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Evaluation of EPDM Elastomeric Seals for Application in Polymer Electrolyte Membrane Fuel Cells

Mohammad Mahdi Barzegari[a] | **Mohammad Momeni**[a]
Pouya Pashaie[b] | **Hamid Hassanzadeh Afrouzi**[b,*]

[a] Northern Research Center for Science and Technology, Malek Ashtar University of Technology, Iran
[b] Department of Mechanical Engineering, National University of Skills (NUS), Tehran, Iran
[*] Corresponding author, Email: h.h.afrouzi@gmail.com

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Abstract

EPDM is a widely used elastomeric polymer for gaskets in PEMFCs. These gaskets play a critical role in maintaining the electrochemical stability of fuel cells and preventing gas leaks. Both chemical and mechanical degradation can occur in EPDM gaskets when exposed to mechanical stress and corrosive acidic conditions. The goal of this study was to enhance the durability of EPDM gaskets by modifying the curing formulation through variations in the proportion of dicumyl peroxide used. The present study investigates how transformations in the material affect its mechanical properties and chemical stability. Accelerated durability tests (ADT) were performed using 1.8 ppm hydrofluoric acid and 12.5 ppm sