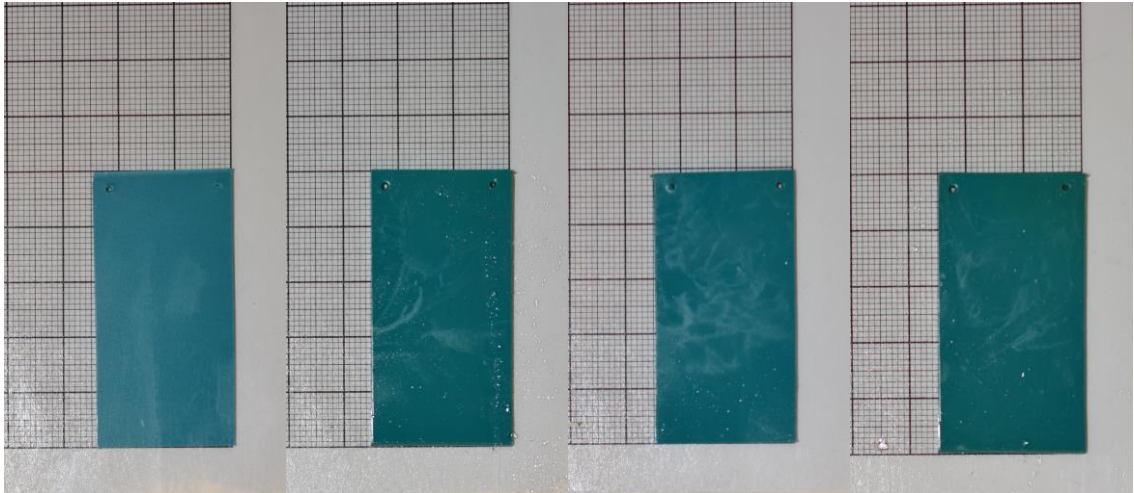


Figure 47. AU, polyester urethane, in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

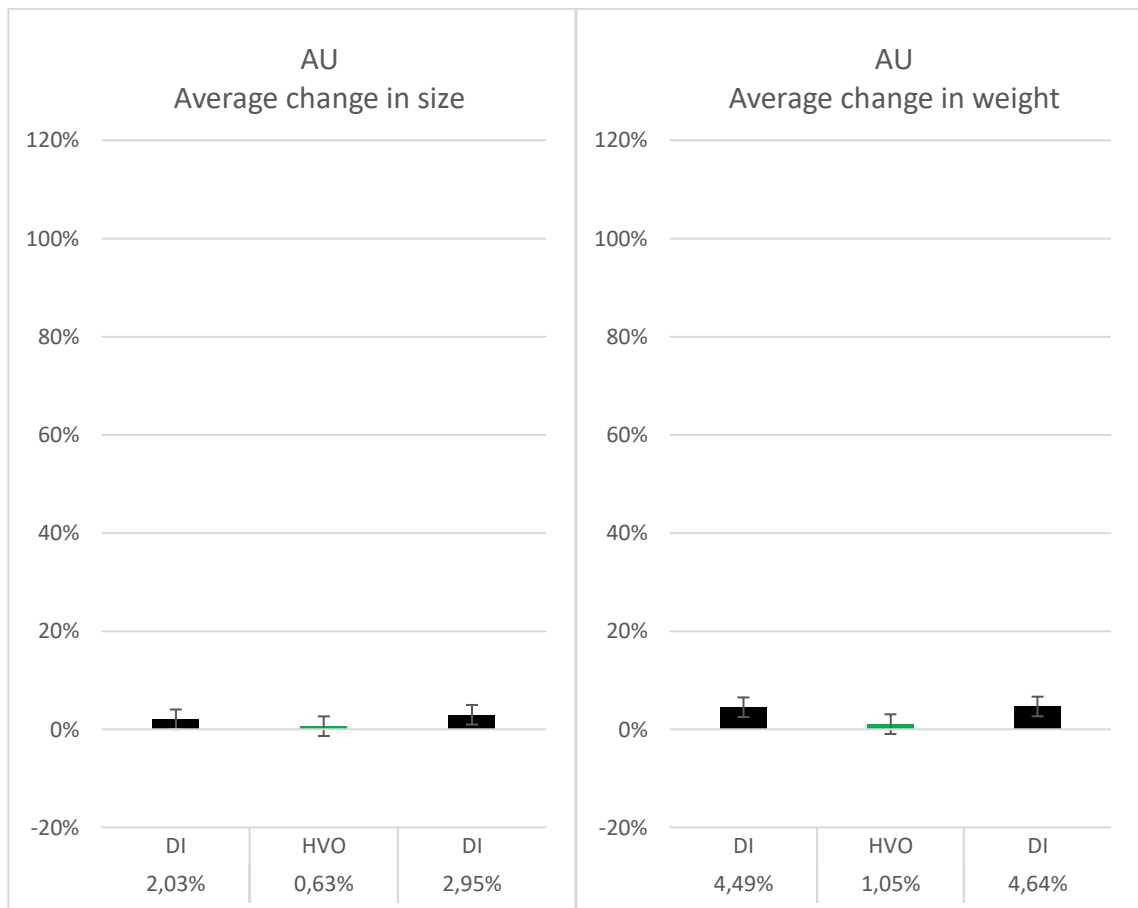


Figure 48. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

VMQ, Silicone Rubber

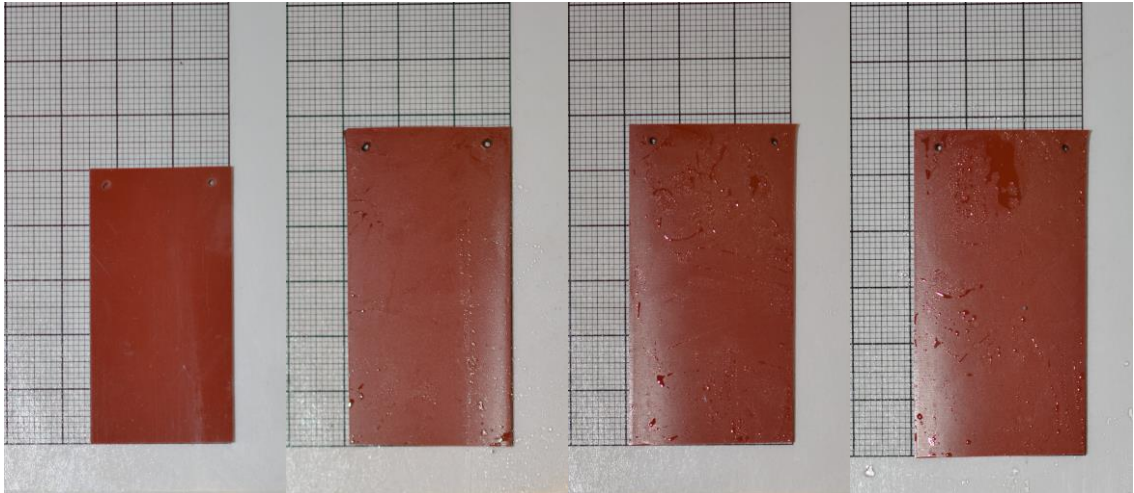


Figure 49. VMQ, silicone rubber, in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

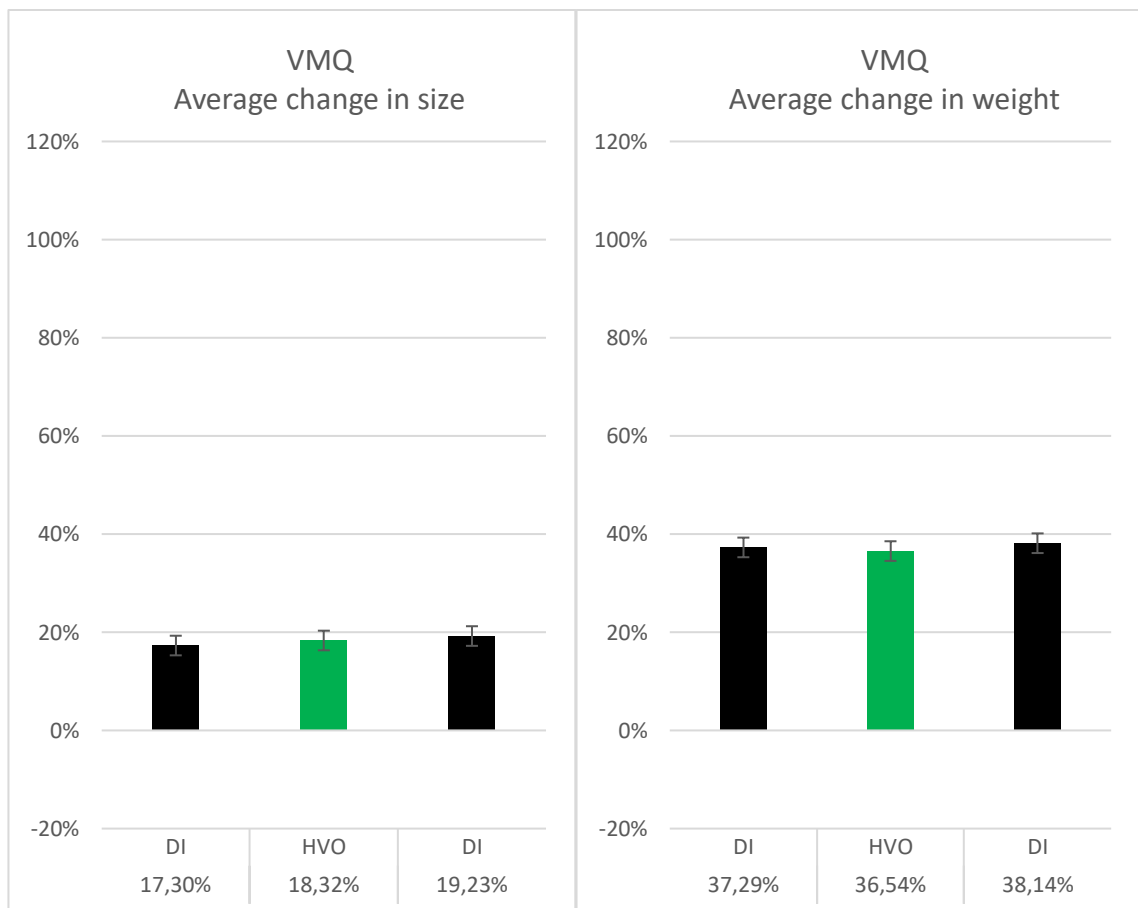


Figure 50. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

Virgin PTFE compounded with Turcon® additive

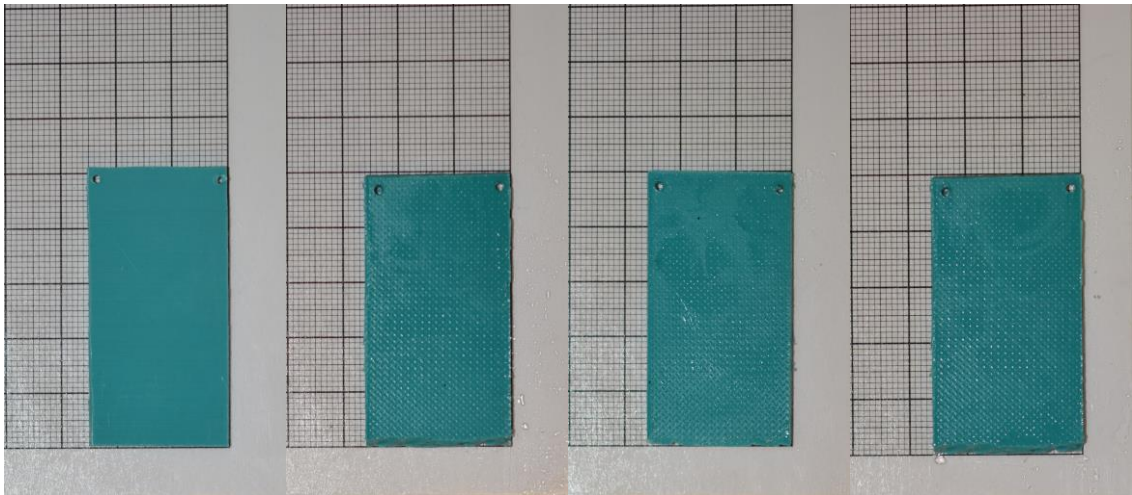


Figure 51. Virgin PTFE compounded with Turcon® additive in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

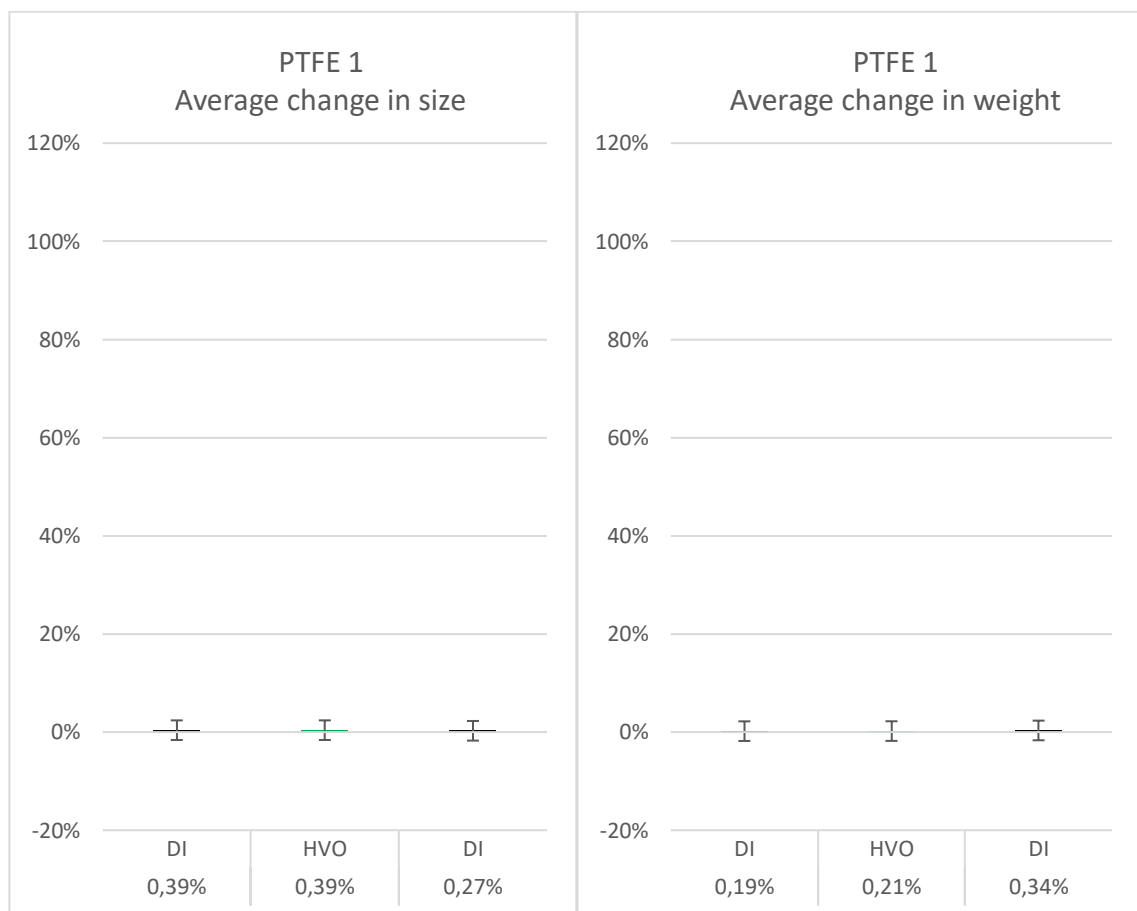


Figure 52. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

Virgin PTFE compounded with carbon and graphite

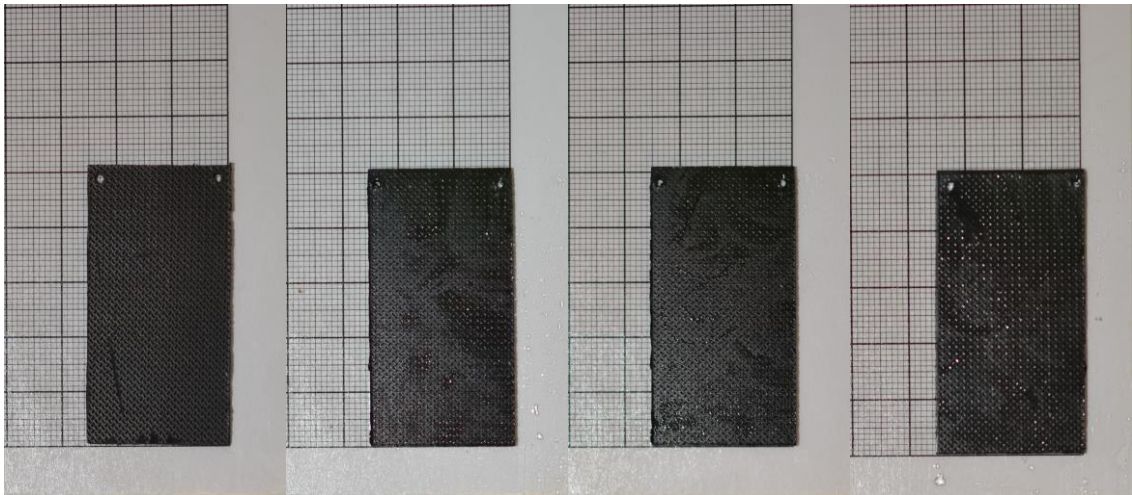


Figure 53. Virgin PTFE compounded with carbon and graphite in its prepared state and after weekly immersions in petroleum diesel → HVO → petroleum diesel from left to right respectively.

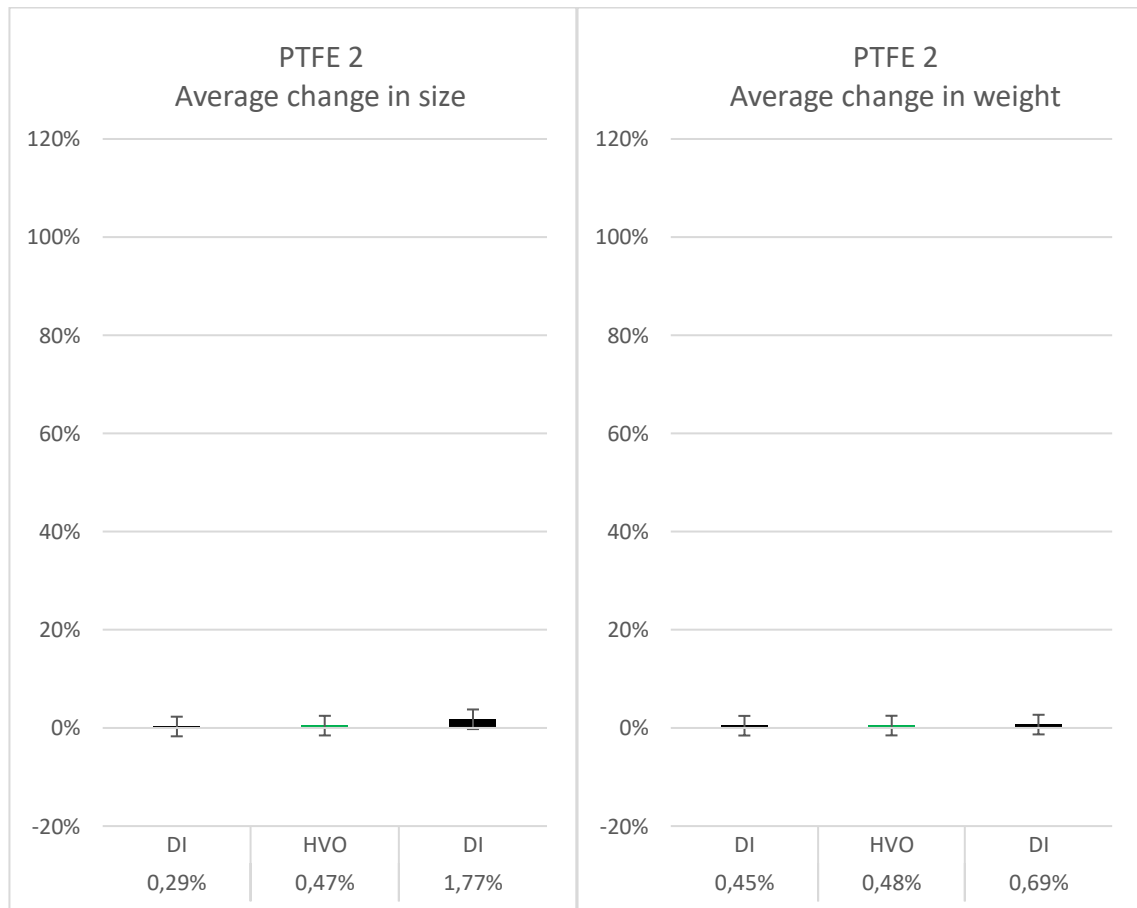


Figure 54. Average changes in size and weight of the specimens compared to the original state after weekly immersions in petroleum diesel → HVO → petroleum diesel.

To summarize the results in the immersion path of petroleum diesel → HVO → petroleum diesel, the elastomeric materials were ranked by the average magnitude of the reactions to give an idea of the suitability in conditions as simulated in the test (table 11).

The following results are based only on the results gained from the previously conducted tests. In actual material selection procedures, many other material properties must be carefully examined to find the most suitable material for the designed application.

PTFE materials were left outside of the ranking system, because of their unique properties which are not comparable to elastomers.

Rank	Material	Effects
1.	FKM 1	FKM 1 showed slight shrinkage in this immersion path. Other than that, the material succeeded with the most minimal alteration.
2.	FKM 2	FKM 2 showed slight shrinkage in this immersion path. Other than that, the material succeeded as well as FKM 1.
3.	NBR	NBR showed minimal swelling and increase in weight in this immersion path.
4.	AU	AU showed minimal swelling and increase in weight in this immersion path.
5.	FVMQ	FVMQ showed minimal swelling and increase in weight in this immersion path.
6.	HNBR	HNBR showed swelling and medium increase in weight in this immersion path.
7.	AEM	AEM showed swelling and medium increase in weight in this immersion path.
8.	VMQ	VMQ showed high swelling and increase in weight in this immersion path.
9.	IIR	IIR showed extremely high swelling and increase in weight in this immersion path.
10.	EPDM	EPDM showed extremely high swelling and increase in weight in this immersion path.

Table 11. Suitability rankings of the elastomeric materials in immersion path of petroleum diesel → HVO → petroleum diesel.

Judging by the results, FKM 1, FKM 2, NBR, AU and FVMQ would be able to function properly in conditions which were simulated in this immersion path. HNBR, AEM, VMQ, IIR and EPDM showed reactions which would not be tolerated in fuel system applications, and therefore, cannot be recommended for usage in such conditions.

5.1.2 HVO → Petroleum Diesel → HVO

This chapter presents the results of the fluctuate immersion path of HVO → petroleum diesel → HVO (figures 55–78).

The photographs of the specimens were taken immediately after thorough examination, which included weighing of the specimens, measuring of the dimensions of the specimens and visual inspections.

The graphs were created on the basis of the data averages, which were acquired from the recorded data (appendix 2) using the previously mentioned equations in chapter 3.3.1 (equations 1–4).

Average change in size was calculated from the change in length, width and thickness of specimen, as it was expected that the size change was equal in each of the dimensions. The measurement accuracy of the caliper and the scale used was calculated to be approximately $\pm 2\%$.

AEM, Ethylene Acrylate Rubber

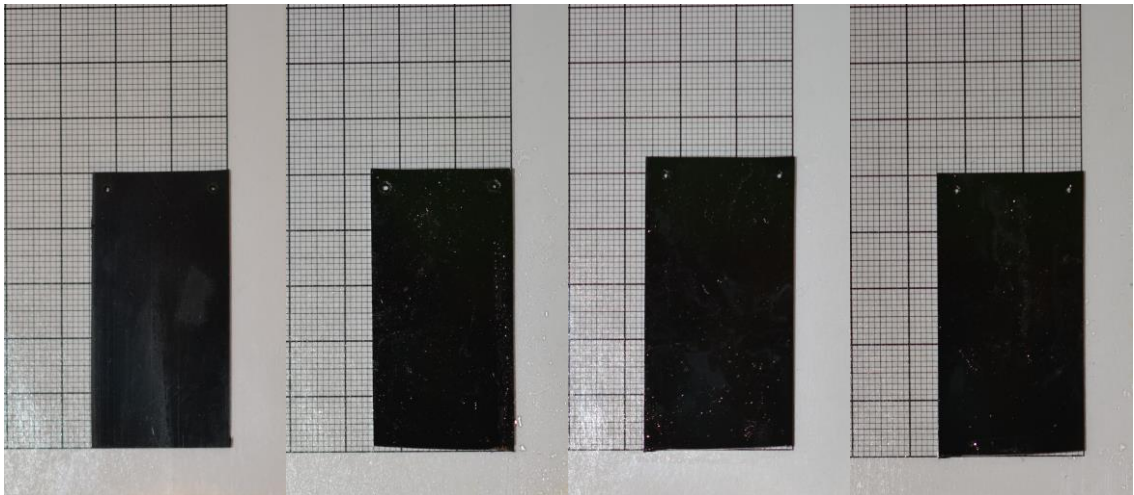


Figure 55. AEM, ethylene acrylate rubber, in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

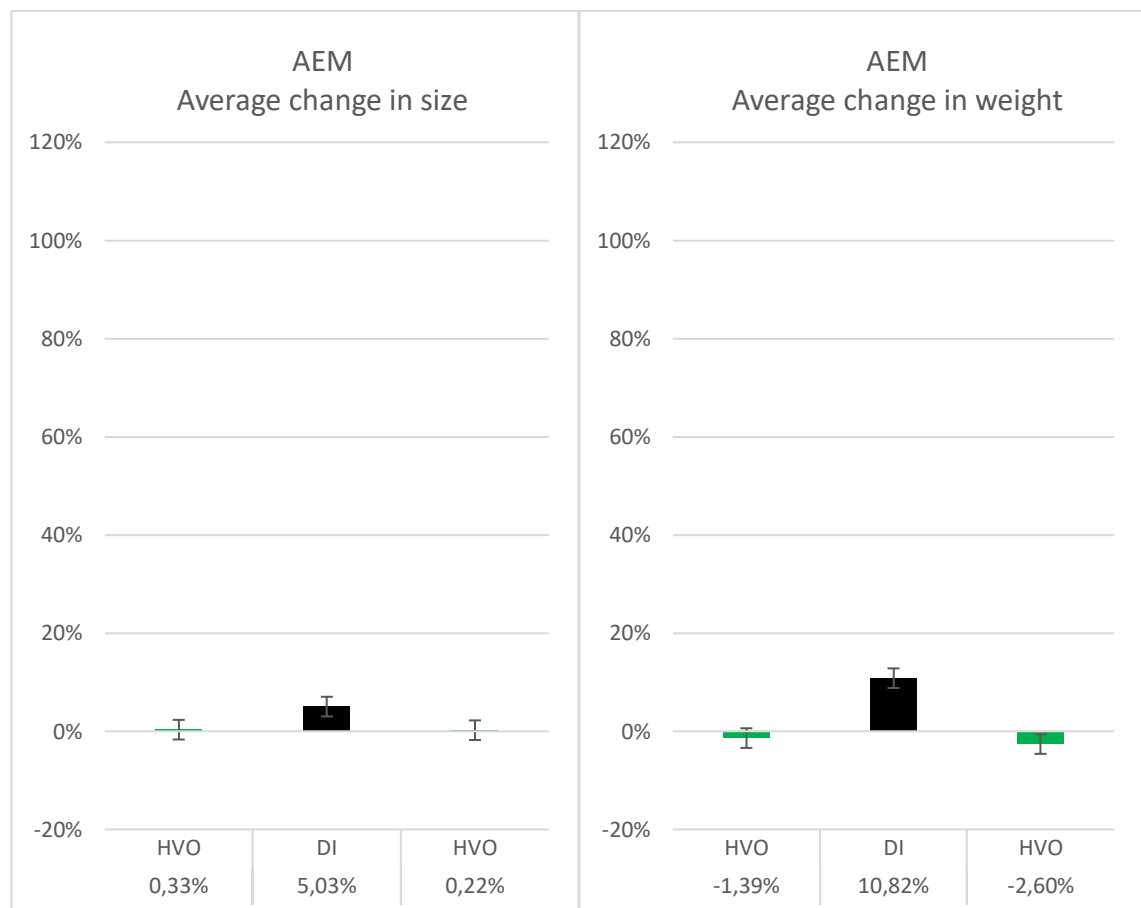


Figure 56. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

EPDM, Ethylene Propylene Diene Rubber

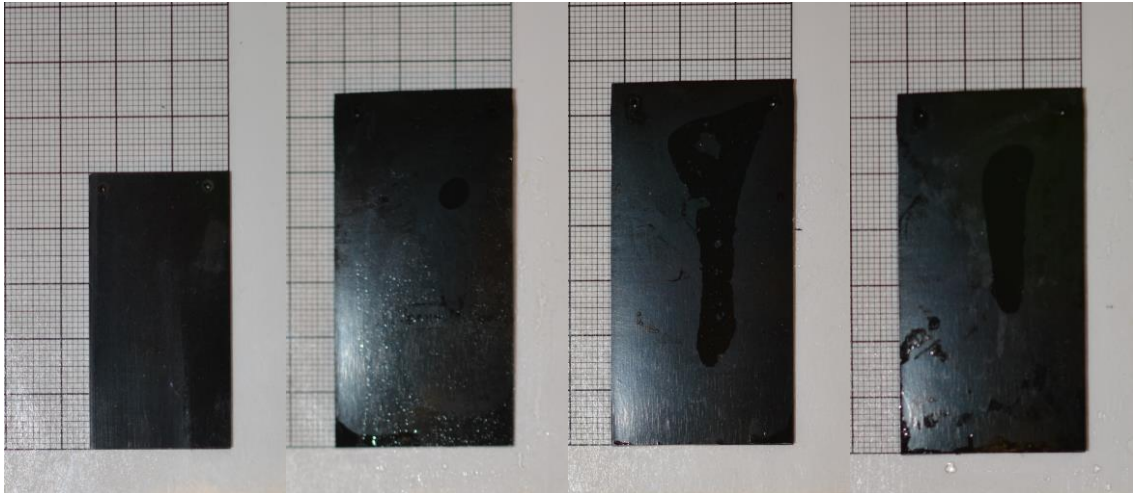


Figure 57. EPDM, ethylene propylene diene rubber, in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

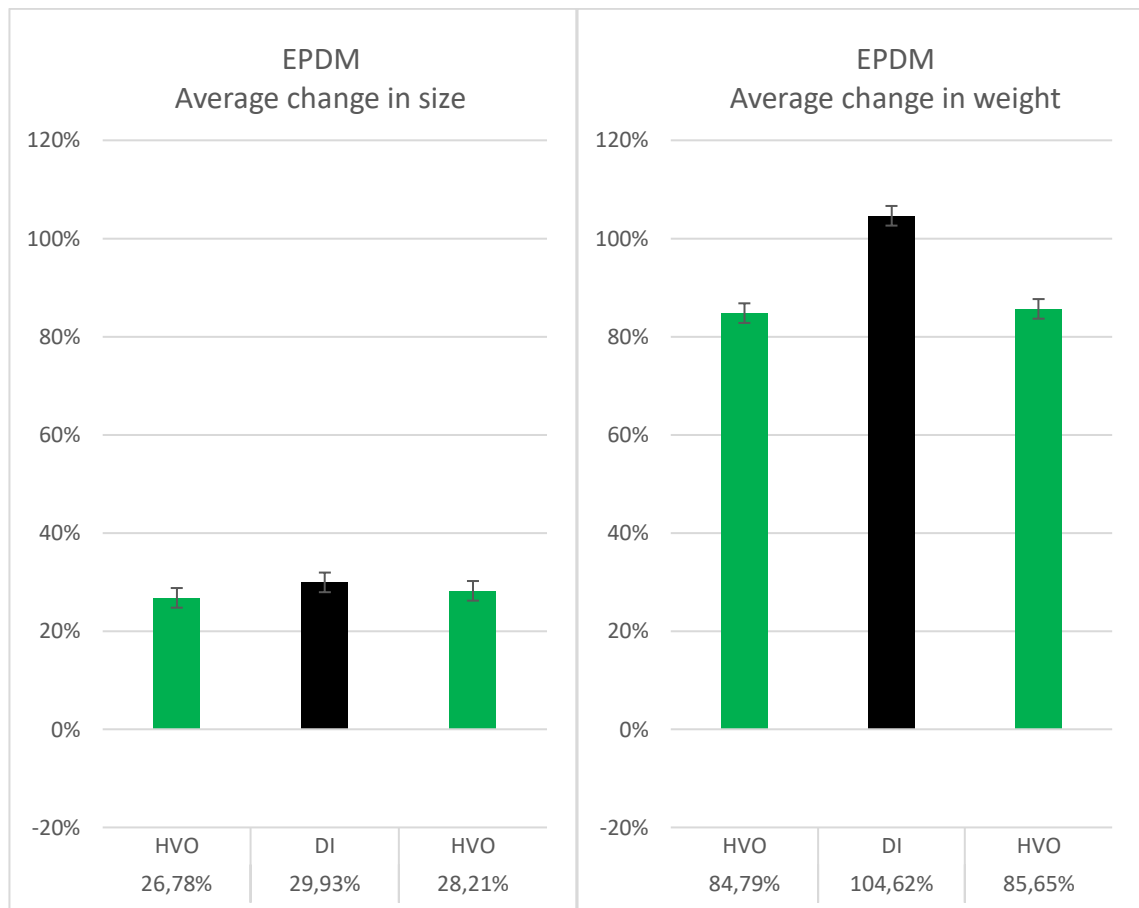


Figure 58. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

FKM, Fluorocarbon Rubber

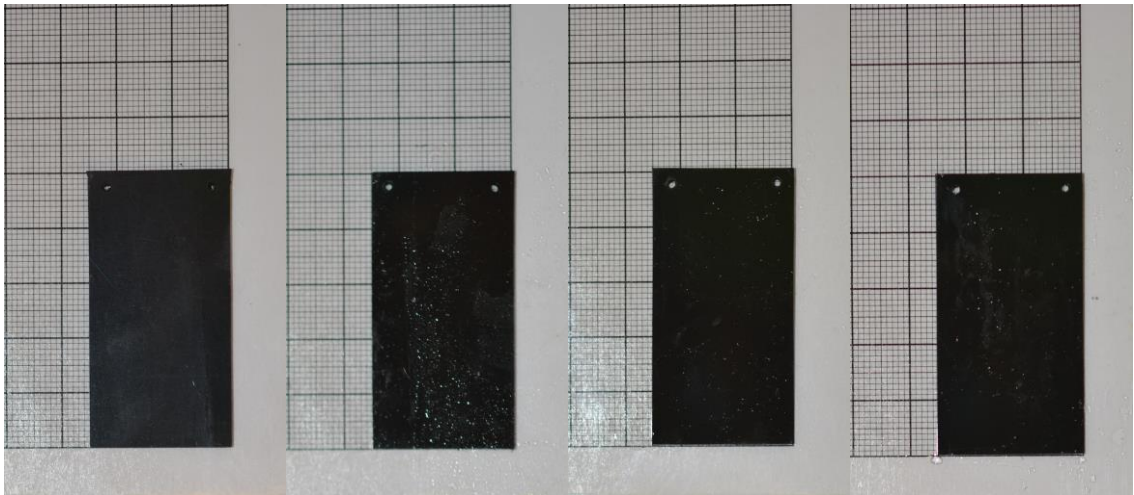


Figure 59. FKM, fluorocarbon rubber, in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

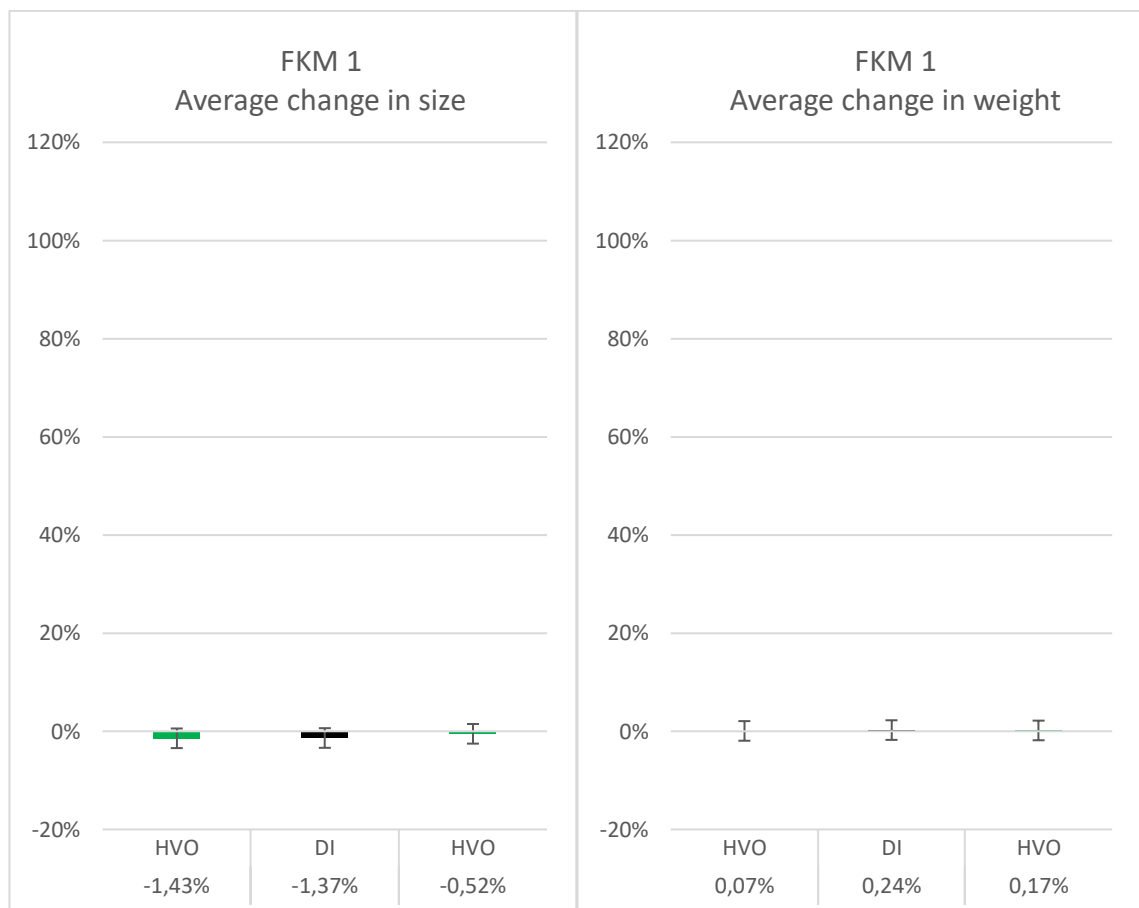


Figure 60. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

FKM, Fluorocarbon Rubber with Higher Fluorine Content

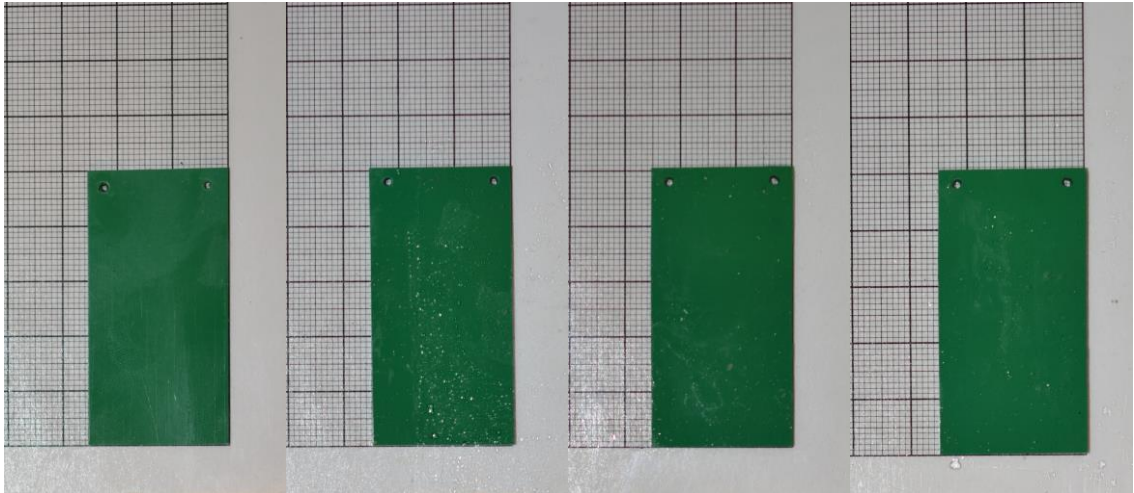


Figure 61. FKM, fluorocarbon rubber with higher fluorine content, in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

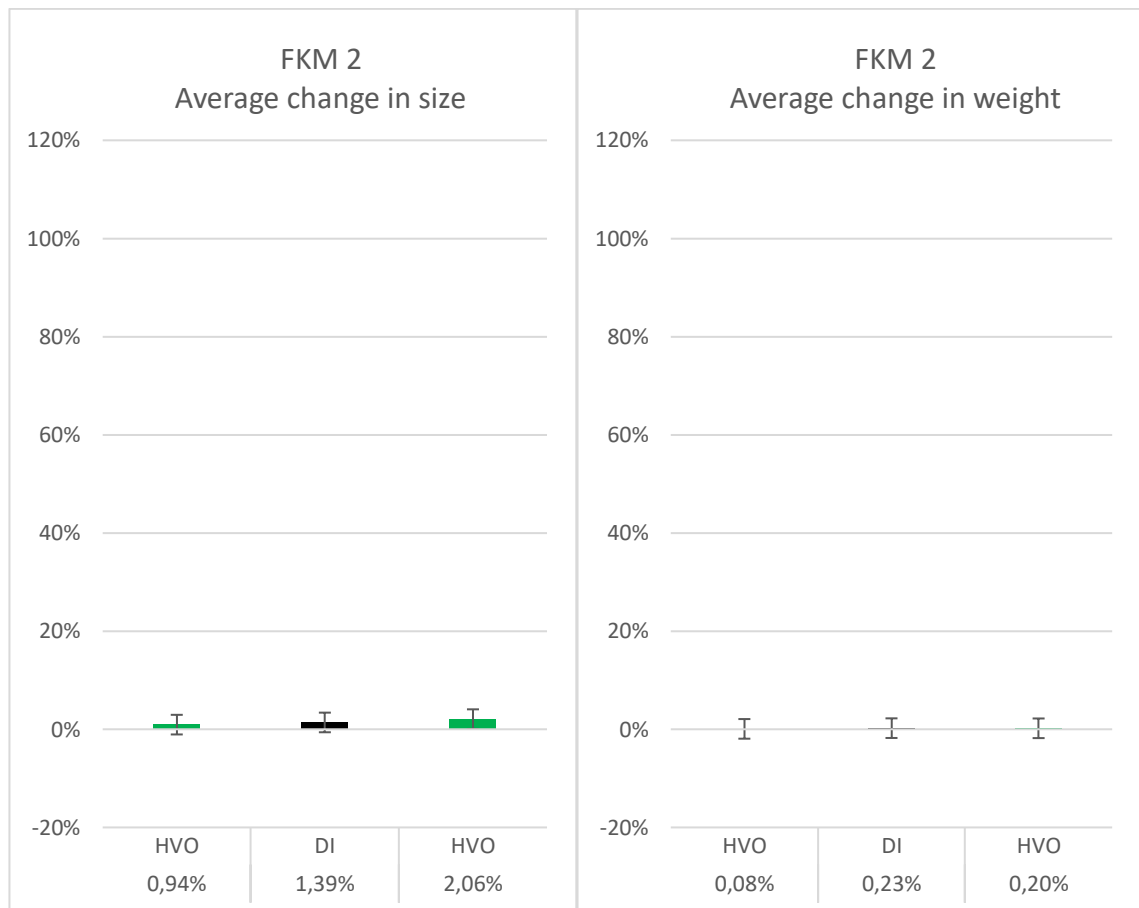


Figure 62. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

FVMQ, Fluorosilicone Rubber

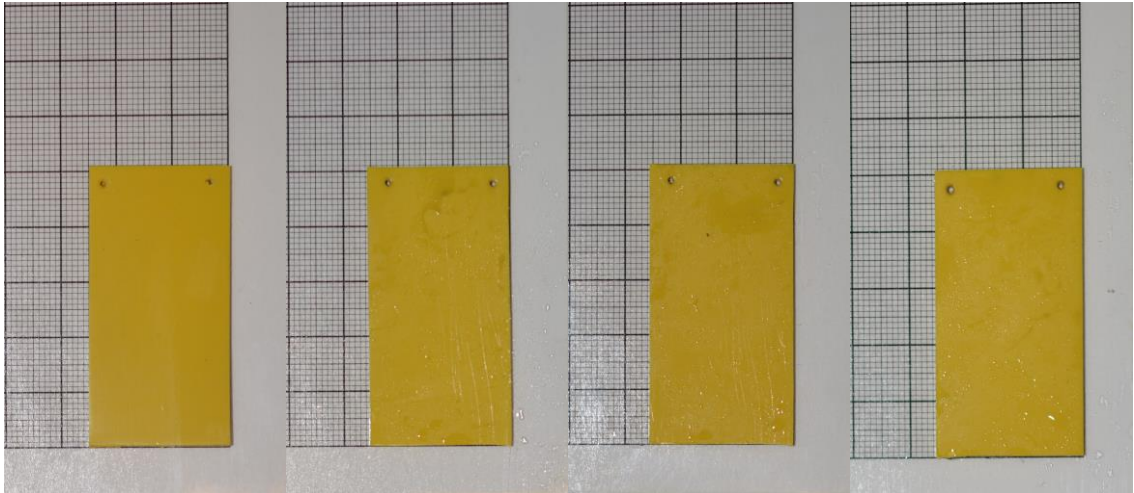


Figure 63. FVMQ, fluorosilicone rubber, in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

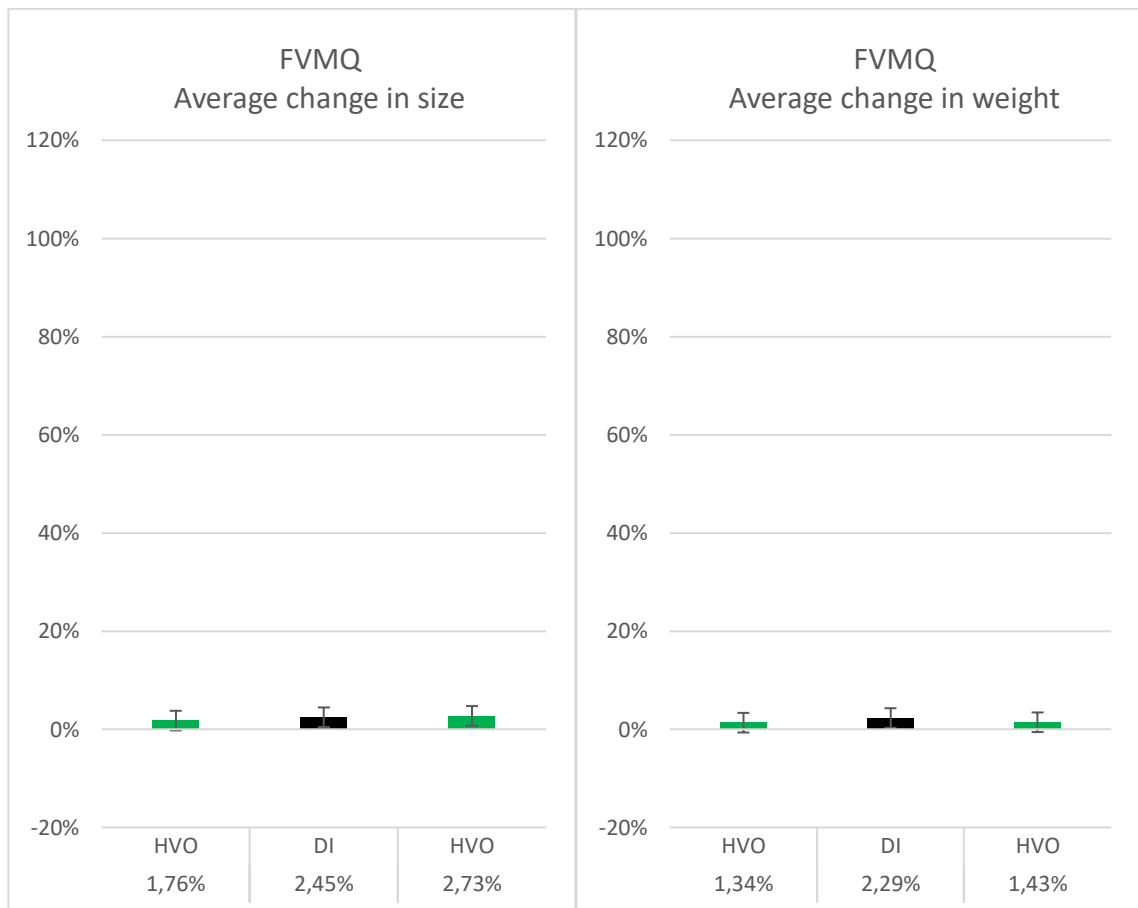


Figure 64. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

HNBR, Hydrogenated Acrylonitrile-Butadiene Rubber

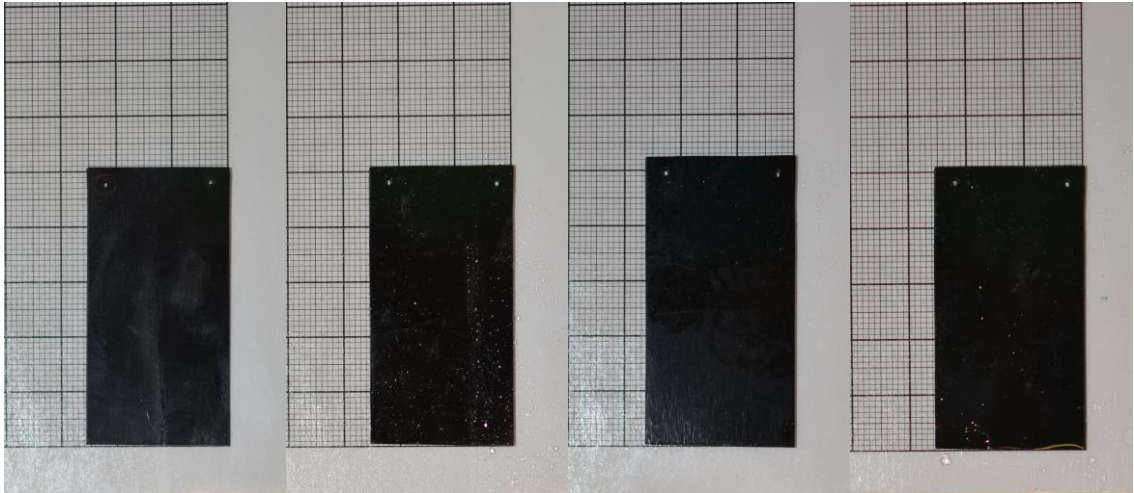


Figure 65. HNBR, hydrogenated acrylonitrile-butadiene rubber, in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

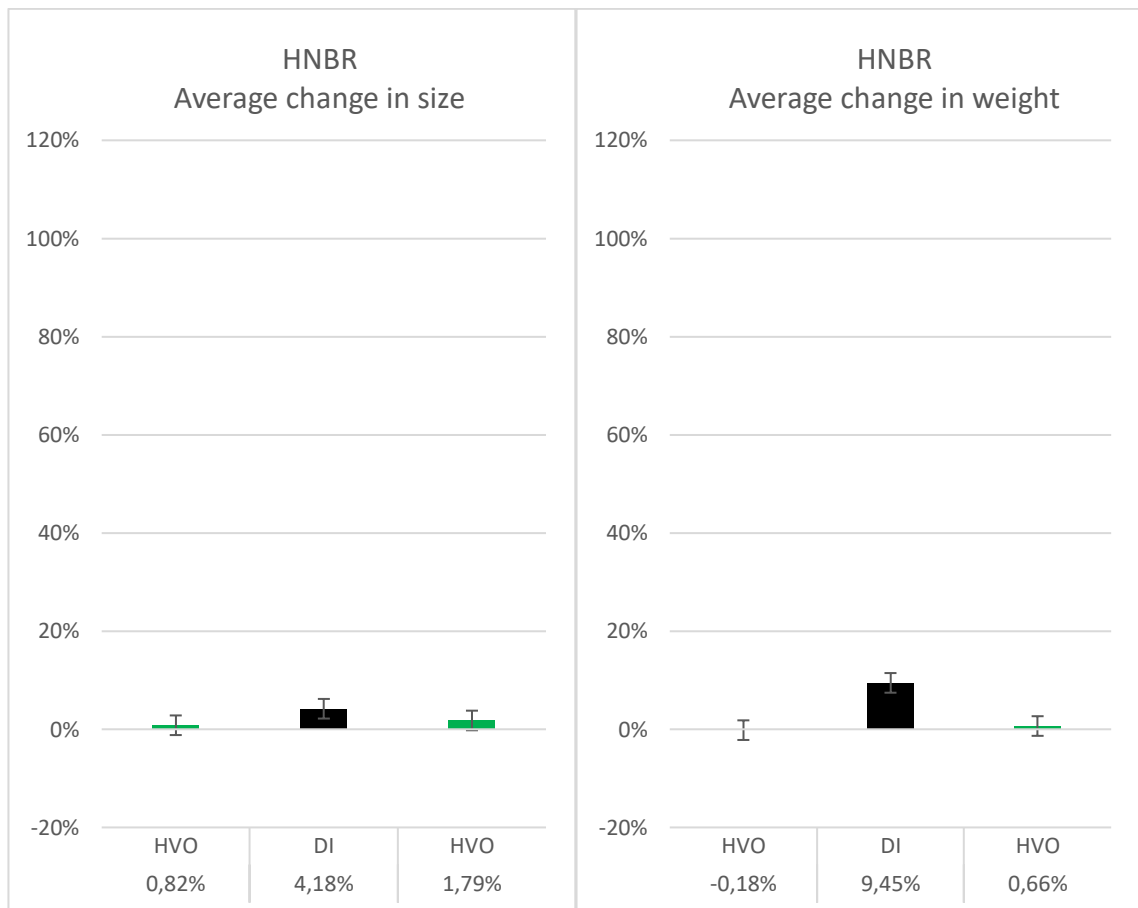


Figure 66. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

IIR, Butyl Rubber

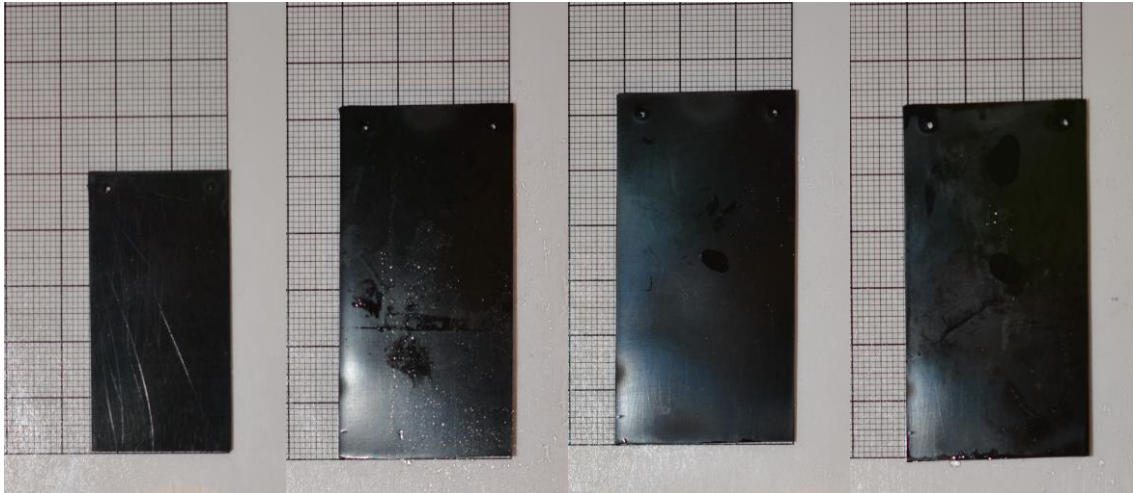


Figure 67. IIR, butyl rubber, in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

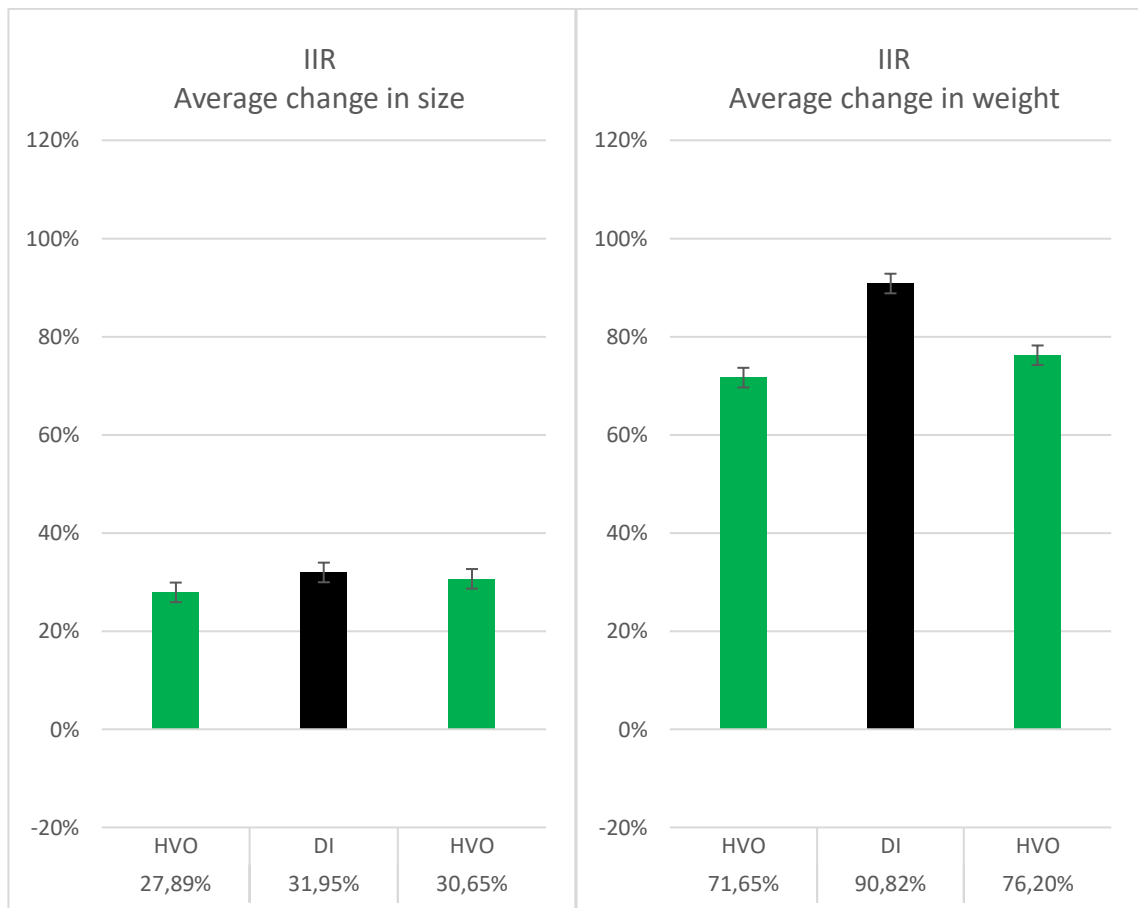


Figure 68. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

NBR, Acrylonitrile-Butadiene Rubber (Nitrile Rubber)

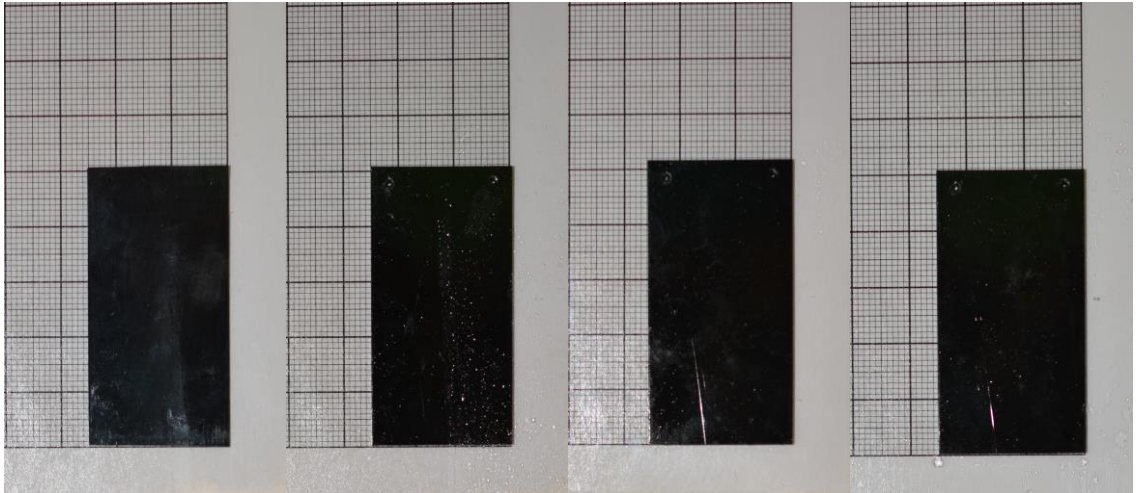


Figure 69. NBR, acrylonitrile-butadiene rubber (nitrile rubber), in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

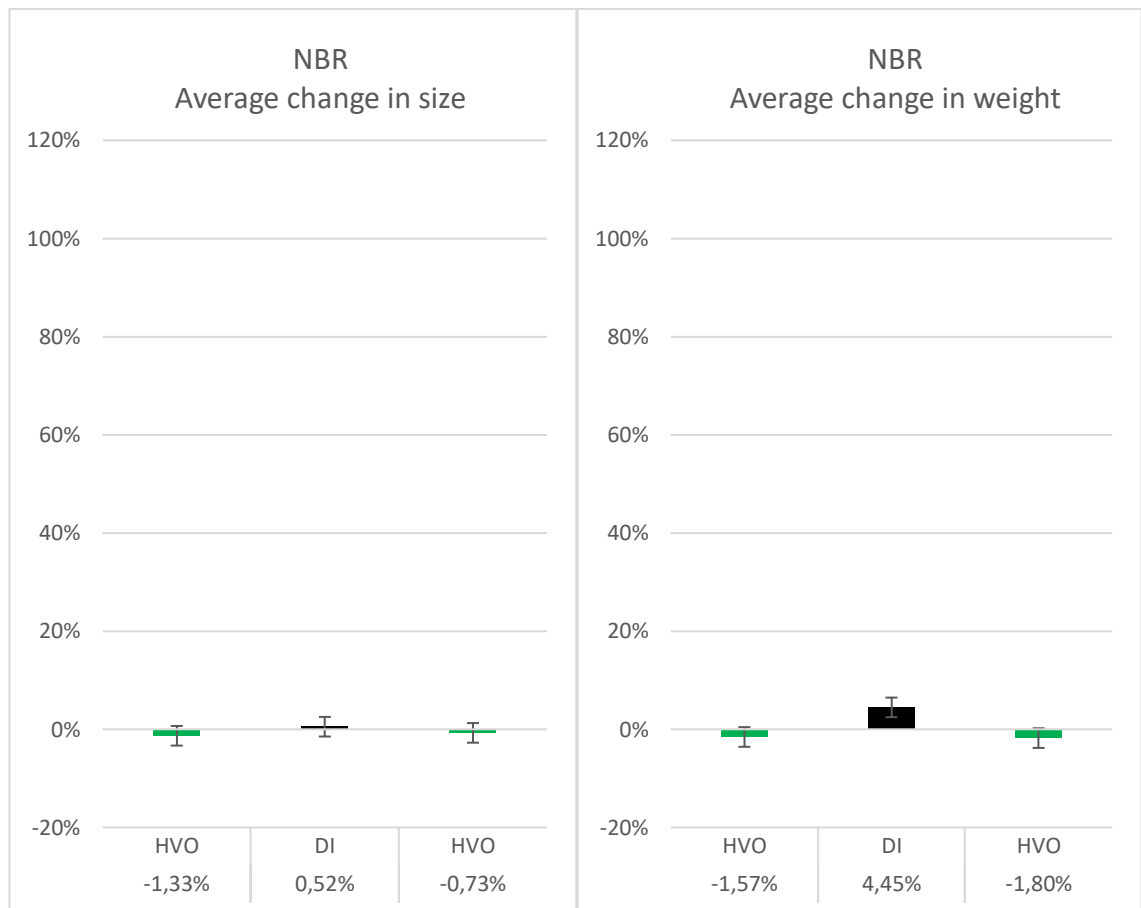


Figure 70. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

AU, Polyester Urethane

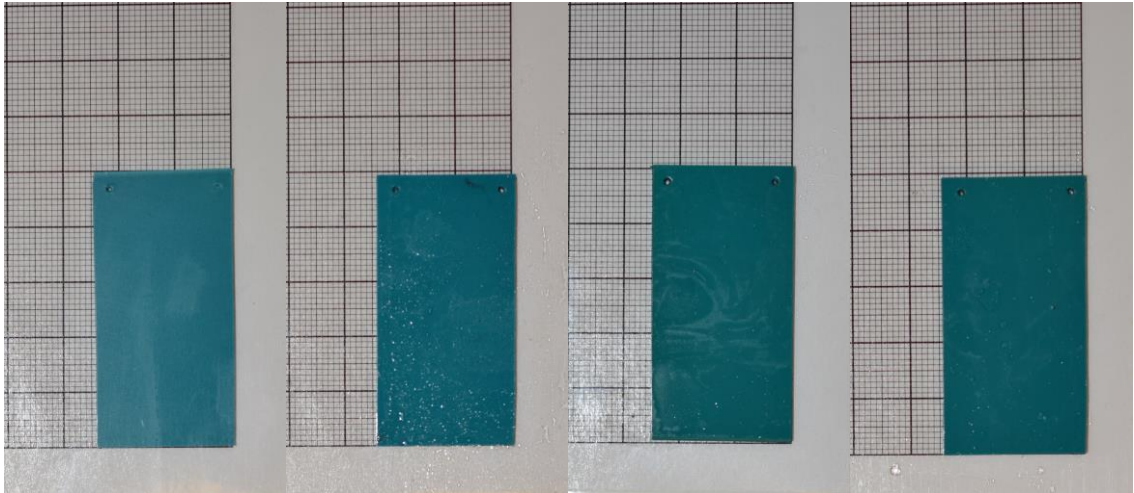


Figure 71. AU, polyester urethane, in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

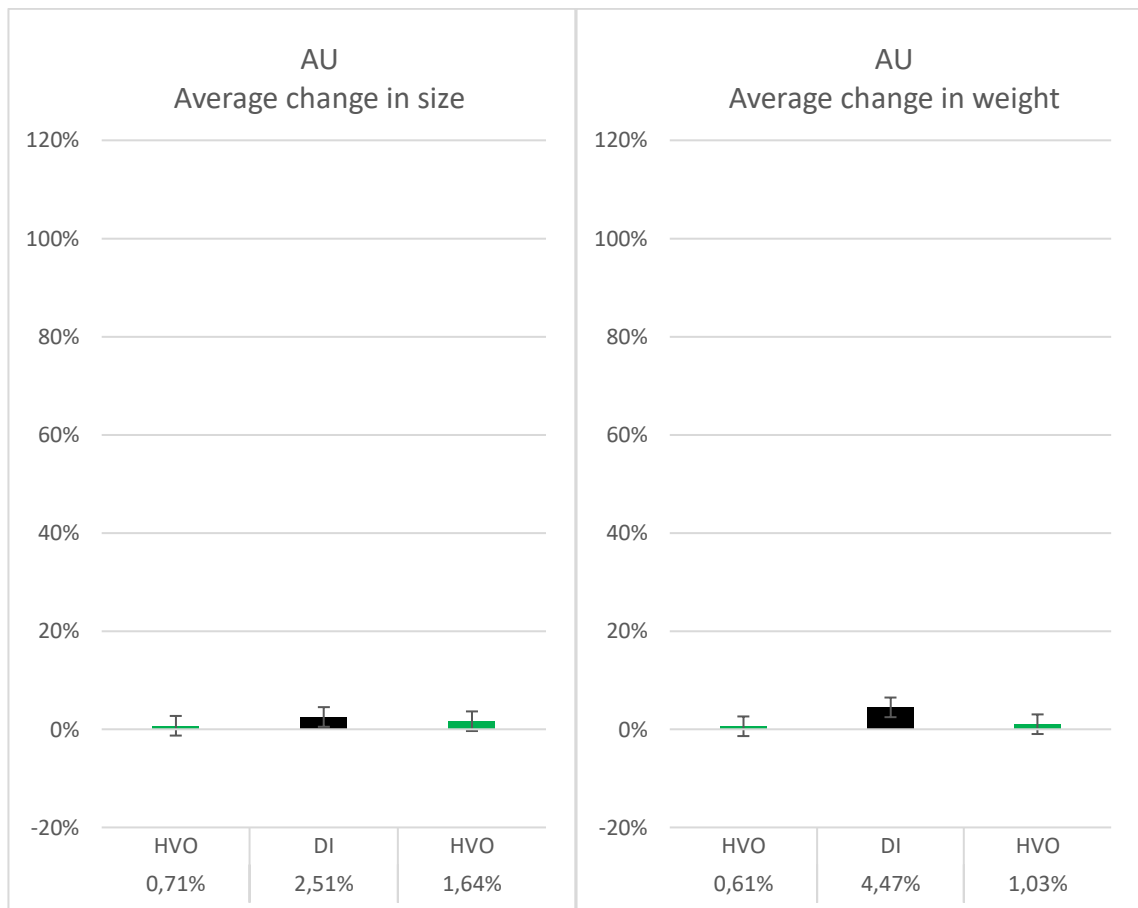


Figure 72. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

VMQ, Silicone Rubber

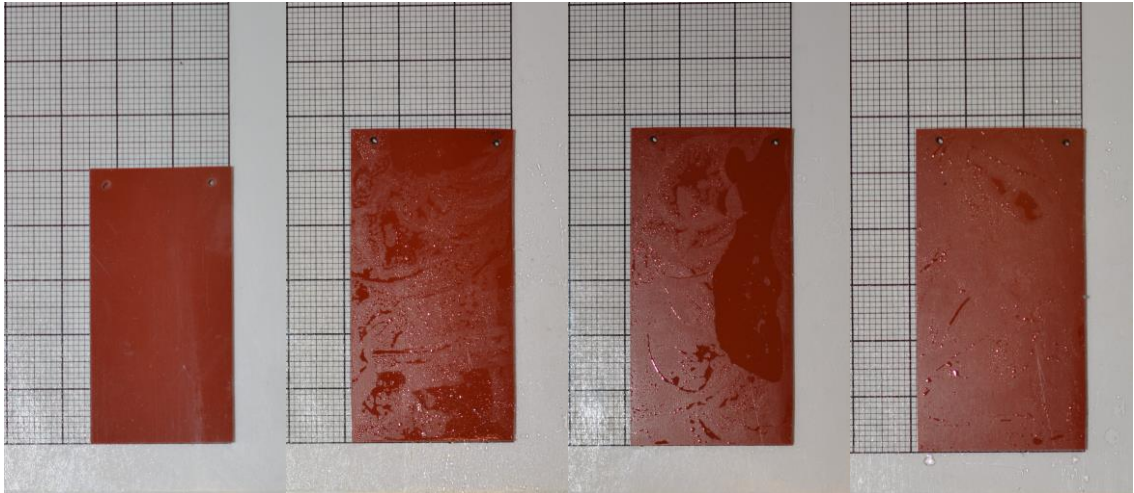


Figure 73. VMQ, silicone rubber, in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

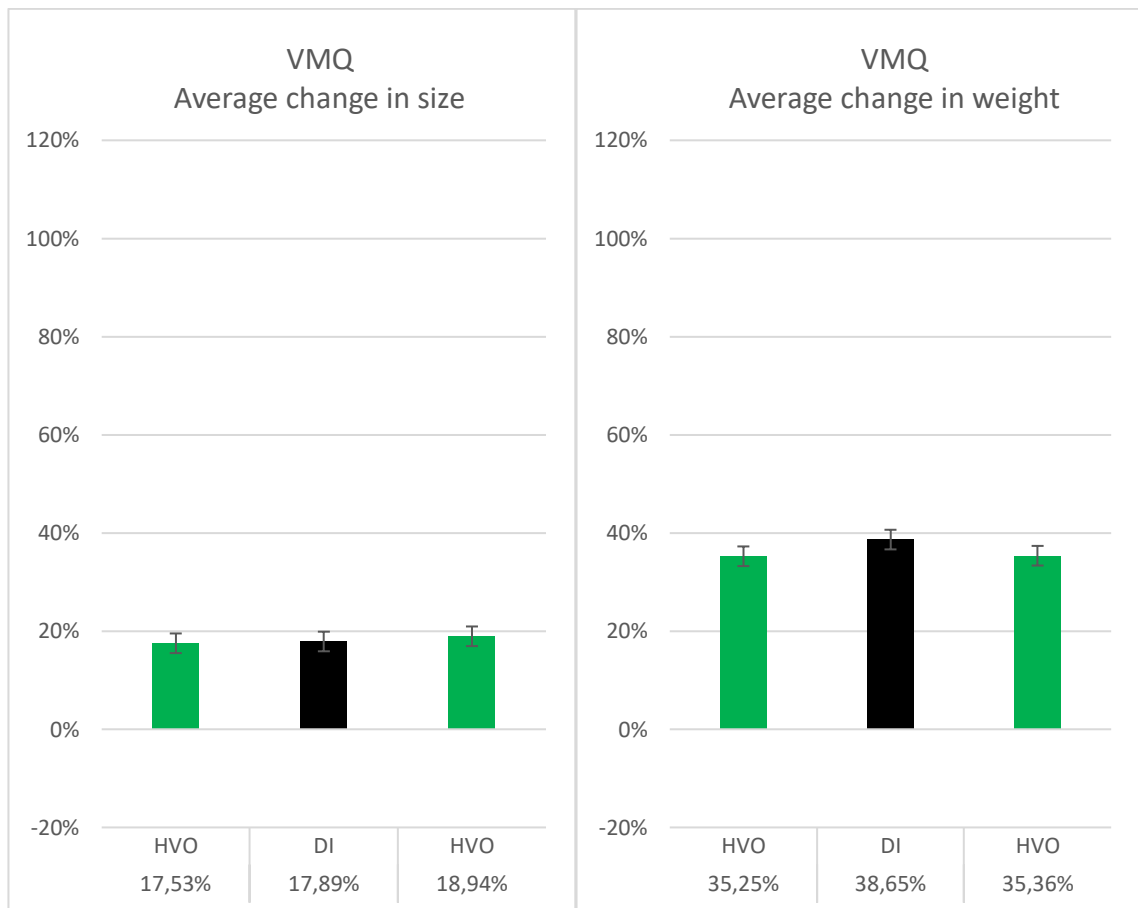


Figure 74. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

Virgin PTFE compounded with Turcon® additive

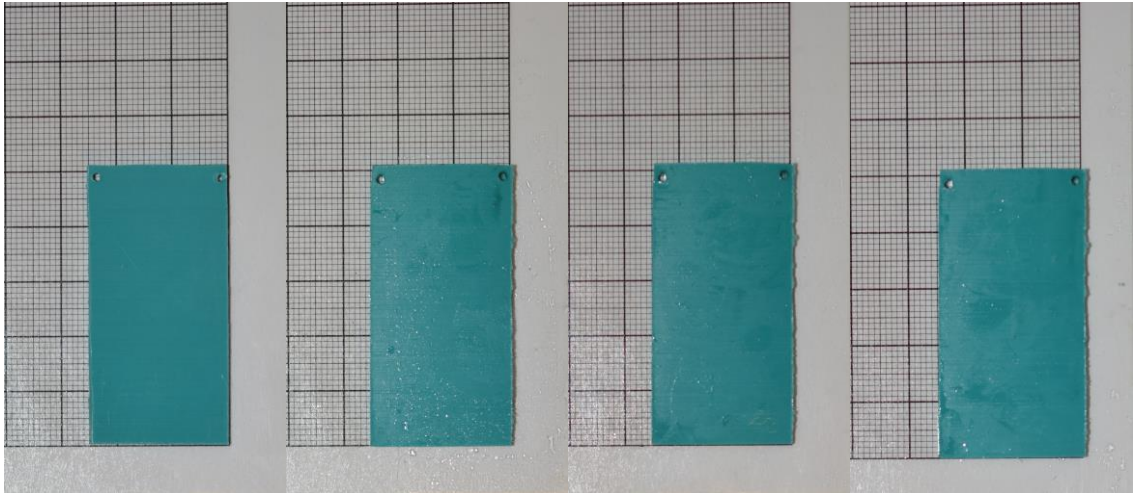


Figure 75. Virgin PTFE compounded with Turcon® additive in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

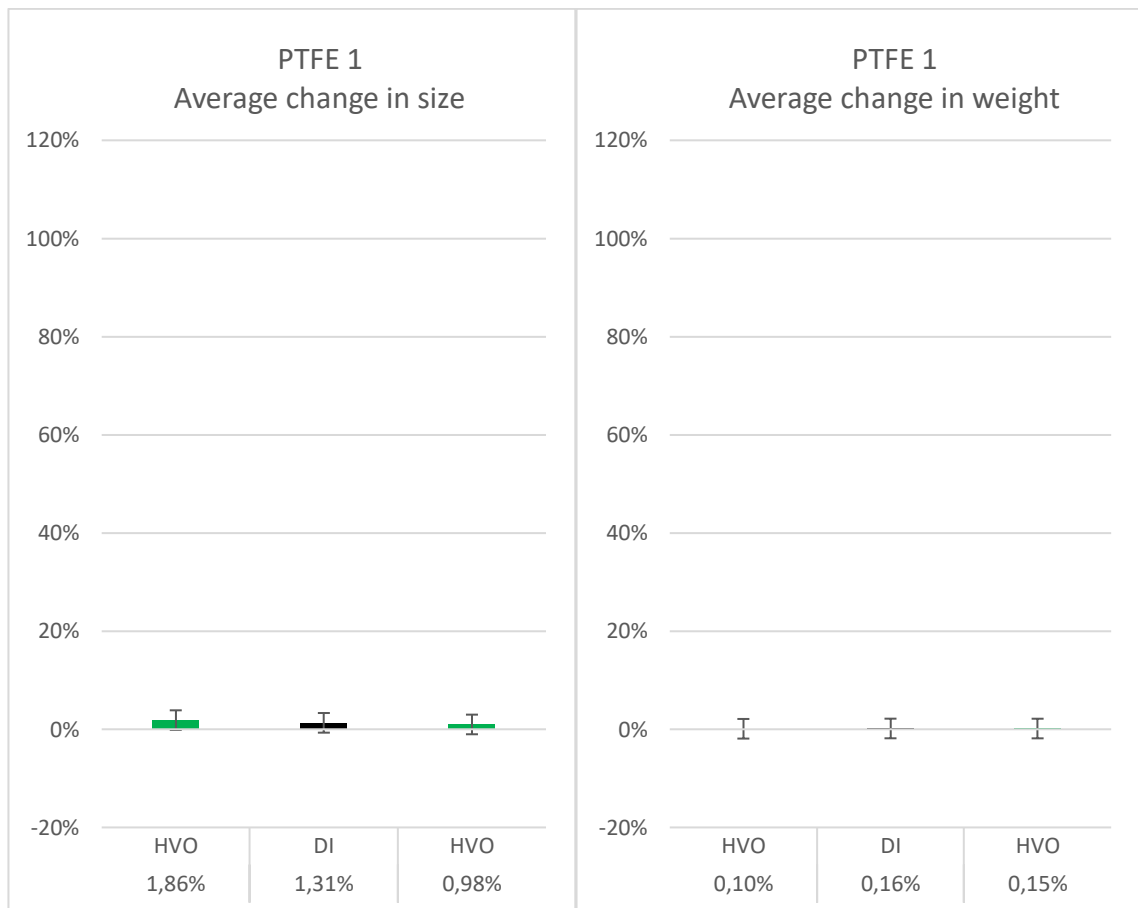


Figure 76. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

Virgin PTFE compounded with carbon and graphite

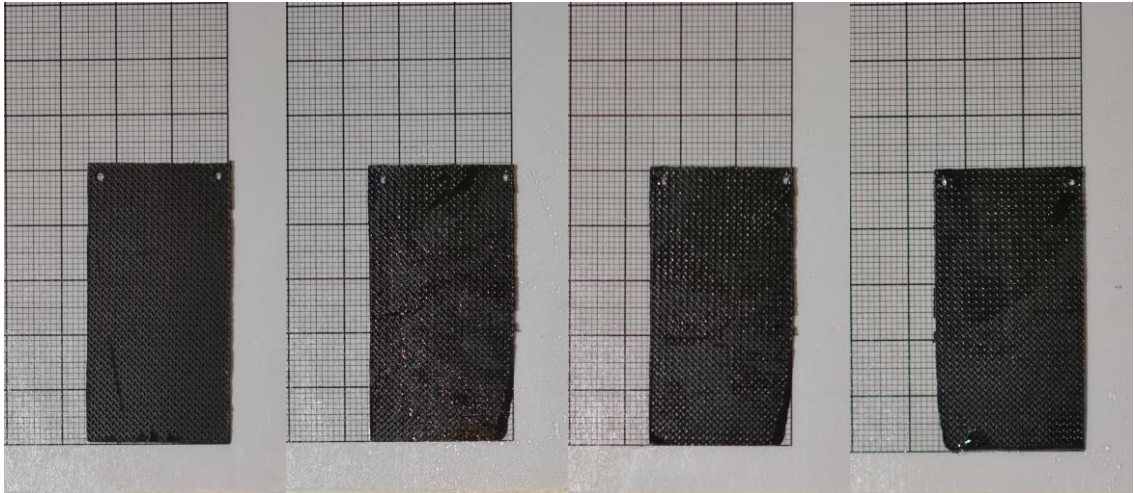


Figure 77. Virgin PTFE compounded with carbon and graphite in its prepared state and after weekly immersions in HVO → petroleum diesel → HVO from left to right respectively.

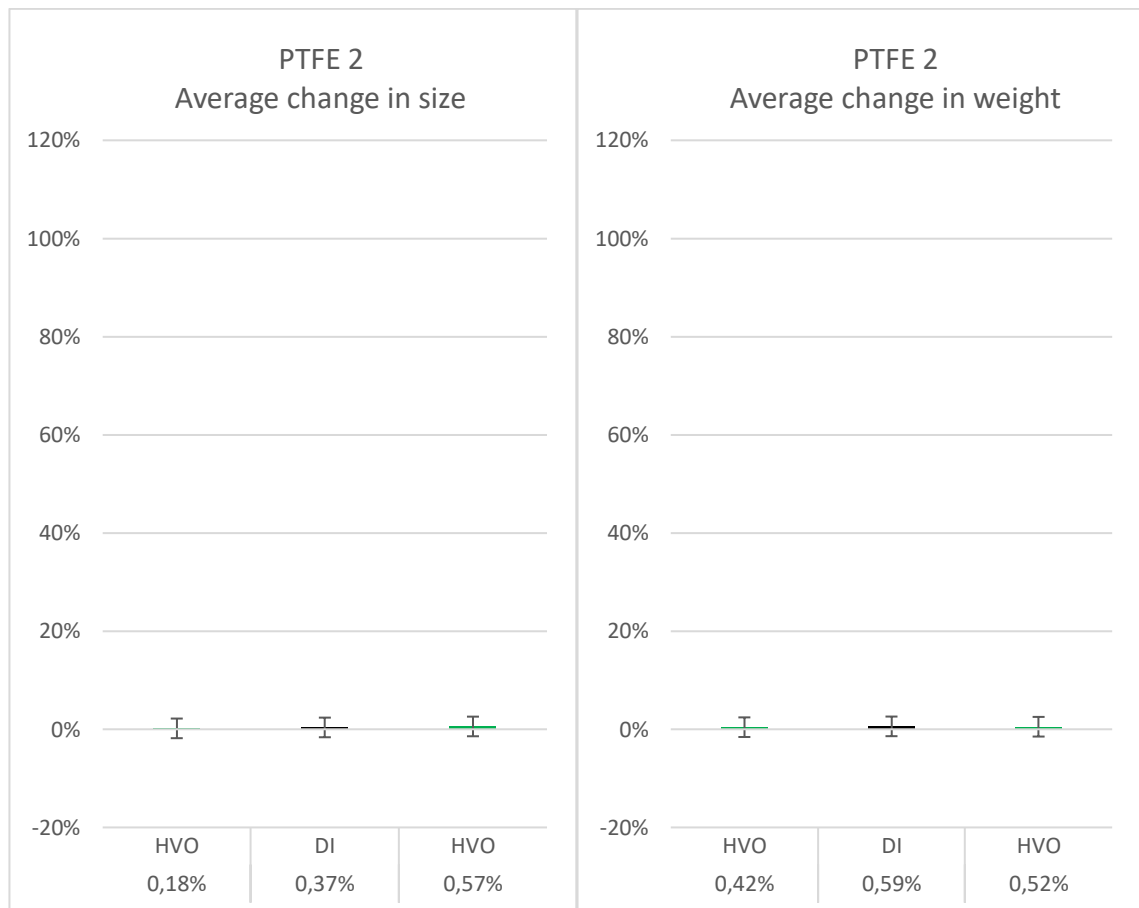


Figure 78. Average changes in size and weight of the specimens compared to the original state after weekly immersions in HVO → petroleum diesel → HVO.

To summarize the results in the immersion path of HVO → petroleum diesel → HVO, the elastomeric materials were ranked by the average magnitude of the reactions to give an idea of the suitability in conditions as simulated in the test (table 12).

The following results are based only on the results gained from the previous test. In actual material selection procedures, many other material properties must be carefully examined to find the most suitable material for the designed application.

PTFE materials were left outside of the ranking system, because of their unique properties which are not comparable to elastomers.

Rank	Material	Effects
1.	FKM 1	FKM 1 showed slight shrinkage in this immersion path. Other than that, the material succeeded with the most minimal alteration.
2.	FKM 2	FKM 2 showed slight shrinkage in this immersion path. Other than that, the material succeeded as well as FKM 1.
3.	NBR	NBR showed minimal swelling and some increase in weight in this immersion path.
4.	AU	AU showed minimal swelling and increase in weight in this immersion path.
5.	FVMQ	FVMQ showed swelling and increase in weight in this immersion path.
6.	AEM	AEM showed swelling and medium increase in weight in this immersion path.
7.	HNBR	HNBR showed swelling and medium increase in weight in this immersion path.
8.	VMQ	VMQ showed high swelling and increase in weight in this immersion path.
9.	EPDM	EPDM showed extremely high swelling and increase in weight in this immersion path.
10.	IIR	IIR showed extremely high swelling and increase in weight in this immersion path.

Table 12. Suitability rankings of the elastomeric materials in immersion path of HVO → petroleum diesel → HVO.

Judging by the results, FKM 1, FKM 2, NBR, AU and FVMQ would be able to function properly in conditions which were simulated in this immersion path. AEM, HNBR, VMQ, EPDM and IIR showed reactions which would not be tolerated in fuel system applications, and therefore, cannot be recommended for usage in such conditions.

5.1.3 FAME → Petroleum Diesel → HVO

This chapter presents the results of the fluctuate immersion path of FAME → petroleum diesel → HVO (figures 79–102).

The photographs of the specimens were taken immediately after thorough examination, which included weighing of the specimens, measuring of the dimensions of the specimens and visual inspections.

The graphs were created on the basis of the data averages, which were acquired from the recorded data (appendix 2) using the previously mentioned equations in chapter 3.3.1 (equations 1–4).

Average change in size was calculated from the change in length, width and thickness of specimen, as it was expected that the size change was equal in each of the dimensions. The measurement accuracy of the caliper and the scale used was calculated to be approximately $\pm 2\%$.

AEM, Ethylene Acrylate Rubber

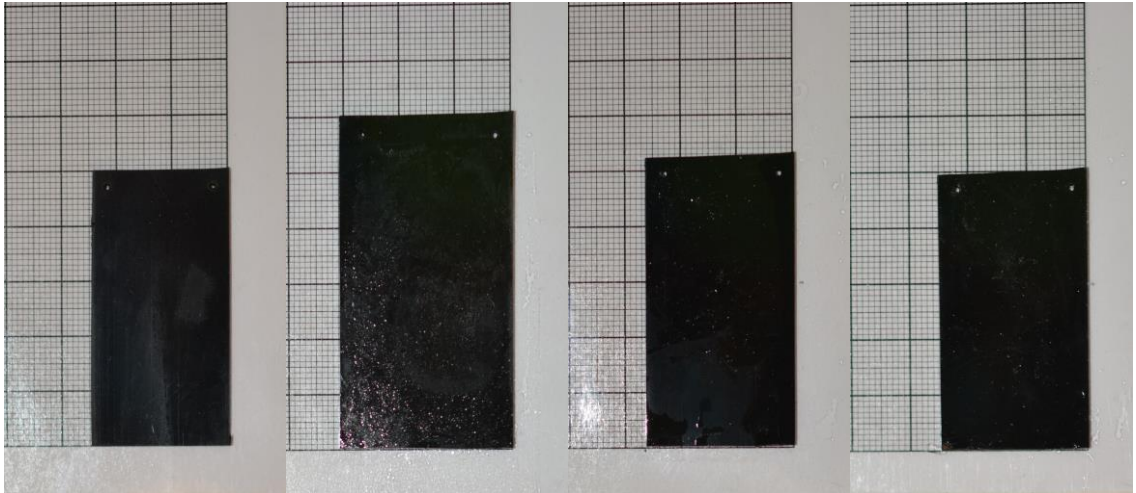


Figure 79. AEM, ethylene acrylate rubber, in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

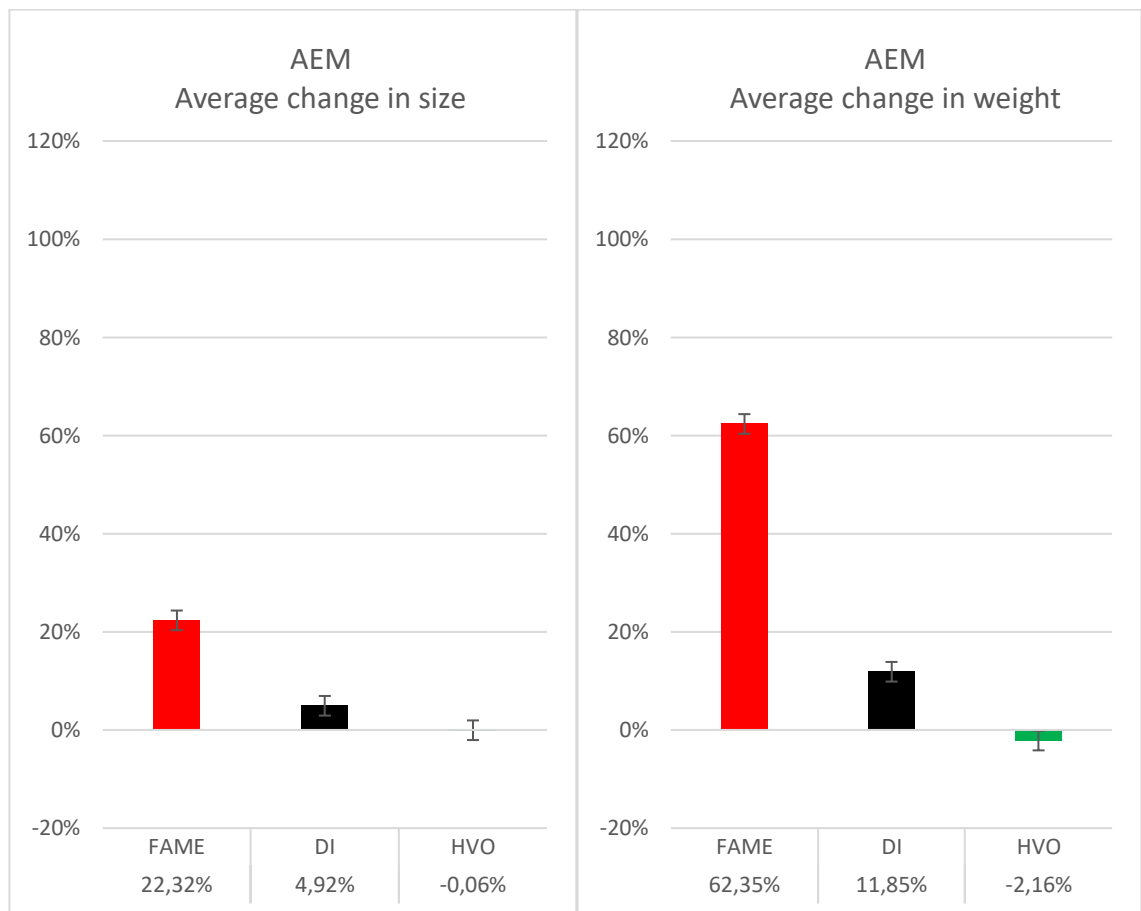


Figure 80. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

EPDM, Ethylene Propylene Diene Rubber

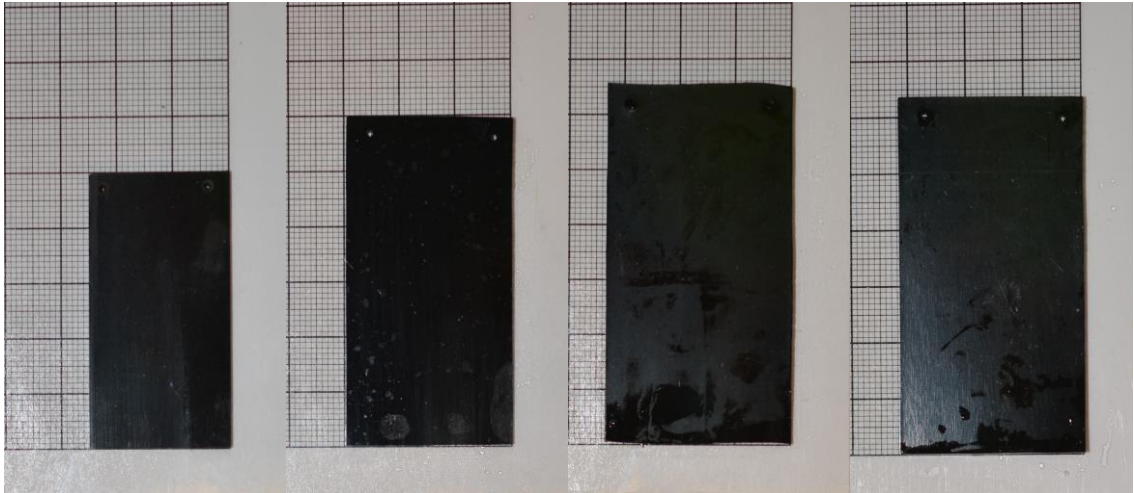


Figure 81. EPDM, ethylene propylene diene rubber, in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

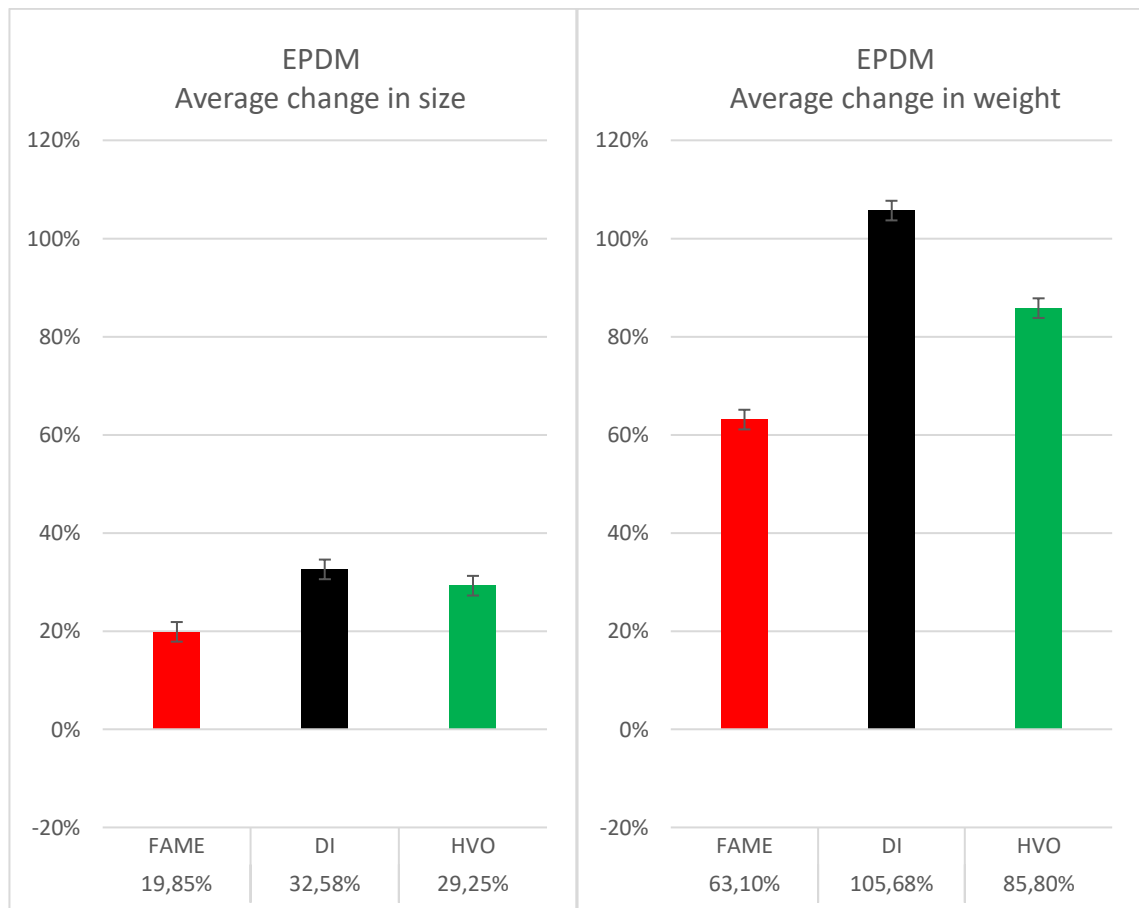


Figure 82. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

FKM, Fluorocarbon Rubber

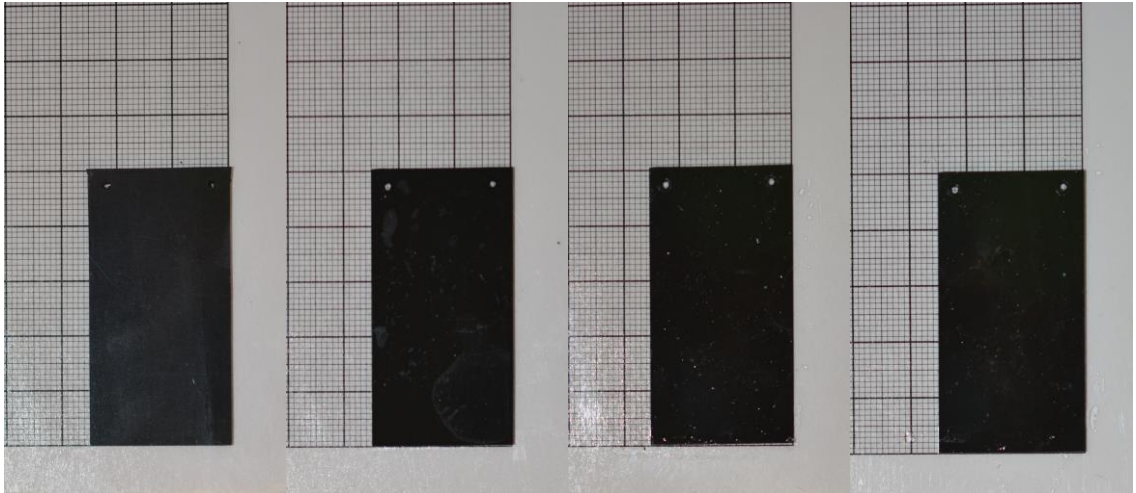


Figure 83. FKM, fluorocarbon rubber, in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

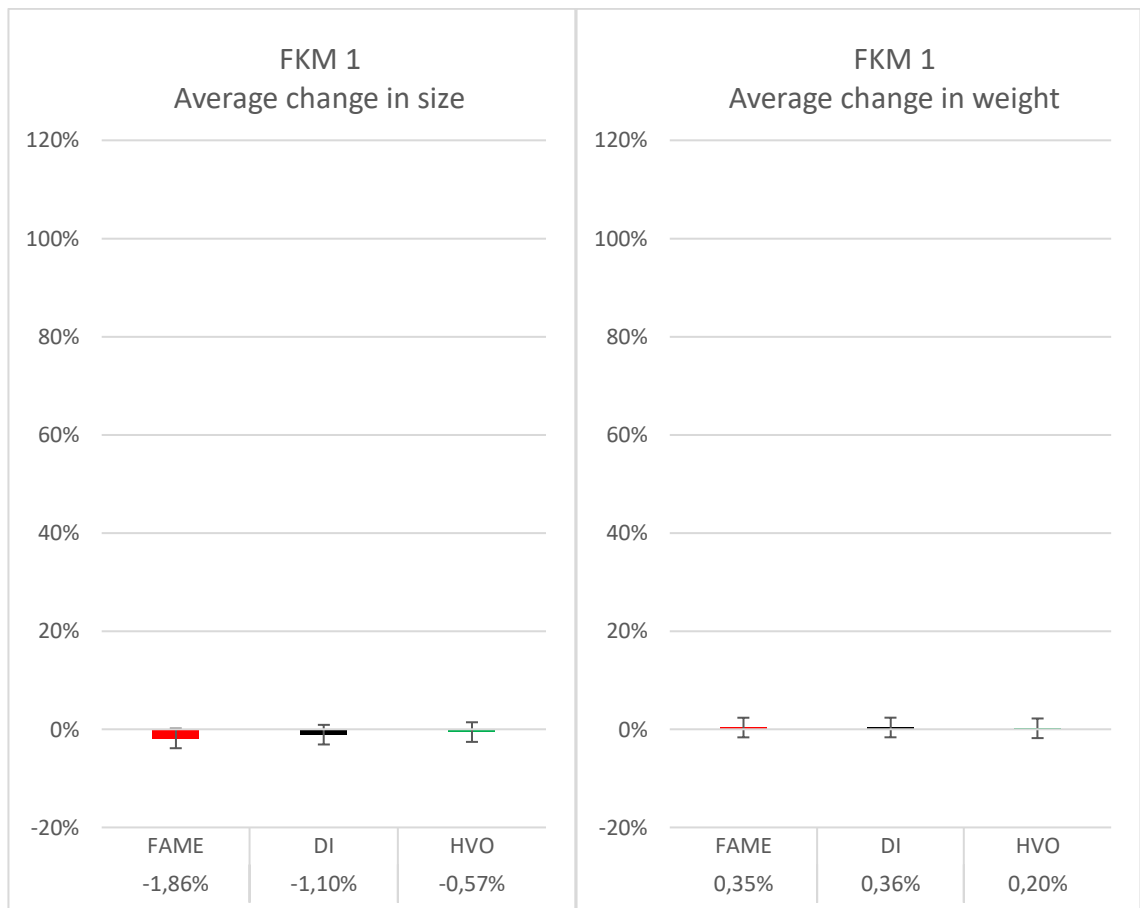


Figure 84. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

FKM, Fluorocarbon Rubber with Higher Fluorine Content

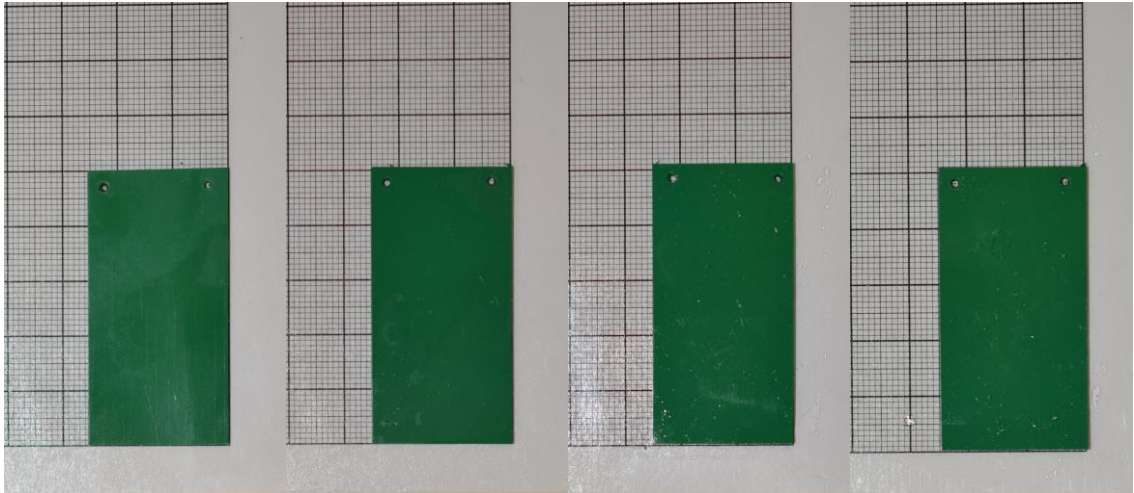


Figure 85. FKM, fluorocarbon rubber with higher fluorine content, in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

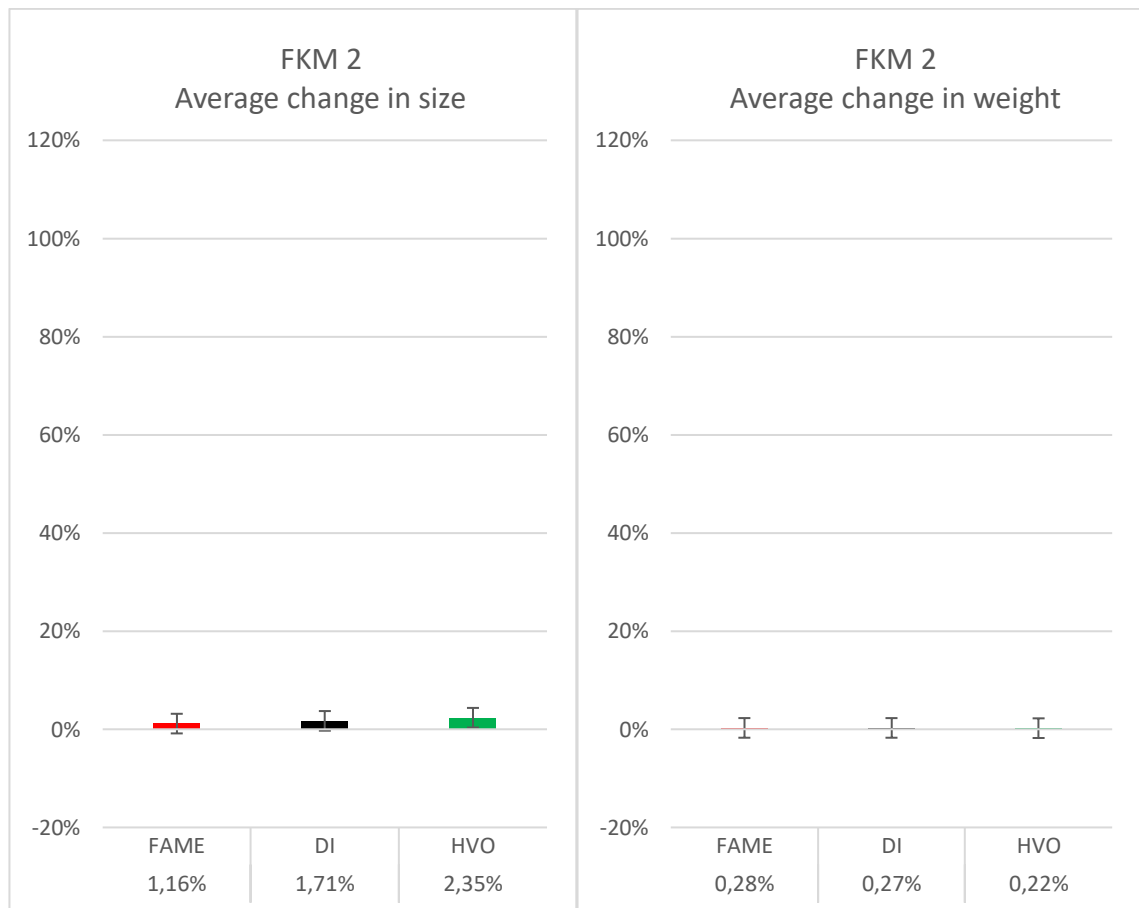


Figure 86. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

FVMQ, Fluorosilicone Rubber

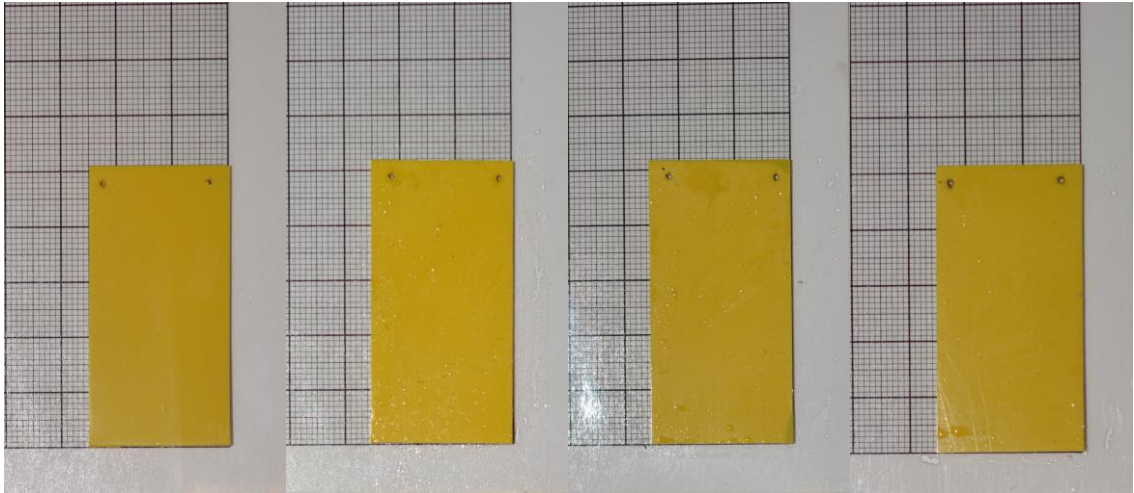


Figure 87. FVMQ, fluorosilicone rubber, in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

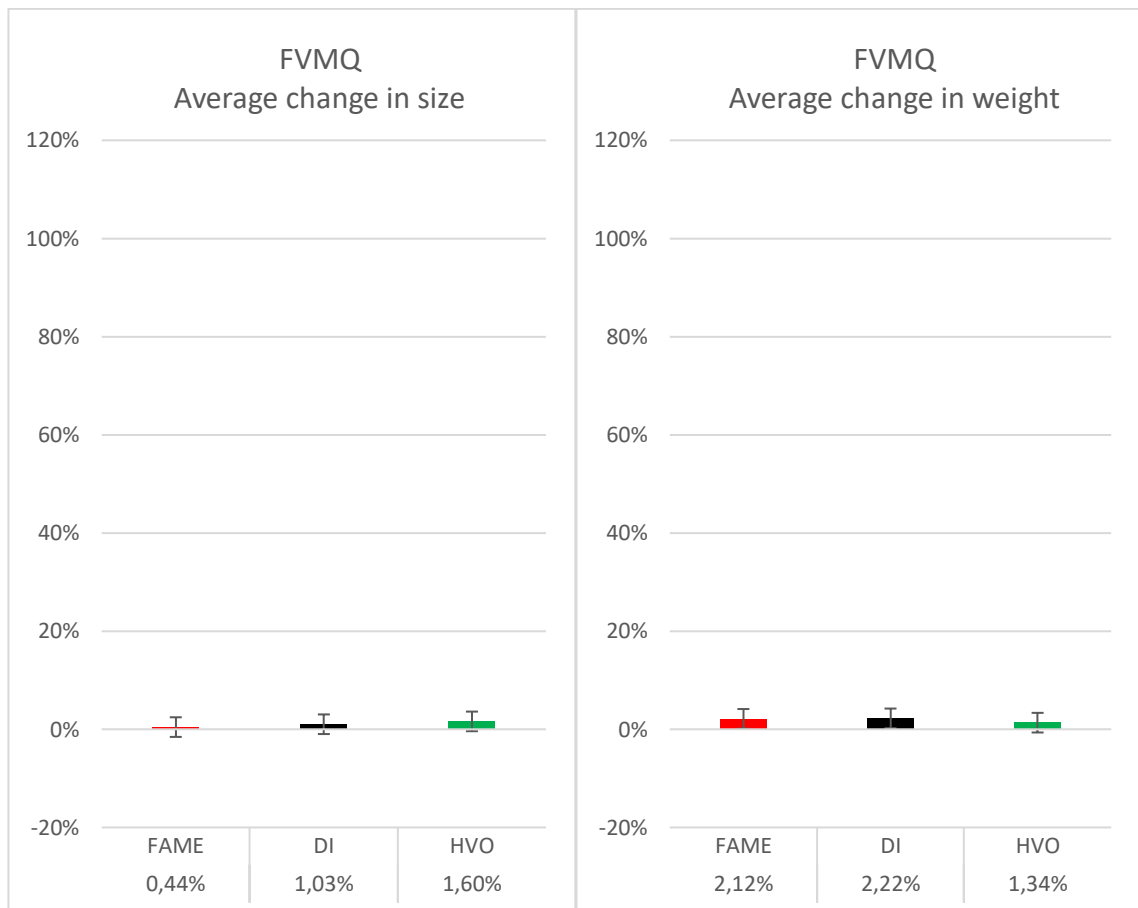


Figure 88. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

HNBR, Hydrogenated Acrylonitrile-Butadiene Rubber

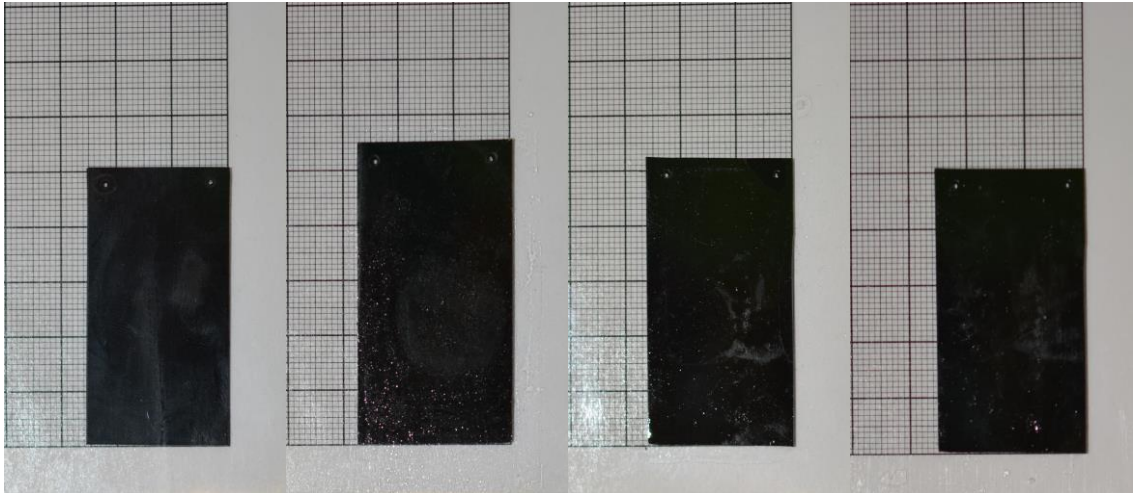


Figure 89. HNBR, hydrogenated acrylonitrile-butadiene rubber, in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

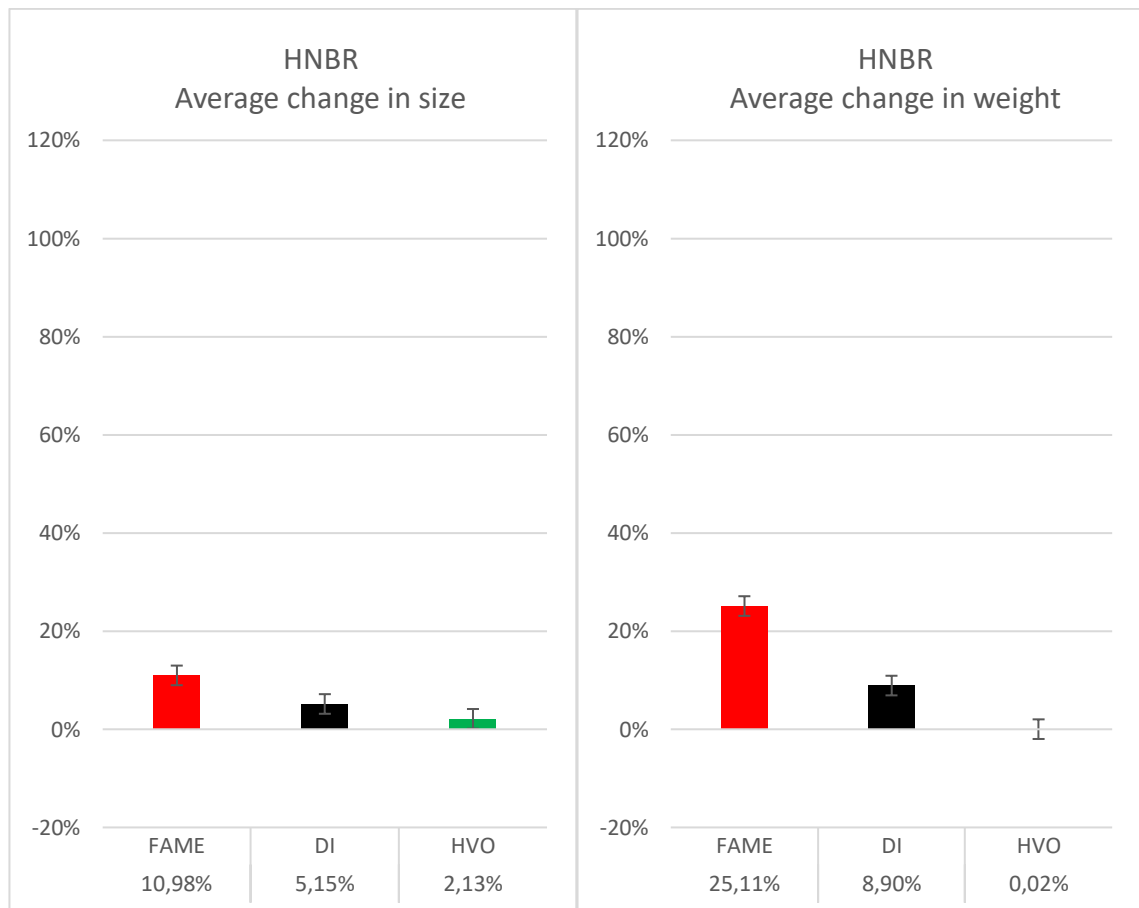


Figure 90. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

IIR, Butyl Rubber

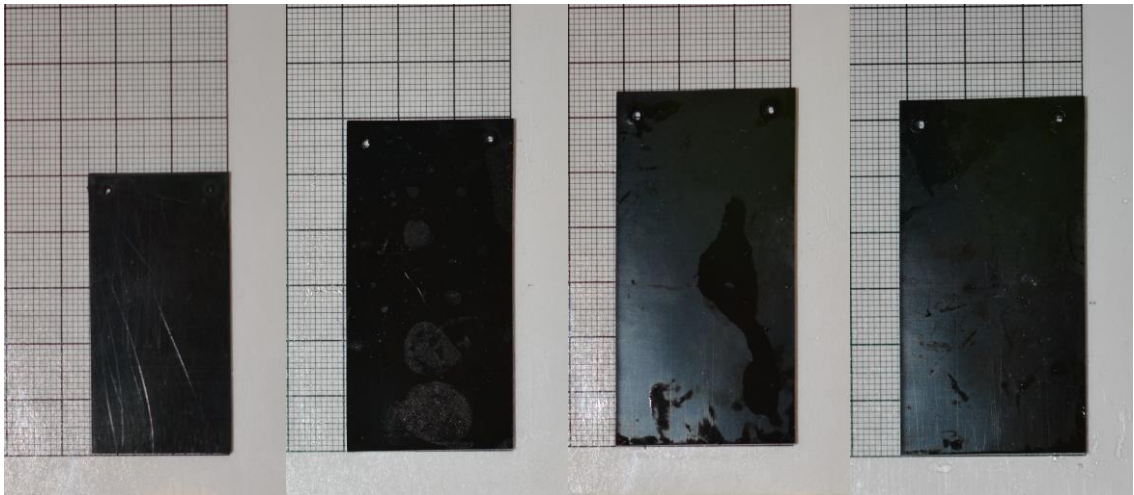


Figure 91. IIR, butyl rubber, in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

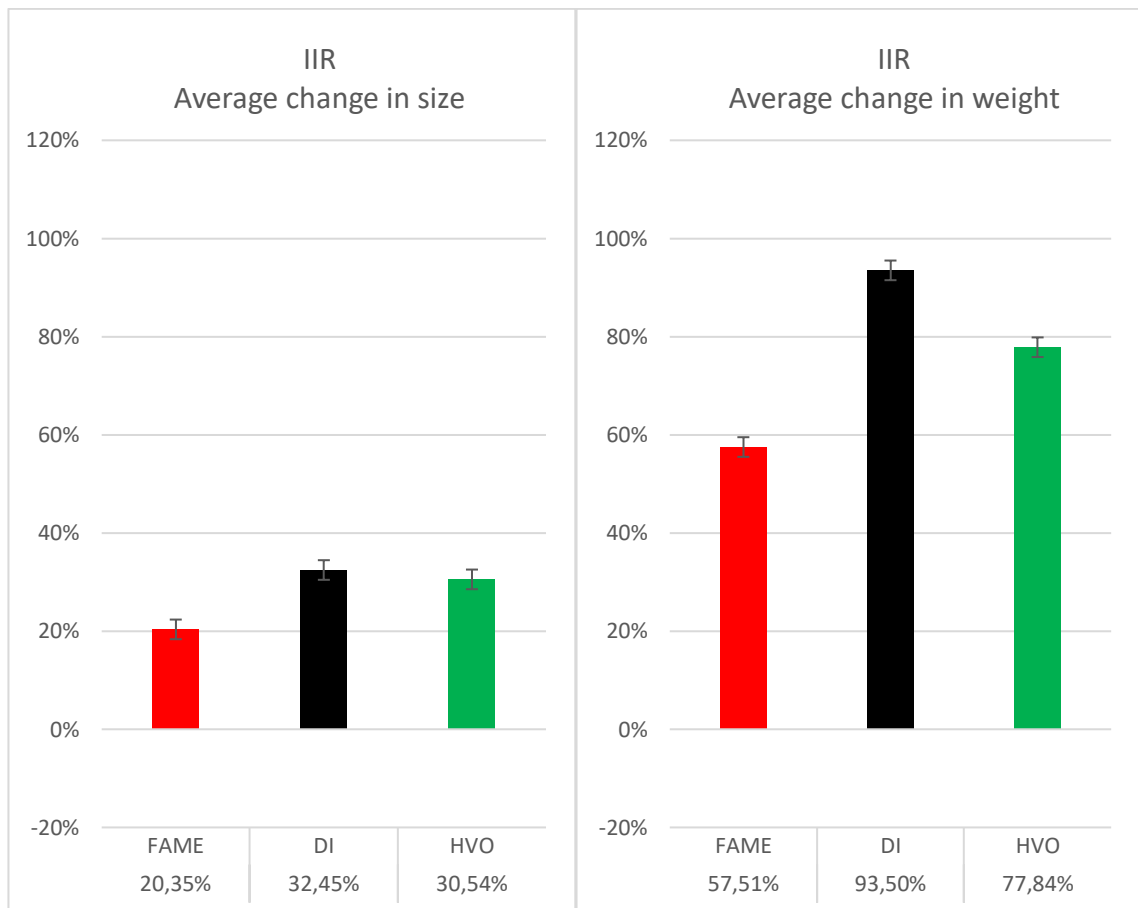


Figure 92. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

NBR, Acrylonitrile-Butadiene Rubber (Nitrile Rubber)

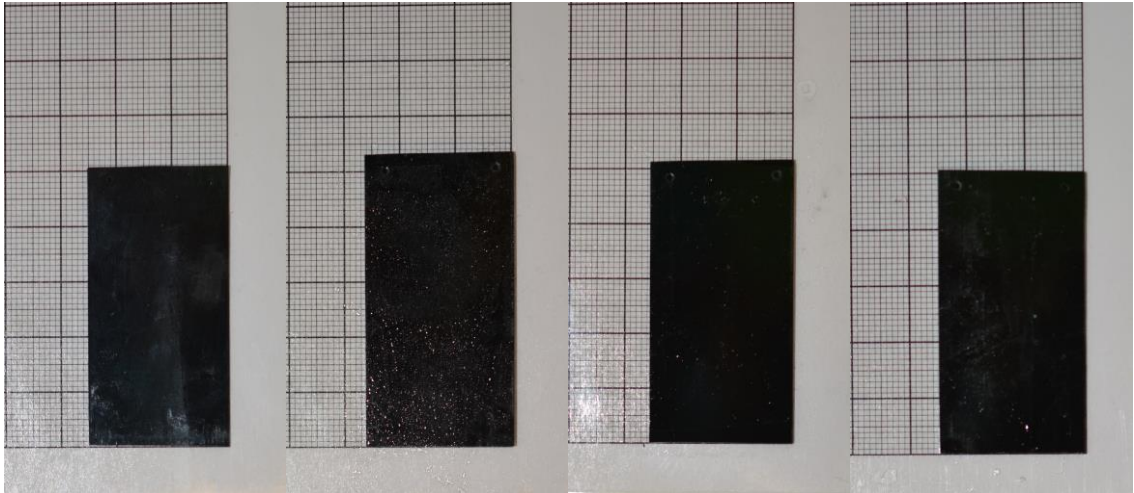


Figure 93. NBR, acrylonitrile-butadiene rubber (nitrile rubber), in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

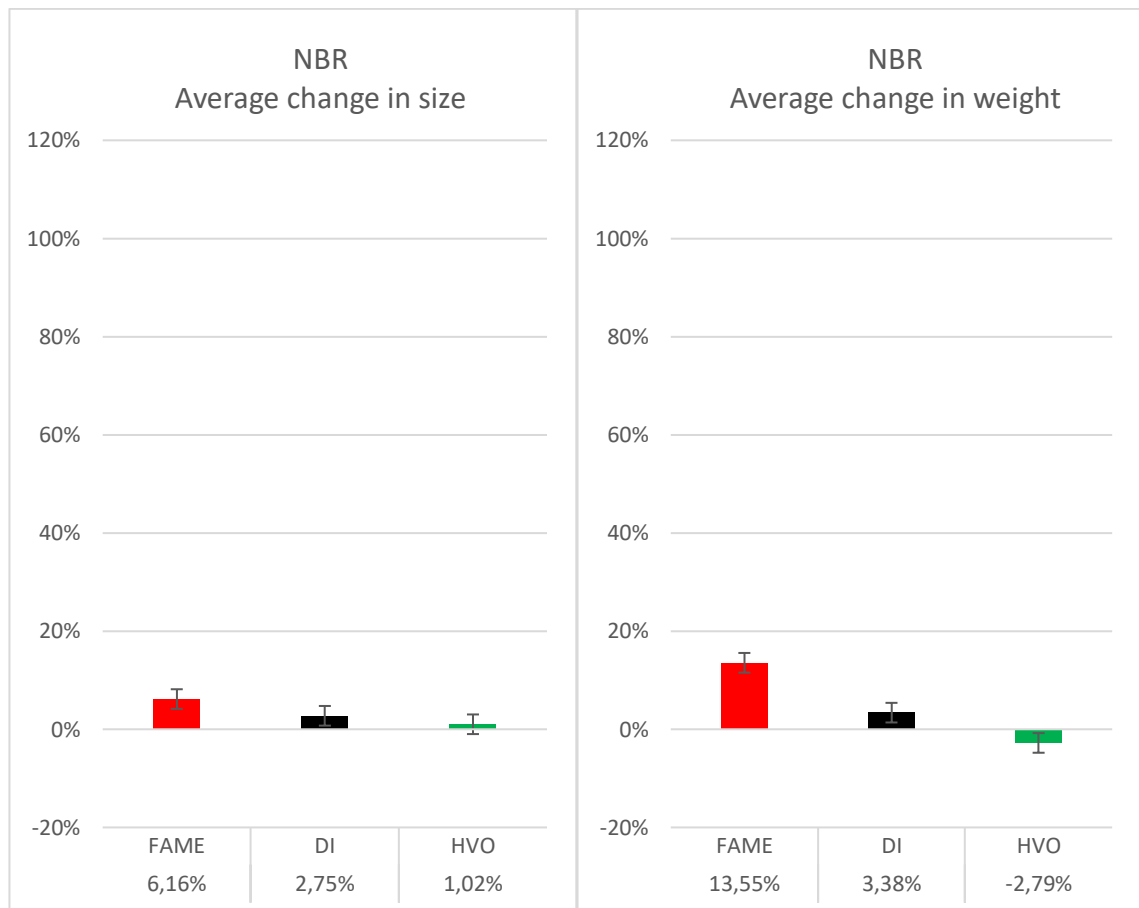


Figure 94. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

AU, Polyester Urethane

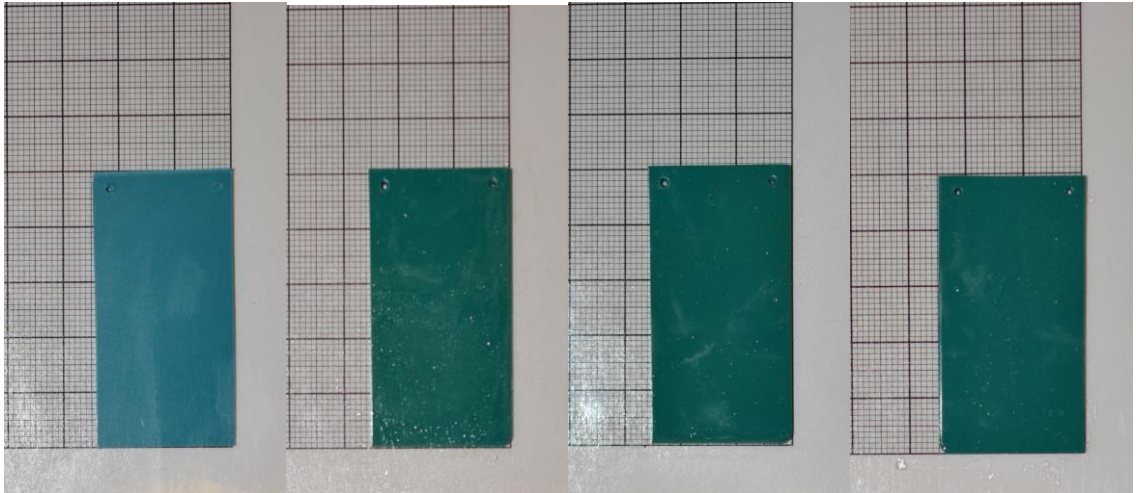


Figure 95. AU, polyester urethane, in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

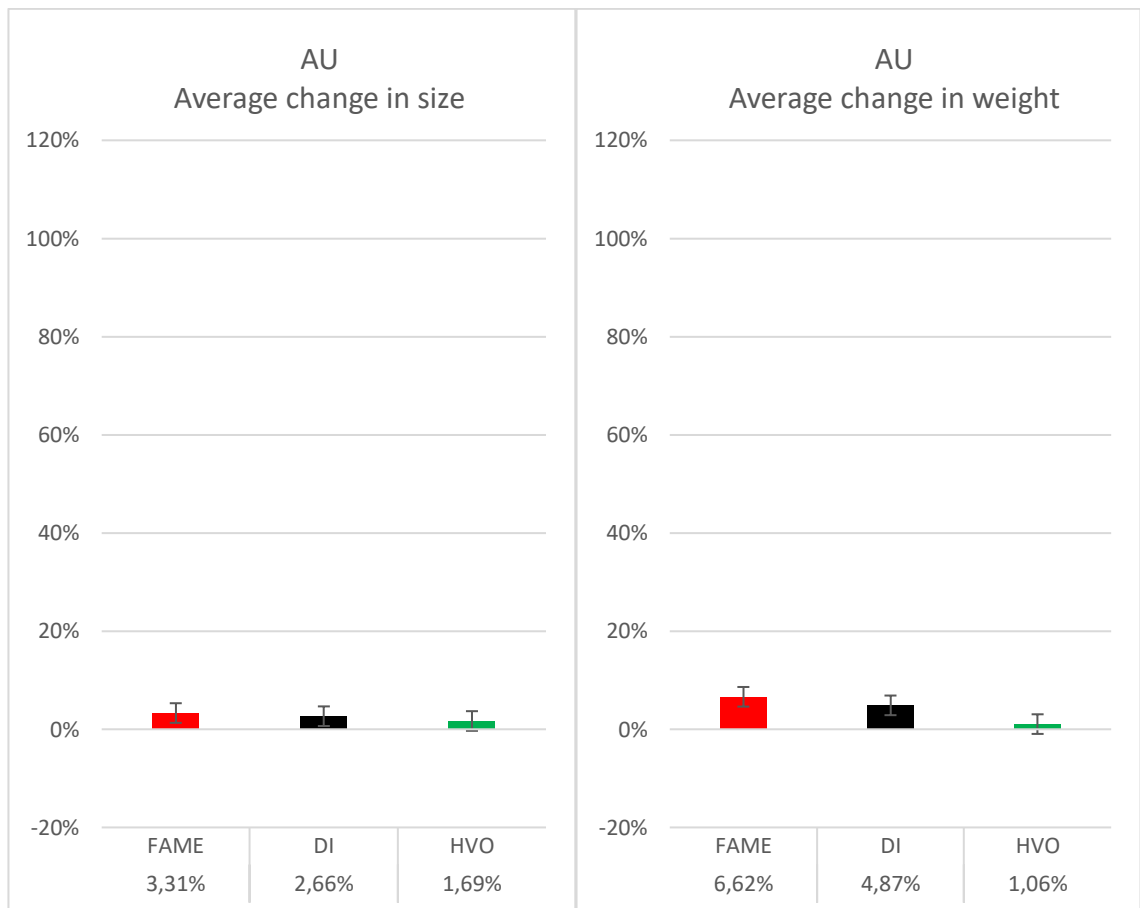


Figure 96. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

VMQ, Silicone Rubber

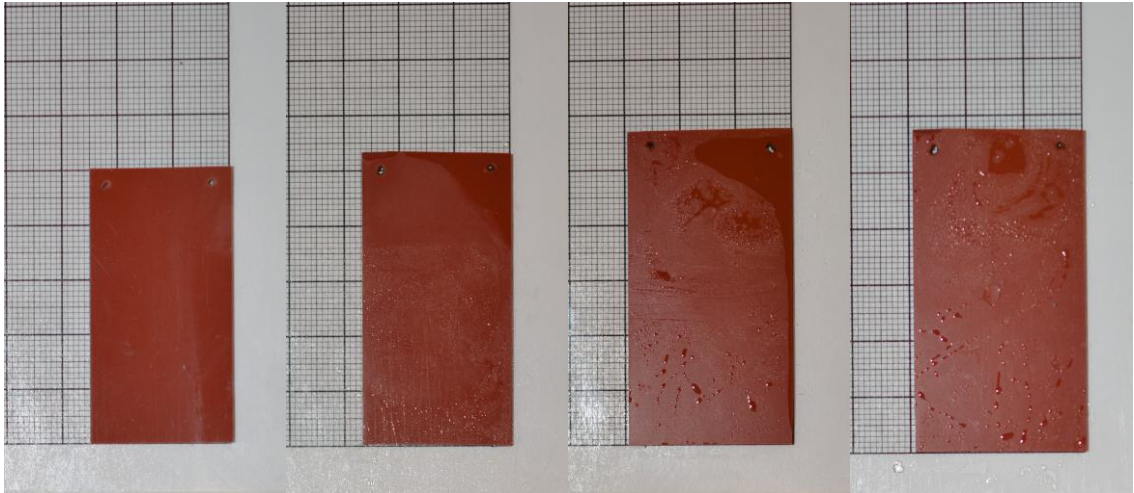


Figure 97. VMQ, silicone rubber, in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

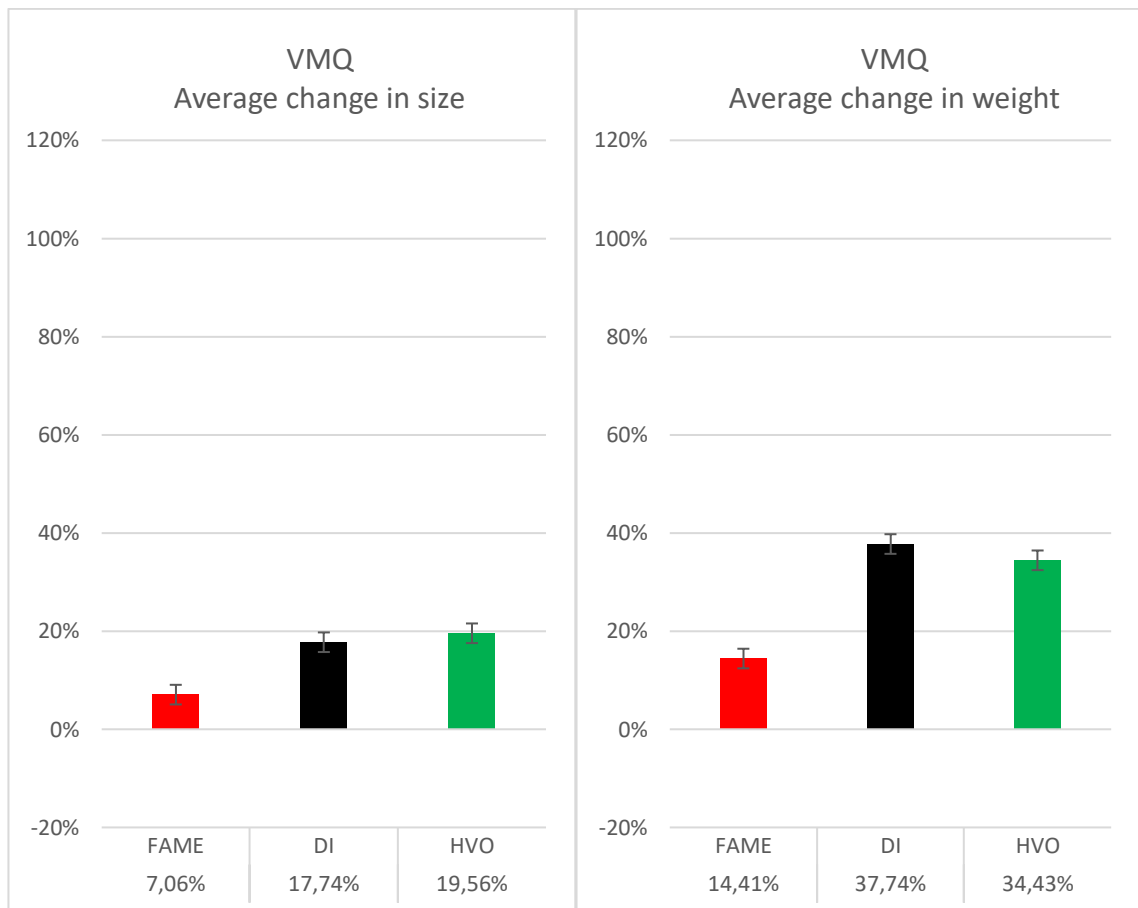


Figure 98. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

Virgin PTFE compounded with Turcon® additive

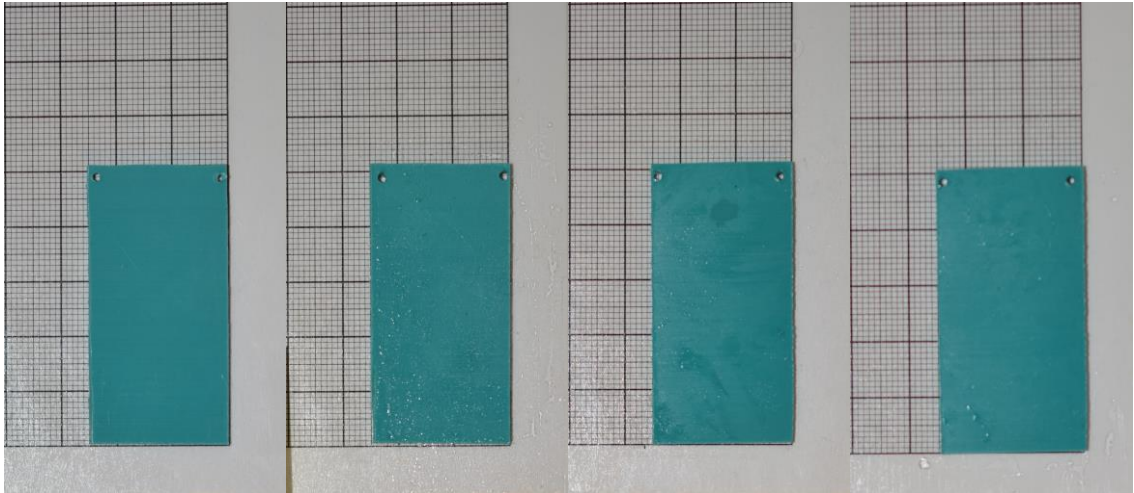


Figure 99. Virgin PTFE compounded with Turcon® additive in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

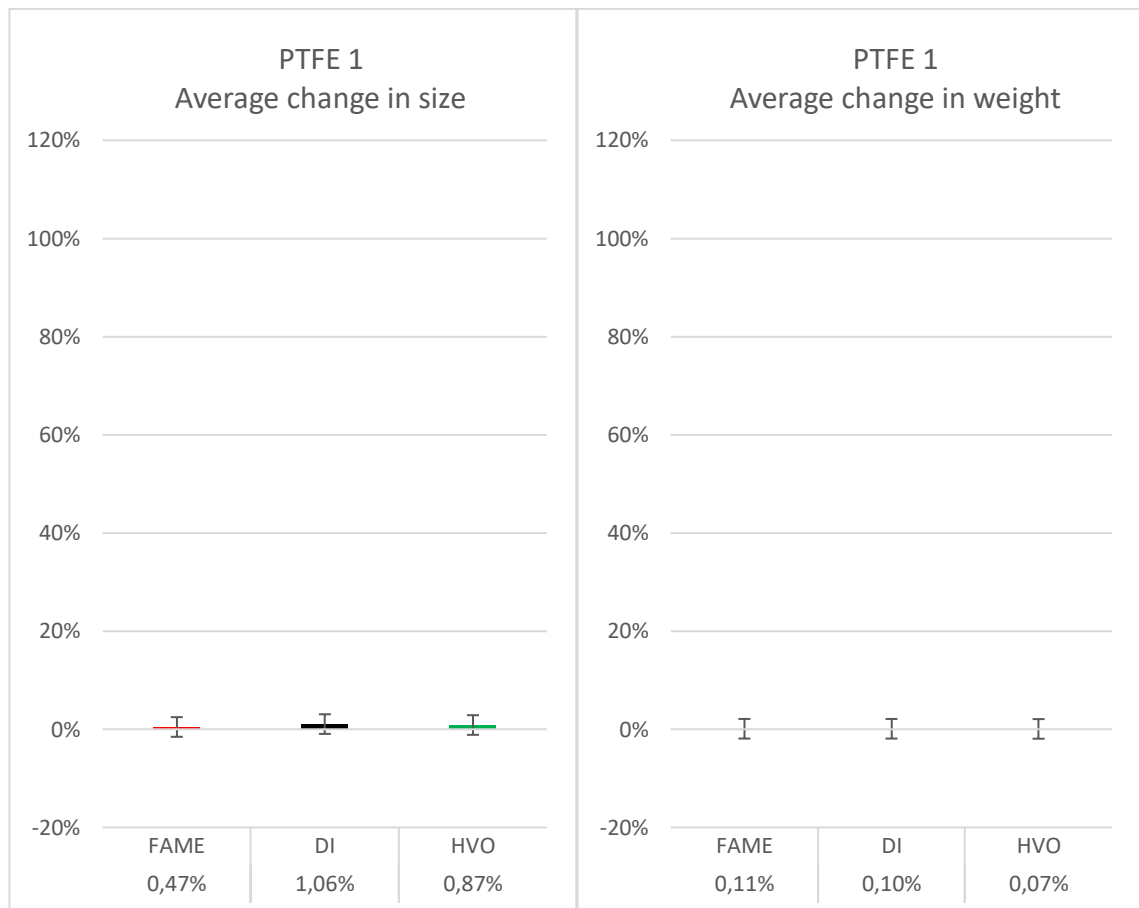


Figure 100. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

Virgin PTFE compounded with carbon and graphite

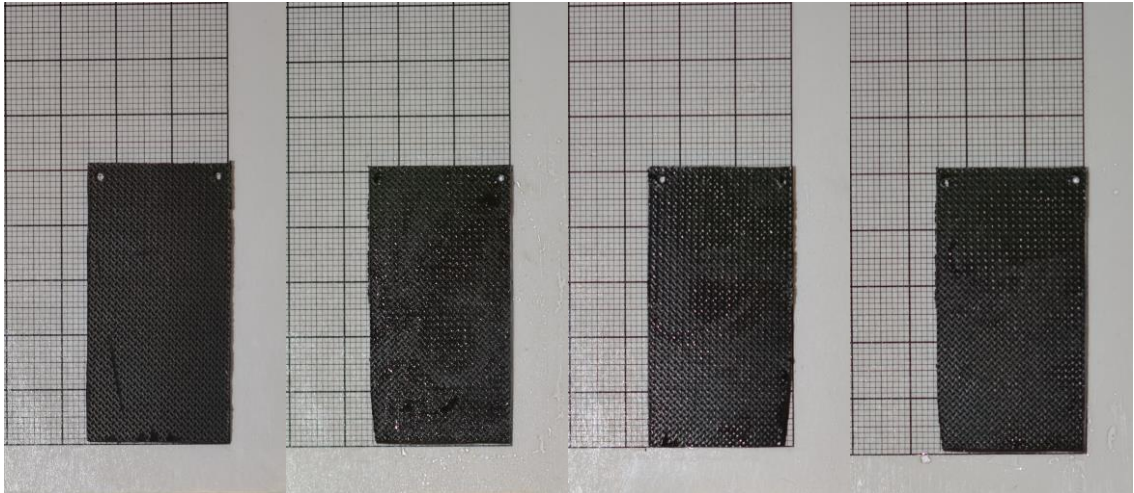


Figure 101. Virgin PTFE compounded with carbon and graphite in its prepared state and after weekly immersions in FAME → petroleum diesel → HVO from left to right respectively.

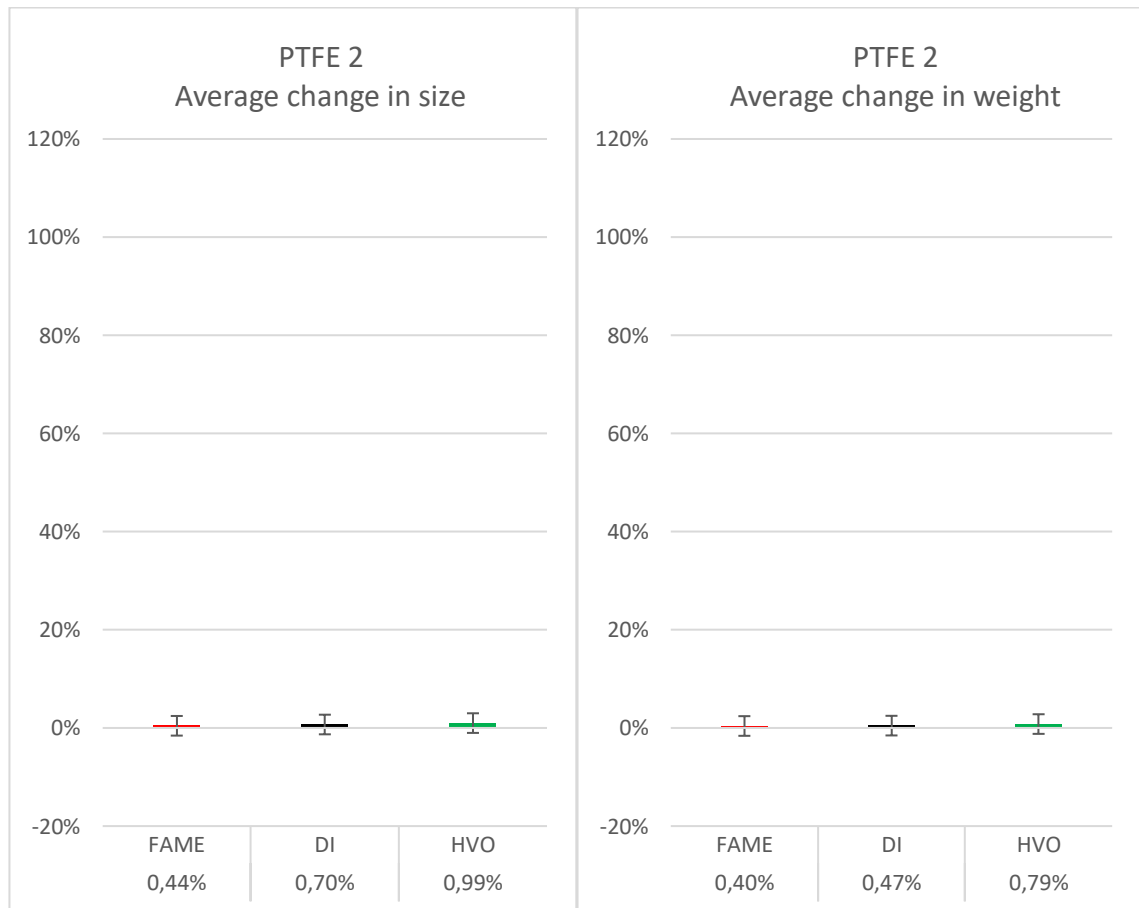


Figure 102. Average changes in size and weight of the specimens compared to the original state after weekly immersions in FAME → petroleum diesel → HVO.

To summarize the results in the immersion path of FAME → petroleum diesel → HVO, the elastomeric materials were ranked by the average magnitude of the reactions to give an idea of the suitability in conditions as simulated in the test (table 13).

The following results are based only on the results gained from the previous test. In actual material selection procedures, many other material properties must be carefully examined to find the most suitable material for the designed application.

PTFE materials were left outside of the ranking system, because of their unique properties which are not comparable to elastomers.

Rank	Material	Effects
1.	FKM 1	FKM 1 showed slight shrinkage in this immersion path. Other than that, the material succeeded with the most minimal alteration.
2.	FKM 2	FKM 2 showed slight shrinkage in this immersion path. Other than that, the material succeeded as well as FKM 1.
3.	FVMQ	FVMQ showed minimal swelling and increase in weight in this immersion path.
4.	AU	AU showed swelling and medium increase in weight in this immersion path.
5.	NBR	NBR showed medium swelling and increase in weight in this immersion path.
6.	HNBR	HNBR showed medium swelling and high increase in weight in this immersion path.
7.	VMQ	VMQ showed high swelling and increase in weight in this immersion path.
8.	AEM	AEM showed high swelling and extremely high increase in weight in this immersion path.
9.	IIR	IIR showed extremely high swelling and increase in weight in this immersion path.
10.	EPDM	EPDM showed extremely high swelling and increase in weight in this immersion path.

Table 13. Suitability rankings of the elastomeric materials in immersion path of FAME → HVO → petroleum diesel.

Judging by the results, FKM 1, FKM 2, FVMQ and AU would be able to function properly in conditions which were simulated in this immersion path. NBR showed notable reactions when introduced to FAME, and therefore, cannot be recommended for usage in such conditions even though the material recovered when exposed to other fuel compositions. HNBR, VMQ, AEM, IIR and EPDM showed reactions which would not be tolerated in fuel system applications, and therefore, cannot be recommended for usage in such conditions.

5.2 Residual Compressions

The results for the residual compressions are individually presented by each of the material. Materials are listed in the appearance order as seen in table 1.

The graphs (figures 103–112) were created on the basis of the recorded data (appendix 3), using the previously mentioned equation in chapter 3.3.2 (equation 5). The measurement accuracy of the micrometer used was calculated to be $\pm 1\%$.

AEM, Ethylene Acrylate Rubber

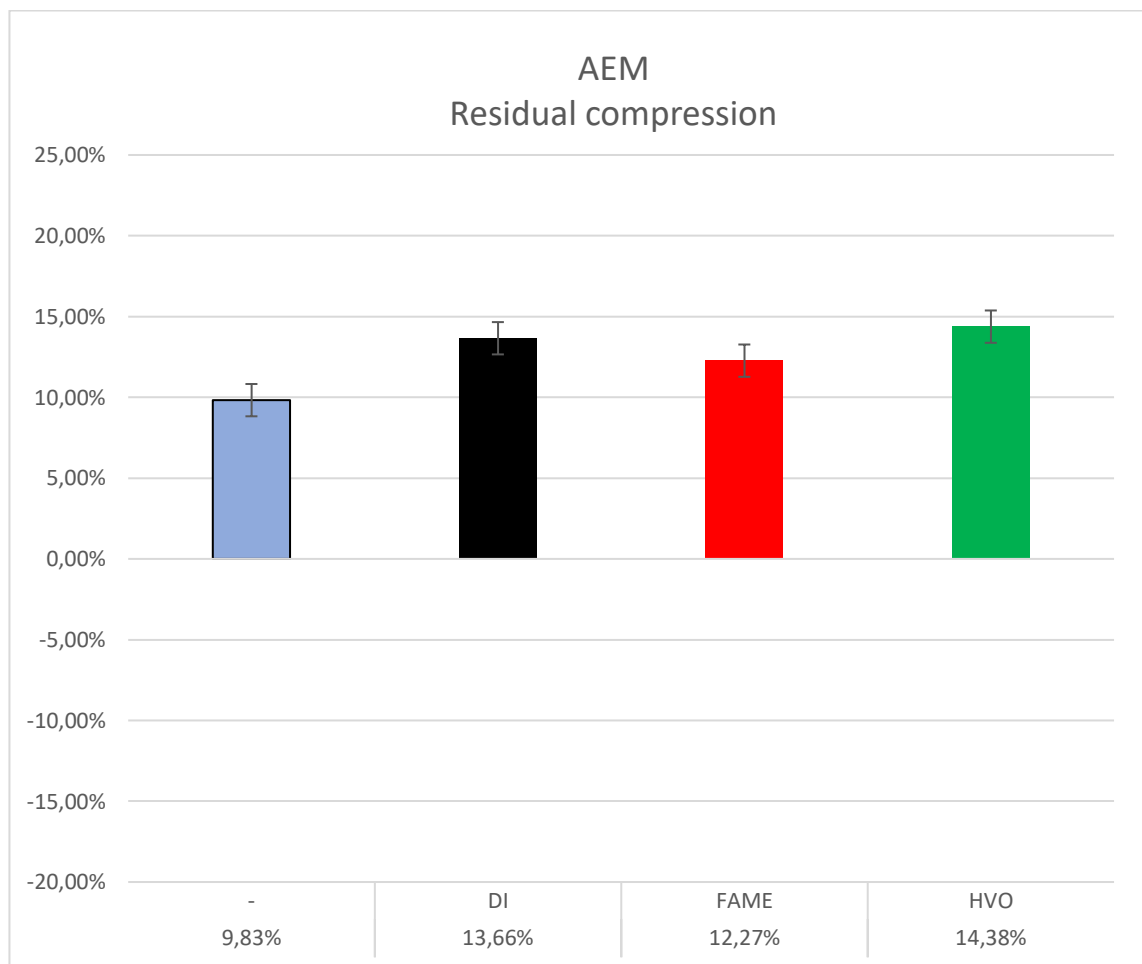


Figure 103. Residual compression in AEM when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

AEM showed propensity to residual compression, which was increased by an effective fuel component. Being exposed to HVO showed the highest amount of residual compression followed by petroleum diesel and FAME respectively.

EPDM, Ethylene Propylene Diene Rubber

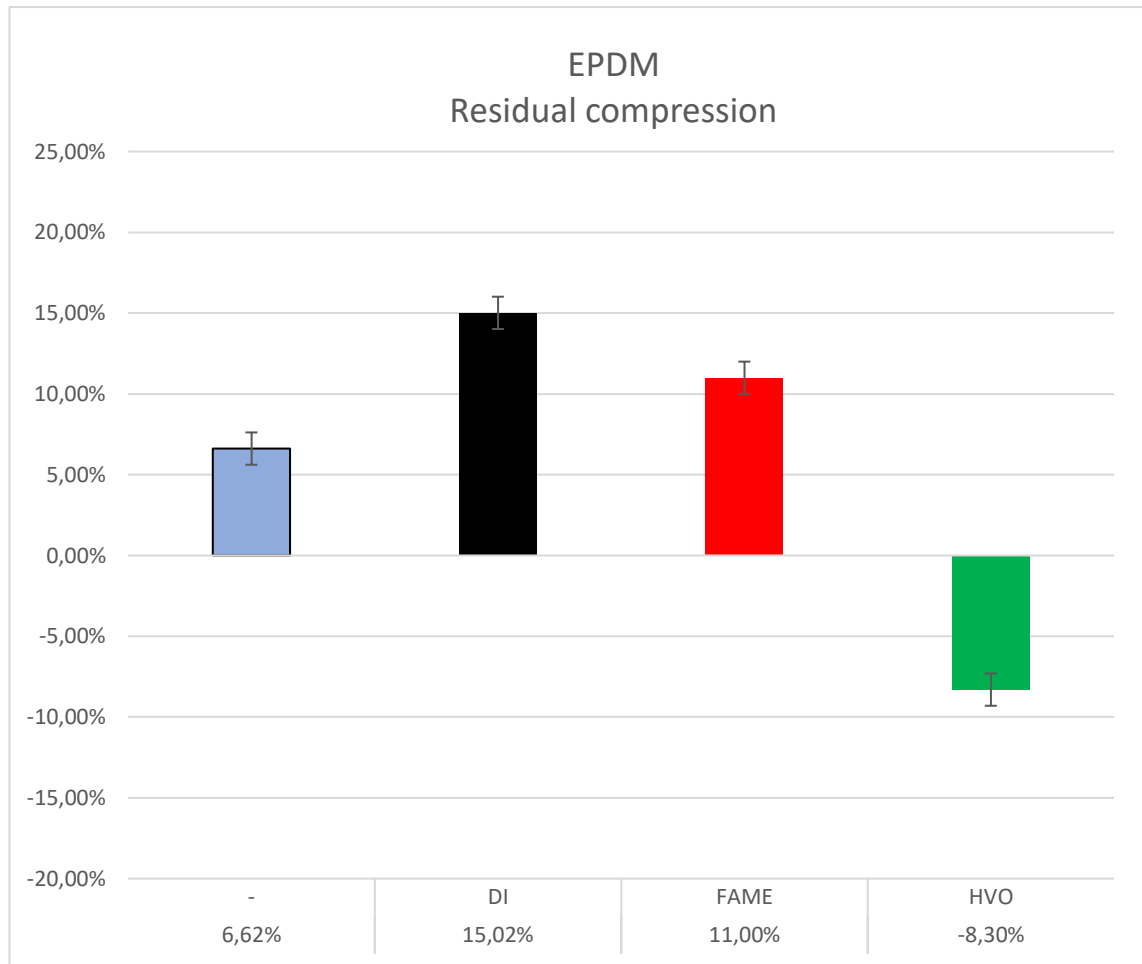


Figure 104. Residual compression in EPDM when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

EPDM showed propensity to residual compression, which was affected by an effective fuel component. Being exposed to petroleum diesel showed the highest amount of residual compression followed by FAME.

HVO caused the material to swell during the recovery period beyond the thickness of the untested specimen, and therefore, the residual compression of the material is negative.

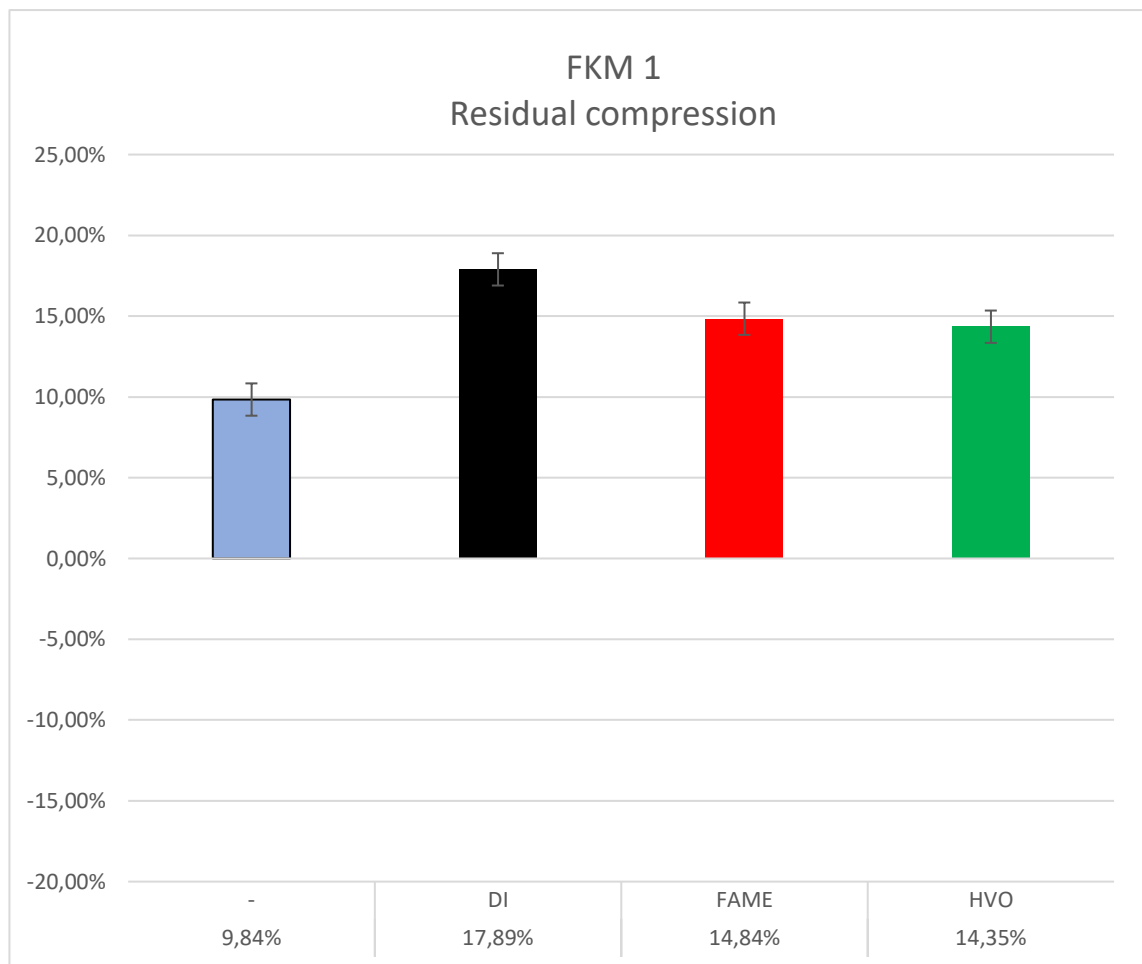
FKM, Fluorocarbon Rubber

Figure 105. Residual compression in FKM 1 when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

FKM 1 showed propensity to residual compression, which was increased by an effective fuel component. Being exposed to petroleum diesel showed the highest amount of residual compression followed by FAME and HVO respectively.

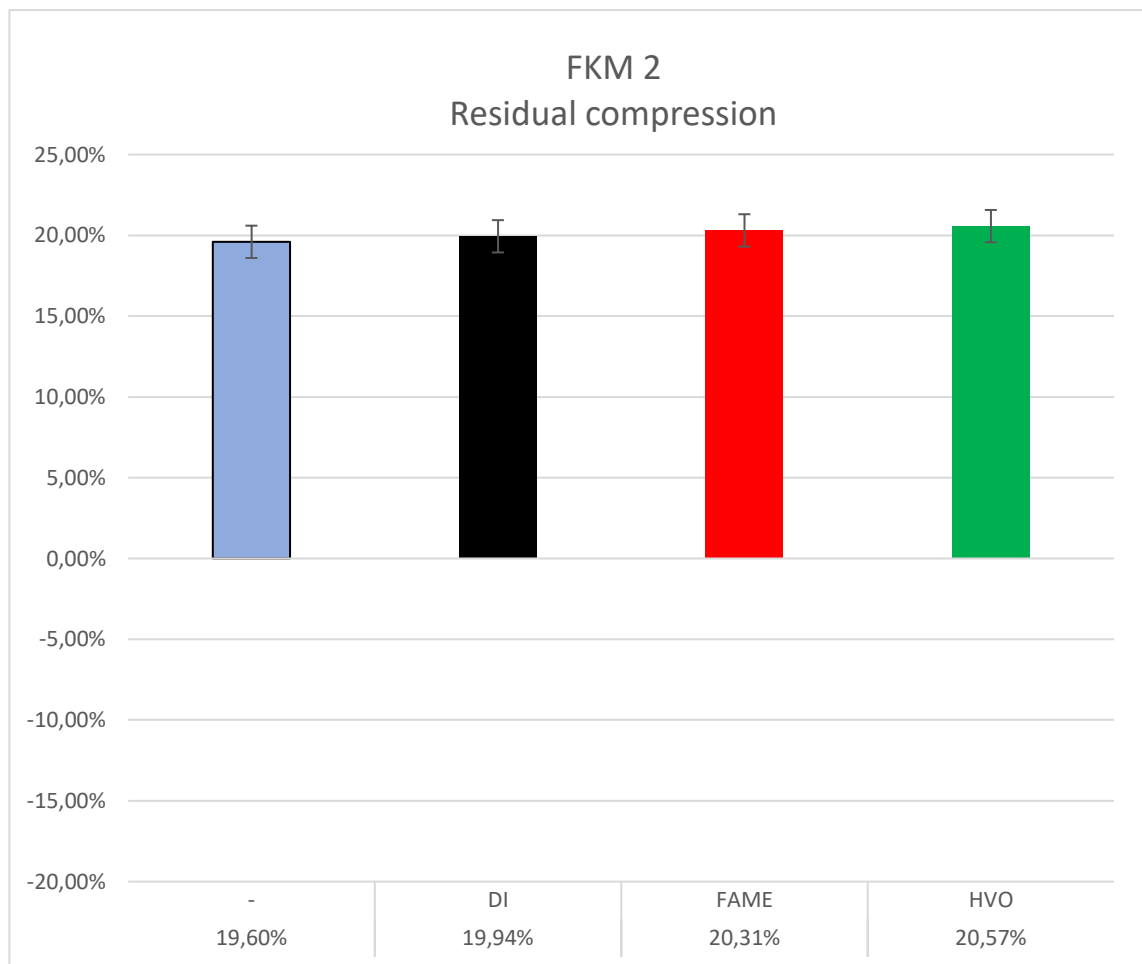
FKM, Fluorocarbon Rubber with Higher Fluorine Content

Figure 106. Residual compression in FKM 2 when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

FKM 2 showed one of the highest propensities to residual compression, but almost completely negated the effects of any fuel type in the results.

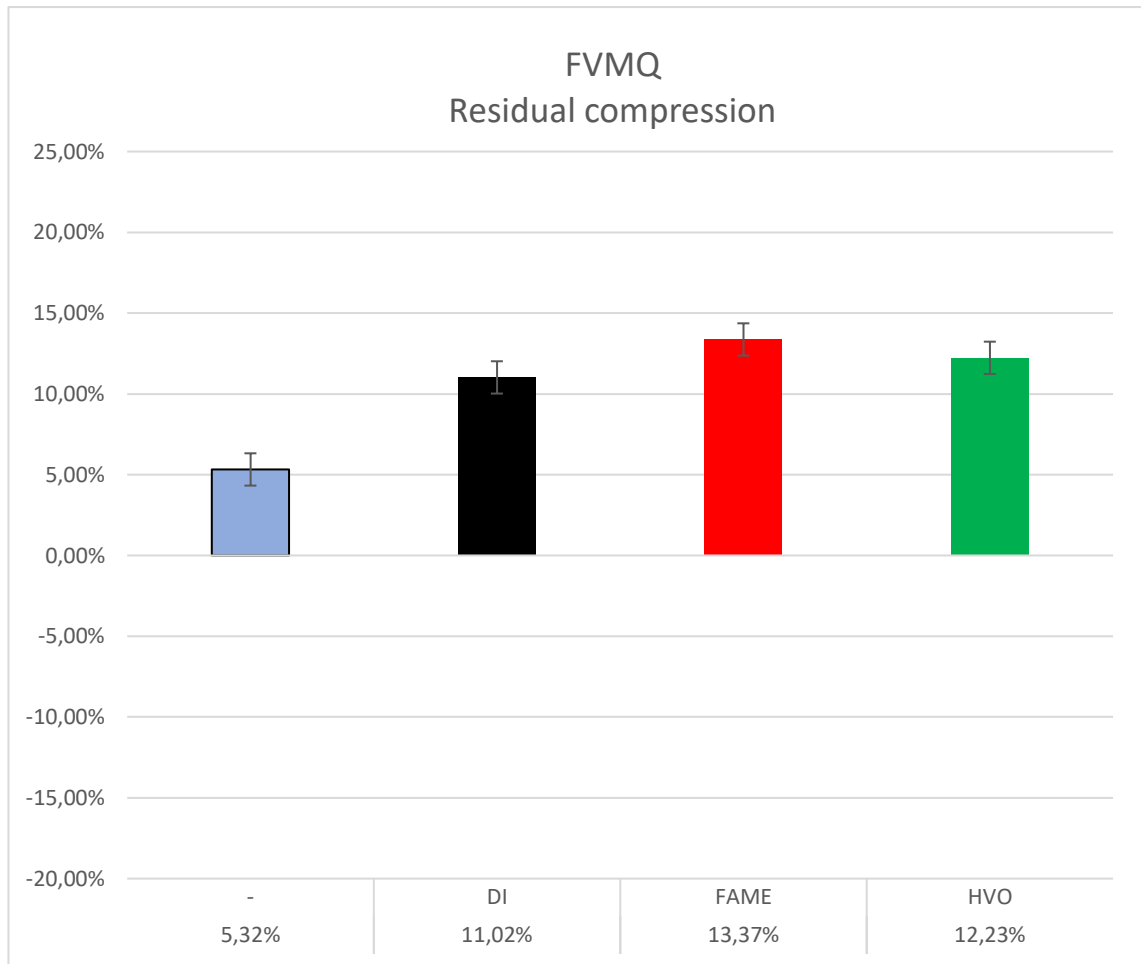
FVMQ, Fluorosilicone Rubber

Figure 107. Residual compression in FVMQ when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

FVMQ showed propensity to residual compression, which was increased by an effective fuel component. Being exposed to FAME showed the highest amount of residual compression followed by HVO and petroleum diesel respectively.

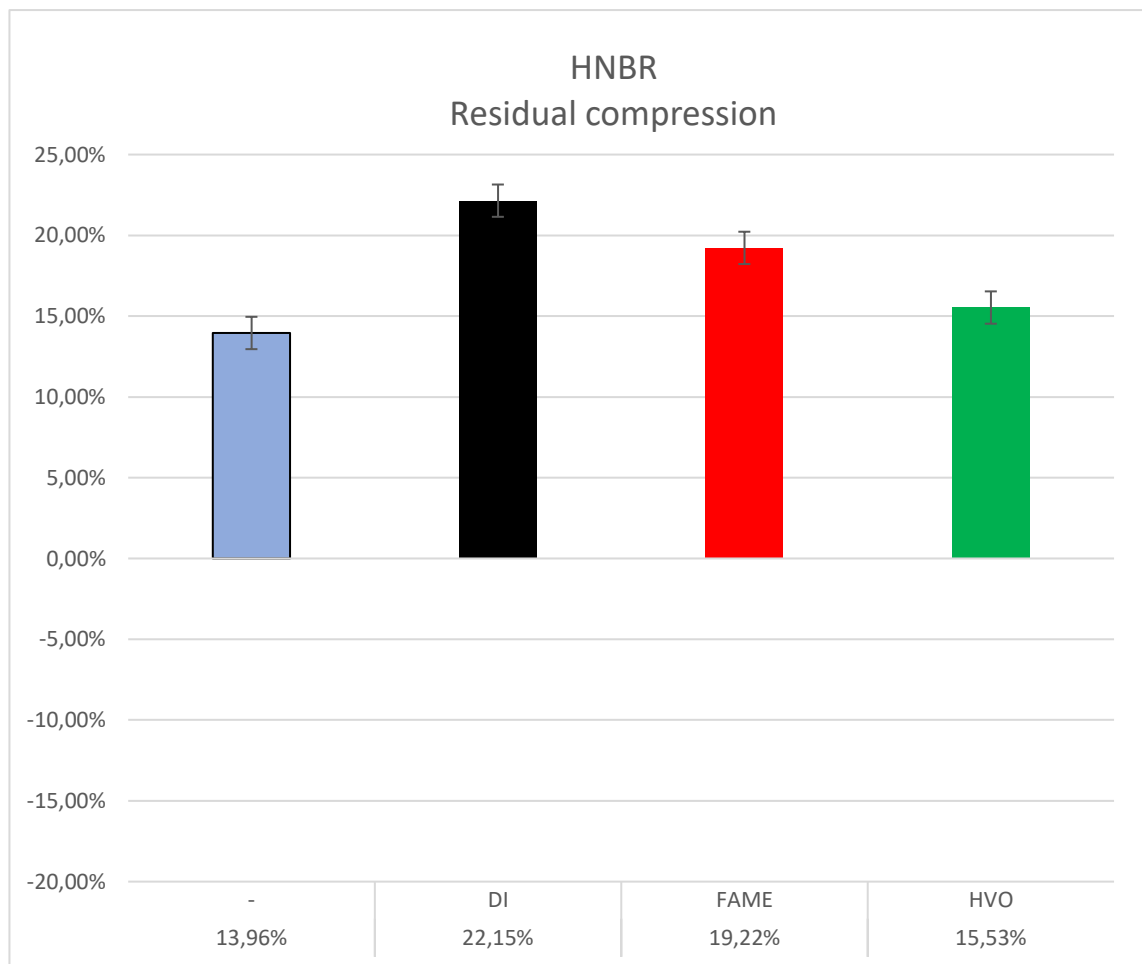
HNBR, Hydrogenated Acrylonitrile-Butadiene Rubber

Figure 108. Residual compression in HNBR when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

HNBR showed propensity to residual compression, which was increased by an effective fuel component. Being exposed to petroleum diesel showed the highest amount of residual compression followed by FAME and HVO respectively.

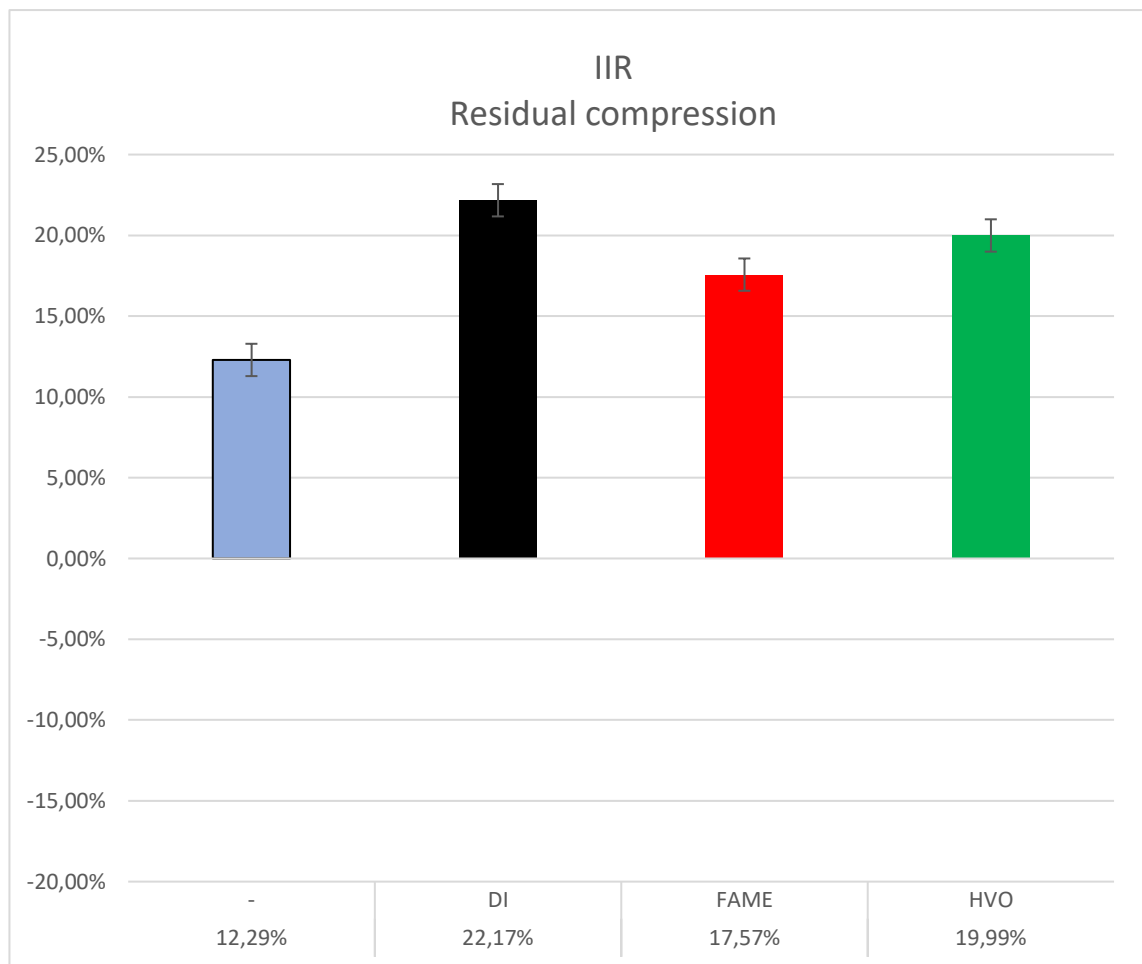
IIR, Butyl Rubber

Figure 109. Residual compression in IIR when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

IIR showed propensity to residual compression, which was increased by an effective fuel component. Being exposed to petroleum diesel showed the highest amount of residual compression followed by HVO and FAME respectively.

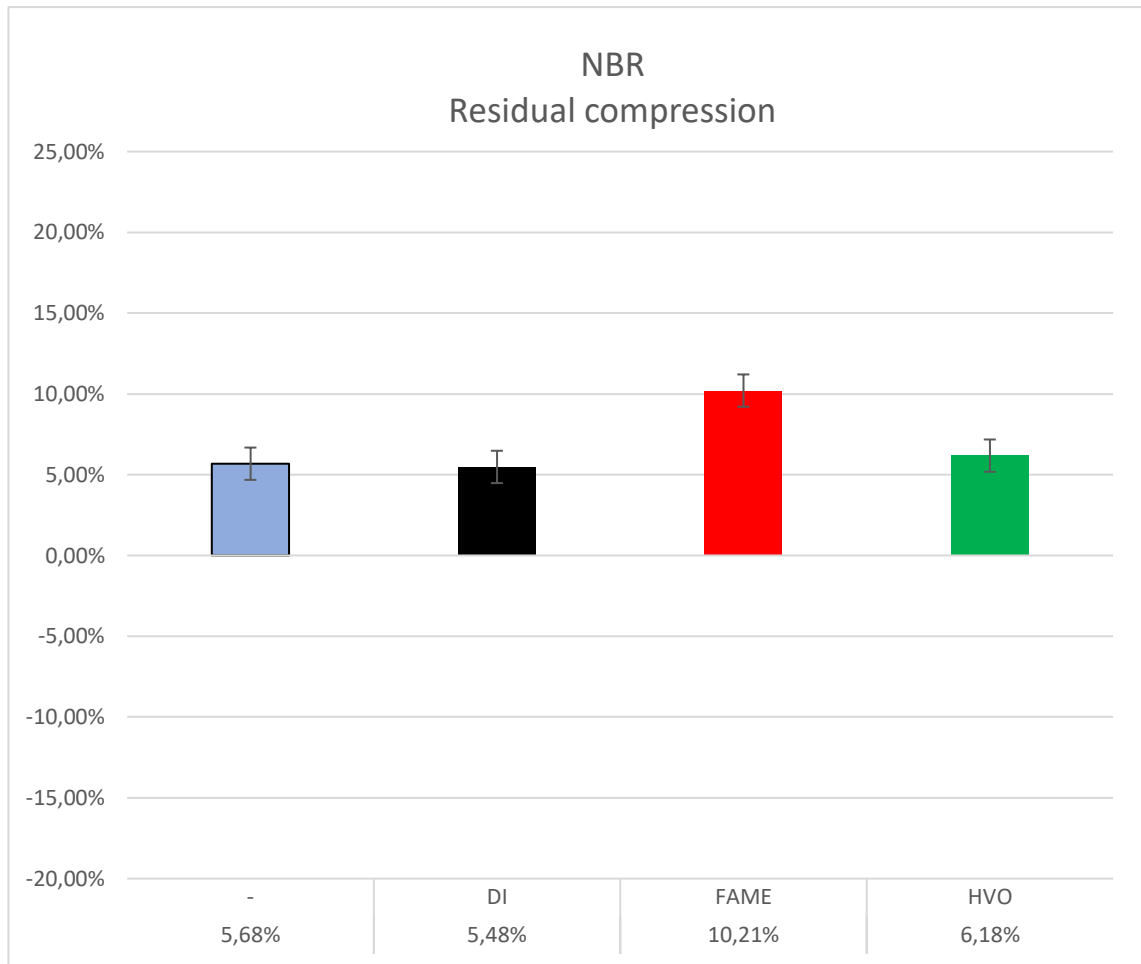
NBR, Acrylonitrile-Butadiene Rubber (Nitrile Rubber)

Figure 110. Residual compression in NBR when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

NBR showed propensity to residual compression which was slightly affected by HVO and petroleum diesel respectively.

As in the immersion test, NBR showed more notable reactions to FAME compared to any other fuel type.

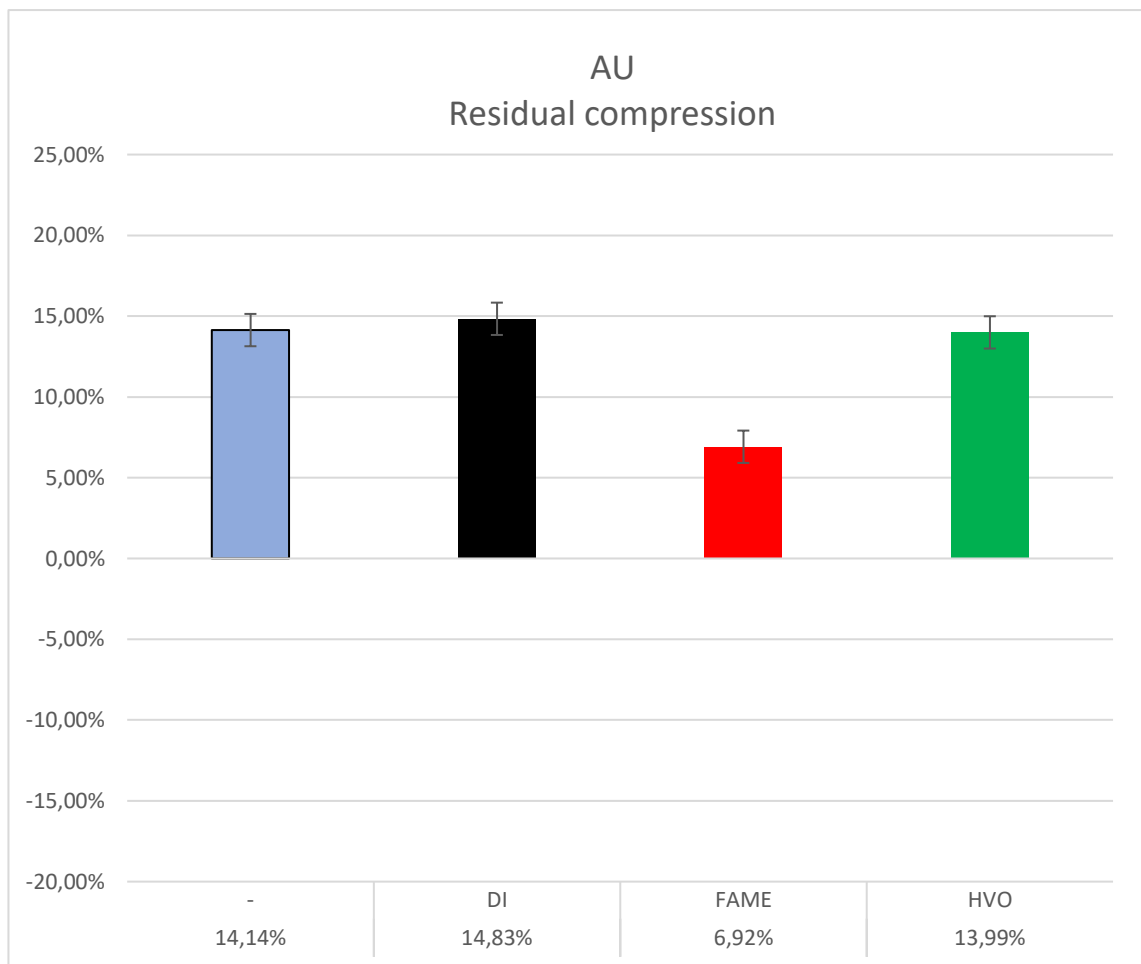
AU, Polyester Urethane

Figure 111. Residual compression in AU when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

AU showed propensity to residual compression which was slightly affected by petroleum diesel and HVO.

Being exposed to FAME showed the least amount of residual compression.

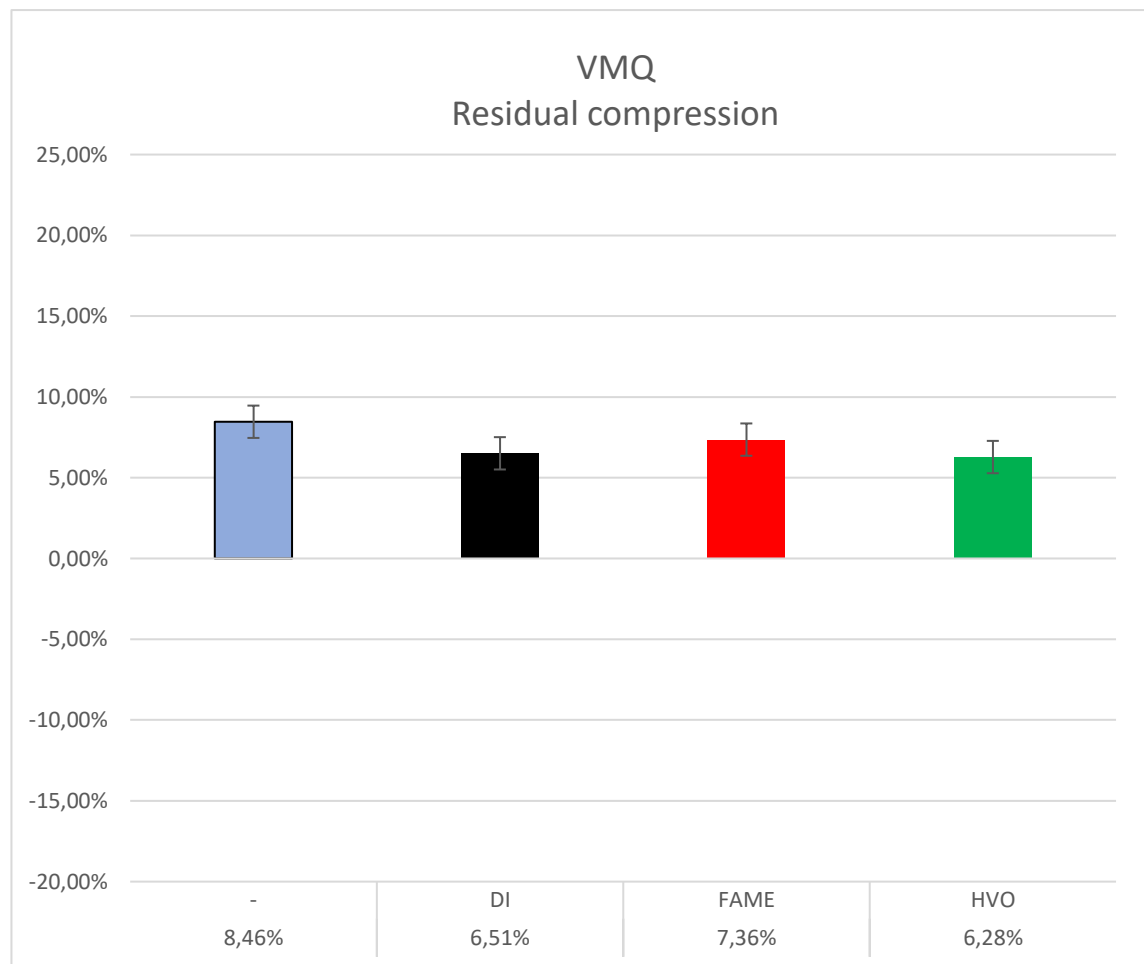
VMQ, Silicone Rubber

Figure 112. Residual compression in VMQ when compressed in air, petroleum diesel, FAME and HVO from left to right respectively.

VMQ showed propensity to residual compression, which was affected by an effective fuel component. Being exposed to HVO showed the least amount of residual compression followed by petroleum diesel and FAME respectively.

6 Summary of the Results

This chapter summarizes the results gained from the conducted tests, individually subtitled by the test method used.

ASTM D471

In the results gained from the immersion tests, it was clearly visible that FKM 1 and FKM 2 transcended the other materials in all of the immersion paths. NBR, AU and FVMQ overall showed excellent results, but with a few exceptions which would require extra attention before usage in the designed application.

AEM, HNBR, VMQ, IIR and EPDM showed varying results in all of the immersion paths from minor to extreme reactions, and therefore, cannot be recommended for usage in any application with imminent fuel contact.

PTFE materials, as anticipated, were completely inert in all of the immersion paths, except for changes which can be explained with the tolerances in the measurement accuracies.

ASTM D395

Residual compression tests showed varying results which could not be directly concluded from the immersion tests. Success in this test method would be either minimal residual compression in the tested conditions, or equal amount of residual compression regardless of the effective fuel composition.

Almost all of the materials showed fluctuation in the results, which made the interpreting of the results dependent on the reviewer and the designated application. However, FKM 2 showed the most equal amount of residual compression in all tested conditions, which points out that the material was not affected by any of the fuel compositions used in the test. NBR also showed some uniformity in the amount of residual compression in various conditions with the exception of FAME, as in the immersion test, in which the material showed considerably higher residual compression than in petroleum diesel or HVO. AU also succeeded in the tests with uniform results except for FAME, in which the material showed the least amount of residual compression.

7 Conclusions

This thesis investigated the effects of diesel fuel composition on sealing materials. The increased use of alternative solutions and sources to produce fuels with different compositions for vehicles equipped with internal combustion engines demand constant research and development in all applications with even the slightest possibility of fuel contact.

The tests carried out in this thesis covered only a part of what could have been done, because most of the defined tests would have required specific equipment and machinery, which are limitedly available and are of high cost. The experiments conducted in this thesis still provided valuable data; though the regulations could not be followed to full extent even in the tests which were carried out. Therefore, the results are not in complete accordance with the test methods, and therefore, cannot be used for other than informational purposes. However, this thesis describes the used testing procedure very precisely and comprehensively.

As for the results gained, it was clearly visible which of the materials succeeded in the tests. Success in this kind of tests points out that the material could be safely used as a sealant in applications with similar conditions as in what was simulated in the experiments. Reactions on each individual material were in most cases as anticipated in comprehensive research and information received from trusted sources.

Due to time limitations set by the extent of a Bachelor's thesis, all the pre-designed tests could not be conducted. However, this thesis covers all the required information for Test Methods ASTM D471 and D395, if the need would arise in the future.

As an interesting continuation for the experiments conducted in this thesis, tests with a wider range of fuel compositions and blends, longer immersion periods and higher temperatures would give new and different kinds of results. Also, simulating the conditions of vehicle usage even further with fluctuating temperature and using fuels with plausible contaminations, such as water or foreign chemicals, which could be found in fuel tanks through condensation or neglectful washing of a vehicle, would be interesting. Other possible contaminants in fuel are micro-organisms and all kinds of debris. Use of deteriorated fuel is also a possible scenario, because of the surprisingly short shelf life of fuel. [26; 27.]

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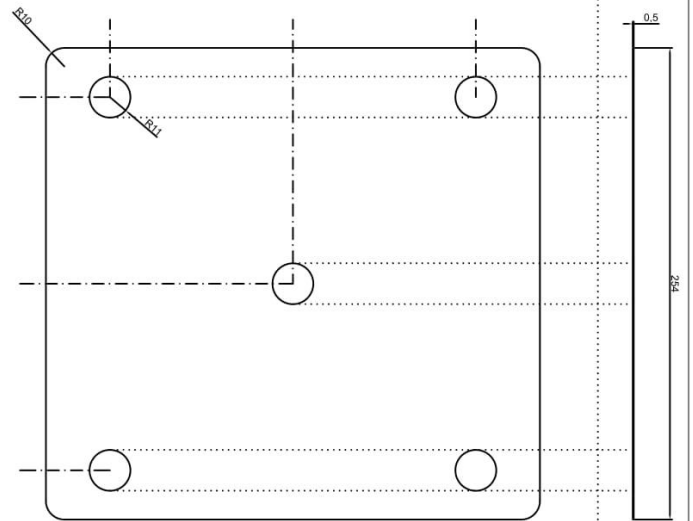
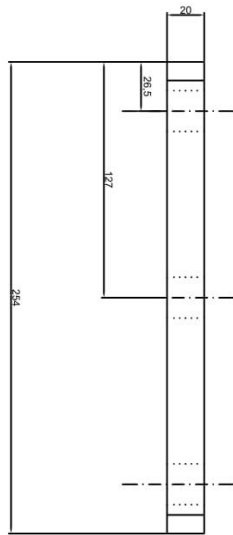
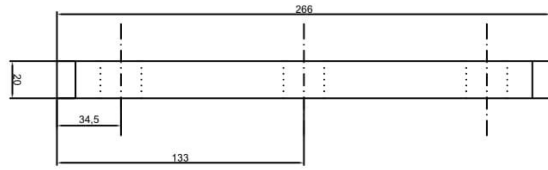
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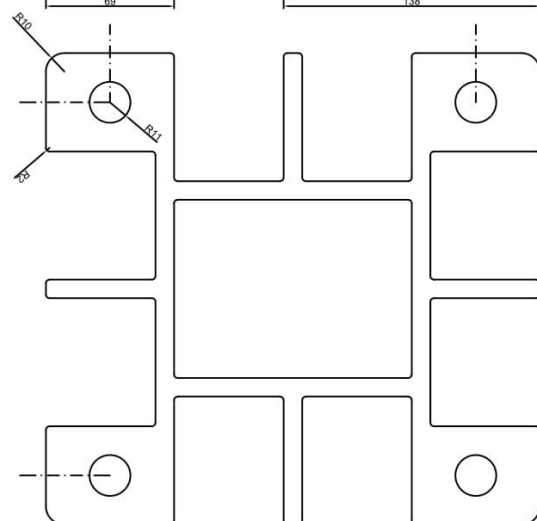
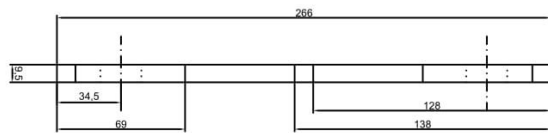
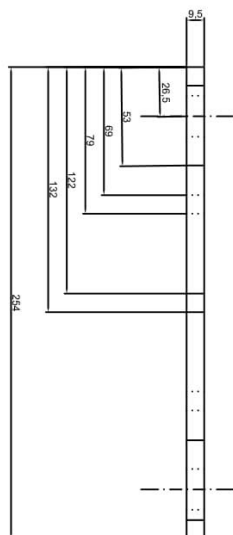
Technical Drawing of the Compression Set

Part	Amount	Material
1.	3	Steel
2.	4	Acid-proof steel
3.	2	Steel



1.

2.



3.

Result Lists for Fluctuating Immersions in Petroleum Diesel, FAME and HVO

DI - HVO - DI		Starting weight (g)	Week 1. fuel	2nd weight (g)	Visual inspections	Week 2. fuel	3rd weight (g)	Visual inspections	Week 3. fuel	Final weight (g)	Visual inspections
AEM	1.	3,2788	DI	3,6689	A1, C1	HVO	3,2383	-	DI	3,6654	A1, C1
	2.	3,1867	DI	3,5682	A1, C1	HVO	3,146	-	DI	3,5652	A1, C1
	3.	3,2488	DI	3,6379	A1, C1	HVO	3,208	-	DI	3,6336	A1, C1
EPDM	1.	3,1193	DI	6,4676	A5, C2, E1	HVO	5,825	A5, C2, E1	DI	6,4293	A5, C2, E1
	2.	3,1211	DI	6,4809	A5, C2, E1	HVO	5,8303	A5, C2, E1	DI	6,4409	A5, C2, E1
	3.	3,0991	DI	6,4176	A5, C2, E1	HVO	5,7802	A5, C2, E1	DI	6,3819	A5, C2, E1
FKM 1	1.	5,1158	DI	5,1223	-	HVO	5,1198	-	DI	5,1299	-
	2.	5,2296	DI	5,2372	-	HVO	5,2346	-	DI	5,2451	-
	3.	5,3131	DI	5,3247	-	HVO	5,3189	-	DI	5,3324	-
FKM 2	1.	5,6839	DI	5,6934	-	HVO	5,6884	-	DI	5,7024	-
	2.	6,2651	DI	6,2744	-	HVO	6,272	-	DI	6,286	-
	3.	6,2029	DI	6,2133	-	HVO	6,2098	-	DI	6,2225	-
FVMQ	1.	3,9993	DI	4,0868	-	HVO	4,0531	-	DI	4,0846	-
	2.	3,9995	DI	4,0932	-	HVO	4,0584	-	DI	4,0911	-
	3.	3,8338	DI	3,9252	-	HVO	3,8913	-	DI	3,9213	-
HNBR	1.	3,4123	DI	3,7439	A1	HVO	3,4482	-	DI	3,7338	A1
	2.	3,5384	DI	3,8796	A1	HVO	3,5772	-	DI	3,8722	A1
	3.	3,422	DI	3,7534	A1	HVO	3,4584	-	DI	3,7435	A1
IIR	1.	3,2322	DI	6,1575	A4, C2, E1	HVO	5,6901	A4, C2, E1	DI	6,1999	A4, C2, E1
	2.	3,2379	DI	6,197	A4, C2, E1	HVO	5,7085	A4, C2, E1	DI	6,2196	A4, C2, E1
	3.	3,0135	DI	5,8075	A4, C2, E1	HVO	5,3486	A4, C2, E1	DI	5,8449	A4, C2, E1
NBR	1.	3,4561	DI	3,6221	A1	HVO	3,4074	-	DI	3,6096	A1
	2.	3,4053	DI	3,5713	A1	HVO	3,3581	-	DI	3,5561	A1
	3.	3,3501	DI	3,5145	A1	HVO	3,3052	-	DI	3,4999	A1
AU	1.	3,0675	DI	3,2049	-	HVO	3,0992	-	DI	3,2097	-
	2.	3,099	DI	3,2376	-	HVO	3,1316	-	DI	3,2419	-
	3.	3,0697	DI	3,2088	-	HVO	3,1022	-	DI	3,2131	-
VMQ	1.	3,6101	DI	4,953	A2, C1	HVO	4,9279	A2, C2	DI	4,9876	A2, C2
	2.	3,8593	DI	5,2987	A2, C1	HVO	5,2649	A2, C2	DI	5,3295	A2, C2
	3.	3,6034	DI	4,9499	A2, C1	HVO	4,9264	A2, C2	DI	4,9794	A2, C2
PTFE 1	1.	7,1974	DI	7,2081	-	HVO	7,2073	-	DI	7,2198	-
	2.	7,629	DI	7,6414	-	HVO	7,6454	-	DI	7,6518	-
	3.	7,9321	DI	7,9523	-	HVO	7,9534	-	DI	7,9634	-
PTFE 2	1.	7,1603	DI	7,1868	-	HVO	7,1901	-	DI	7,203	-
	2.	7,6725	DI	7,711	-	HVO	7,7116	-	DI	7,7265	-
	3.	7,6033	DI	7,6401	-	HVO	7,6429	-	DI	7,6603	-

DI - HVO - DI		Starting length (mm)	Starting width (mm)	Starting thickness (mm)	Week 1. fuel	2nd length (mm)	2nd width (mm)	2nd thickness (mm)	Week 2. fuel	3rd length (mm)	3rd width (mm)	3rd thickness (mm)	Week 3. fuel	Final length (mm)	Final width (mm)	Final thickness (mm)
AEM	1.	49,69	24,87	2,08	DI	52,13	26,34	2,17	HVO	49,49	25,03	2,07	DI	52,09	26,45	2,24
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
EPDM	1.	49,75	25,02	2,27	DI	65,23	32,25	3,16	HVO	63,74	31,71	3,03	DI	65,16	32,4	3,19
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
FKM 1	1.	50,1	25,24	2,21	DI	49,86	25,32	2,14	HVO	49,8	25,3	2,15	DI	49,93	25,32	2,22
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
FKM 2	1.	50,15	25,33	2,18	DI	50,11	25,11	2,06	HVO	49,98	25,07	2,08	DI	50,09	25,19	2,12
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
FVMQ	1.	50,41	25,08	2,05	DI	50,5	25,86	2,1	HVO	50,24	25,55	2,1	DI	50,79	25,6	2,17
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
HNBR	1.	49,93	25,31	2,17	DI	52,24	26,34	2,2	HVO	50,52	25,49	2,14	DI	52,15	26,35	2,28
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
IIR	1.	50,02	25,14	2,1	DI	63,39	31,89	3,01	HVO	62,24	31,44	2,94	DI	63,48	32,05	3,09
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
NBR	1.	50,2	25,04	2,26	DI	51,04	25,48	2,31	HVO	49,77	24,73	2,25	DI	51,06	25,27	2,37
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
AU	1.	49,54	24,7	2,06	DI	49,85	24,97	2,15	HVO	49,25	24,71	2,11	DI	49,7	25,13	2,2
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
VMQ	1.	50,08	25,15	2,02	DI	57,37	29,31	2,44	HVO	57,73	29,53	2,47	DI	57,65	29,51	2,53
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
PTFE 1	1.	49,78	25,69	2,87	DI	49,72	25,75	2,9	HVO	49,77	25,82	2,89	DI	49,85	26,04	2,85
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
PTFE 2	1.	50,5	25,78	2,7	DI	50,41	25,67	2,74	HVO	50,38	25,73	2,75	DI	50,53	26,08	2,81
	2.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-
	3.	-	-	-	DI	-	-	-	HVO	-	-	-	DI	-	-	-

HVO - DI - HVO		Starting weight (g)	Week 1. fuel	2nd weight (g)	Visual inspections	Week 2. fuel	3rd weight (g)	Visual inspections	Week 3. fuel	Final weight (g)	Visual inspections
AEM	1.	3.3573	HVO	3,2229	-	DI	3,6252	A1	HVO	3,1837	-
	2.	3.3573	HVO	3,3564	-	DI	3,7692	A1	HVO	3,3139	-
	3.	3.29	HVO	3,2866	-	DI	3,6927	A1	HVO	3,2466	-
EPDM	1.	2.9309	HVO	5,4453	A4, C3, E1	DI	6,0363	A5, C3, E2	HVO	5,4698	A4, C3, E1
	2.	3.0905	HVO	5,7054	A4, C3, E1	DI	6,3175	A5, C3, E2	HVO	5,7285	A4, C3, E1
	3.	3.008	HVO	5,5346	A4, C3, E1	DI	6,1225	A5, C3, E2	HVO	5,5648	A4, C3, E1
FKM 1	1.	5.0023	HVO	5,0029	-	DI	5,0125	-	HVO	5,0094	-
	2.	5.1201	HVO	5,1248	-	DI	5,1337	-	HVO	5,1299	-
	3.	4.8561	HVO	4,8616	-	DI	4,8688	-	HVO	4,8642	-
FKM 2	1.	6.2213	HVO	6,2273	-	DI	6,2347	-	HVO	6,2345	-
	2.	6.1473	HVO	6,1518	-	DI	6,1613	-	HVO	6,158	-
	3.	5.7004	HVO	5,7043	-	DI	5,7145	-	HVO	5,7126	-
FVMQ	1.	4.0109	HVO	4,0633	-	DI	4,1008	-	HVO	4,0675	-
	2.	3.9889	HVO	4,0425	-	DI	4,0815	-	HVO	4,0462	-
	3.	3.8663	HVO	3,9193	-	DI	3,9558	-	HVO	3,9221	-
HNBR	1.	3.513	HVO	3,5068	-	DI	3,8453	A1	HVO	3,5388	-
	2.	3.3057	HVO	3,2972	-	DI	3,6154	A1	HVO	3,3245	-
	3.	3.2988	HVO	3,2951	-	DI	3,613	A1	HVO	3,321	-
IIR	1.	3.1868	HVO	5,4579	A4, C3, E1	DI	6,0651	A5, C3, E2	HVO	5,6025	A4, C3, E1
	2.	3.2159	HVO	5,5153	A4, C3, E1	DI	6,1258	A5, C3, E2	HVO	5,6581	A4, C3, E1
	3.	3.0784	HVO	5,3011	A4, C3, E1	DI	5,901	A5, C3, E2	HVO	5,4454	A4, C3, E1
NBR	1.	3.4027	HVO	3,3499	-	DI	3,5532	-	HVO	3,3398	-
	2.	3.3368	HVO	3,2835	-	DI	3,4864	-	HVO	3,2768	-
	3.	3.4308	HVO	3,3771	-	DI	3,5837	-	HVO	3,3708	-
AU	1.	3.0755	HVO	3,0974	-	DI	3,2127	D1	HVO	3,1066	D1
	2.	3.1057	HVO	3,1239	-	DI	3,2442	D1	HVO	3,138	D1
	3.	3.1035	HVO	3,1202	-	DI	3,2425	D1	HVO	3,1359	D1
VMQ	1.	3.5895	HVO	4,8495	A2, C3	DI	4,9746	A2, C3	HVO	4,8545	A2, C3
	2.	3.63	HVO	4,9095	A2, C3	DI	5,0316	A2, C3	HVO	4,9135	A2, C3
	3.	3.6231	HVO	4,9057	A2, C3	DI	5,0268	A2, C3	HVO	4,9088	A2, C3
PTFE 1	1.	7.3336	HVO	7,3378	-	DI	7,3421	-	HVO	7,341	-
	2.	8.0471	HVO	8,0589	-	DI	8,0649	-	HVO	8,0646	-
	3.	7.0879	HVO	7,0945	-	DI	7,0984	-	HVO	7,0969	-
PTFE 2	1.	7.6213	HVO	7,6601	-	DI	7,6688	-	HVO	7,662	-
	2.	7.6325	HVO	7,6657	-	DI	7,6812	-	HVO	7,6784	-
	3.	6.8562	HVO	6,8776	-	DI	6,8904	-	HVO	6,8841	-

HVO - DI - HVO		Starting length (mm)	Starting width (mm)	Starting thickness (mm)	Week 1. fuel	2nd length (mm)	2nd width (mm)	2nd thickness (mm)	Week 2. fuel	3rd length (mm)	3rd width (mm)	3rd thickness (mm)	Week 3. fuel	Final length (mm)	Final width (mm)	Final thickness (mm)
AEM	1.	49,69	24,87	2,08	HVO	50,33	25,39	2,03	DI	52,22	26,4	2,16	HVO	49,97	25,13	2,06
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
EPDM	1.	49,75	25,02	2,27	HVO	64,18	31,69	2,83	DI	65,48	32,3	2,93	HVO	64,26	31,84	2,91
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
FKM 1	1.	50,1	25,24	2,21	HVO	50,04	25,33	2,11	DI	50,02	25,27	2,12	HVO	50,13	25,29	2,17
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
FKM 2	1.	50,15	25,33	2,18	HVO	50,02	25,3	2,25	DI	50,12	25,24	2,28	HVO	50,15	25,27	2,32
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
FVMQ	1.	50,41	25,08	2,05	HVO	50,39	25,56	2,12	DI	50,51	25,65	2,15	HVO	50,41	25,54	2,18
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
HNBR	1.	49,93	25,31	2,17	HVO	50,28	25,64	2,18	DI	51,78	26,15	2,29	HVO	50,2	25,6	2,25
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
IIR	1.	50,02	25,14	2,1	HVO	61,67	31,1	2,87	DI	63,22	31,83	3	HVO	62,4	31,38	2,99
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
NBR	1.	50,2	25,04	2,26	HVO	50,23	25,47	2,13	DI	51,14	25,85	2,18	HVO	50,09	25,32	2,19
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
AU	1.	49,54	24,7	2,06	HVO	49,42	24,81	2,1	DI	49,92	25,05	2,17	HVO	49,21	24,76	2,17
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
VMQ	1.	50,08	25,15	2,02	HVO	57,18	29,08	2,48	DI	56,86	28,89	2,53	HVO	57,17	29,16	2,56
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
PTFE 1	1.	50,58	25,2	2,7	HVO	50,82	25,18	2,84	DI	50,77	25,35	2,78	HVO	50,79	25,28	2,76
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
PTFE 2	1.	50,5	25,78	2,91	HVO	50,41	25,79	2,93	DI	50,47	25,73	2,95	HVO	50,41	25,65	2,98
	2.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	HVO	-	-	-	DI	-	-	-	HVO	-	-	-

FAME - DI - HVO		Starting weight (g)	Week 1. fuel	2nd weight (g)	Visual inspections	Week 2. fuel	3rd weight (g)	Visual inspections	Week 3. fuel	Final weight (g)	Visual inspections
AEM	1.	3,2262	FAME	5,2685	A4, C4	DI	3,6076	A1, C2	HVO	3,1547	-
	2.	3,3733	FAME	5,4555	A4, C4	DI	3,7751	A1, C2	HVO	3,3035	-
	3.	3,3018	FAME	5,3506	A4, C4	DI	3,6922	A1, C2	HVO	3,2288	-
EPDM	1.	3,0403	FAME	4,9515	A4, C3	DI	6,2324	A5, C3	HVO	5,6346	A3, C2
	2.	2,9059	FAME	4,7691	A4, C3	DI	6,0449	A5, C3	HVO	5,4482	A3, C2
	3.	3,1166	FAME	5,0607	A4, C3	DI	6,3632	A5, C3	HVO	5,756	A3, C2
FKM 1	1.	5,0253	FAME	5,0395	-	DI	5,0443	-	HVO	5,0352	-
	2.	4,9162	FAME	4,9342	-	DI	4,9351	-	HVO	4,9258	-
	3.	5,0654	FAME	5,0863	-	DI	5,0821	-	HVO	5,0763	-
FKM 2	1.	6,2255	FAME	6,2444	-	DI	6,2415	-	HVO	6,2386	-
	2.	5,9926	FAME	6,0096	-	DI	6,0103	-	HVO	6,0069	-
	3.	5,6842	FAME	5,6982	-	DI	5,6996	-	HVO	5,697	-
FVMQ	1.	3,8975	FAME	3,9792	-	DI	3,9815	-	HVO	3,9484	-
	2.	3,8774	FAME	3,96	-	DI	3,9645	-	HVO	3,9308	-
	3.	3,9662	FAME	4,0511	-	DI	4,0559	-	HVO	4,0197	-
HNBR	1.	3,577	FAME	4,4737	A2, C2	DI	3,8965	-	HVO	3,5818	-
	2.	3,4351	FAME	4,3028	A2, C2	DI	3,7458	-	HVO	3,4377	-
	3.	3,3015	FAME	4,1265	A2, C2	DI	3,5895	-	HVO	3,2963	-
IIR	1.	3,1693	FAME	4,981	A3, C2	DI	6,1011	A4, C3	HVO	5,611	A3, C2
	2.	3,1404	FAME	4,9318	A3, C2	DI	6,0494	A4, C3	HVO	5,5656	A3, C2
	3.	2,9648	FAME	4,6952	A3, C2	DI	5,7957	A4, C3	HVO	5,3174	A3, C2
NBR	1.	3,6019	FAME	4,0877	A1, C1	DI	3,7243	-	HVO	3,5033	-
	2.	3,3731	FAME	3,831	A1, C1	DI	3,4861	-	HVO	3,2764	-
	3.	3,5025	FAME	3,9783	A1, C1	DI	3,6215	-	HVO	3,406	-
AU	1.	3,0828	FAME	3,2873	A1, D2	DI	3,2317	A1, D2	HVO	3,1149	-
	2.	3,0082	FAME	3,2061	A1, D2	DI	3,155	A1, D2	HVO	3,0403	-
	3.	3,1004	FAME	3,3064	A1, D2	DI	3,2526	A1, D2	HVO	3,1332	-
VMQ	1.	3,5998	FAME	4,1194	A1, C2	DI	4,9603	A3, C2	HVO	4,9184	A2, C2
	2.	3,5751	FAME	4,0889	A1, C2	DI	4,922	A3, C2	HVO	4,8792	A2, C2
	3.	3,7716	FAME	4,3155	A1, C2	DI	5,1958	A3, C2	HVO	4,9173	A2, C2
PTFE 1	1.	7,1943	FAME	7,1998	E1 (bending)	DI	7,2019	E1 (bending)	HVO	7,1983	E1 (bending)
	2.	7,2394	FAME	7,247	E1 (bending)	DI	7,246	E1 (bending)	HVO	7,2449	E1 (bending)
	3.	7,3526	FAME	7,363	E1 (bending)	DI	7,3605	E1 (bending)	HVO	7,3592	E1 (bending)
PTFE 2	1.	7,6669	FAME	7,702	-	DI	7,7088	-	HVO	7,709	-
	2.	7,6795	FAME	7,7125	-	DI	7,7178	-	HVO	7,719	-
	3.	7,0919	FAME	7,1131	-	DI	7,1174	-	HVO	7,188	-

FAME - DI - HVO		Starting length (mm)	Starting width (mm)	Starting thickness (mm)	Week 1. fuel	2nd length (mm)	2nd width (mm)	2nd thickness (mm)	Week 2. fuel	3rd length (mm)	3rd width (mm)	3rd thickness (mm)	Week 3. fuel	Final length (mm)	Final width (mm)	Final thickness (mm)
AEM	1.	49,69	24,87	2,08	FAME	59,99	31,11	2,52	DI	51,74	26,44	2,17	HVO	49,56	25,13	2,06
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
EPDM	1.	49,75	25,02	2,27	FAME	59,25	29,52	2,78	DI	64,71	33,13	3,07	HVO	63,29	31,68	3,04
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
FKM 1	1.	50,1	25,24	2,21	FAME	49,9	24,96	2,12	DI	49,89	25,2	2,15	HVO	50,05	25,29	2,17
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
FKM 2	1.	50,15	25,33	2,18	FAME	50,32	24,96	2,28	DI	50,35	25,02	2,31	HVO	50,6	25,03	2,34
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
FVMQ	1.	50,41	25,08	2,05	FAME	51,19	25,27	2,03	DI	51,11	25,26	2,07	HVO	51,18	25,29	2,1
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
HNBR	1.	49,93	25,31	2,17	FAME	54,78	27,57	2,48	DI	51,57	26,06	2,37	HVO	50,07	25,34	2,3
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
IIR	1.	50,02	25,14	2,1	FAME	58,71	29,42	2,66	DI	63,73	31,83	3,01	HVO	62,91	31,4	2,96
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
NBR	1.	50,2	25,04	2,26	FAME	52,57	26,6	2,43	DI	50,99	25,49	2,37	HVO	49,98	25,03	2,34
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
AU	1.	49,54	24,7	2,06	FAME	50,41	25,52	2,16	DI	50,01	25,36	2,15	HVO	49,38	24,95	2,15
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
VMQ	1.	50,08	25,15	2,02	FAME	53,04	27,12	2,17	DI	56,82	29,42	2,48	HVO	57,29	29,69	2,55
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
PTFE 1	1.	50,58	25,2	2,7	FAME	50,5	25,22	2,74	DI	50,52	25,19	2,79	HVO	50,58	25,11	2,78
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
PTFE 2	1.	50,5	25,78	2,91	FAME	50,6	25,89	2,93	DI	50,5	25,79	2,97	HVO	50,51	25,83	2,99
	2.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-
	3.	-	-	-	FAME	-	-	-	DI	-	-	-	HVO	-	-	-

Result List for the Compression Set Tests

Residual Compression	Starting Thickness (mm)	Fuel	Final Thickness (mm)	Residual Compression (%)		Starting Thickness (mm)	Fuel	Final Thickness (mm)	Residual Compression (%)
AEM	12,085	-	11,831	9,83 %	IIR	12,104	-	11,784	12,29 %
	11,975	DI	11,637	13,66 %		12,188	DI	11,592	22,17 %
	12,051	FAME	11,738	12,27 %		11,976	FAME	11,541	17,57 %
	12,032	HVO	11,668	14,38 %		12,126	HVO	11,601	19,99 %
EPDM	12,19	-	12,012	6,62 %	NBR	11,754	-	11,626	5,68 %
	12,137	DI	11,741	15,02 %		11,945	DI	11,811	5,48 %
	12,1	FAME	11,814	11,00 %		12,106	FAME	11,84	10,21 %
	12,198	HVO	12,422	-8,30 %		11,911	HVO	11,762	6,18 %
FKM 1	12,011	-	11,764	9,84 %	AU	11,898	-	11,559	14,14 %
	12,16	DI	11,684	17,89 %		11,893	DI	11,538	14,83 %
	12,148	FAME	11,755	14,84 %		11,886	FAME	11,721	6,92 %
	12,121	HVO	11,745	14,35 %		11,887	HVO	11,553	13,99 %
FKM 2	11,893	-	11,424	19,60 %	VMQ	12,159	-	11,934	8,46 %
	11,902	DI	11,423	19,94 %		12,204	DI	12,028	6,51 %
	11,78	FAME	11,317	20,31 %		12,164	FAME	11,968	7,36 %
	11,877	HVO	11,388	20,57 %		12,192	HVO	12,023	6,28 %
FVMQ	11,904	-	11,776	5,32 %	$C = [(t_o - t_f)/(t_o - t_s)] * 100$ <p> <i>C</i> residual compression as percentage <i>t_o</i> original thickness of the specimen <i>t_f</i> final thickness of the specimen <i>t_s</i> spacer bar thickness </p>				
	11,859	DI	11,599	11,02 %					
	11,886	FAME	11,567	13,37 %					
11,854	HVO	11,566	12,23 %						
HNBR	11,764	-	11,448	13,96 %					
	11,866	DI	11,342	22,15 %					
	11,768	FAME	11,332	19,22 %					
	11,644	HVO	11,311	15,53 %					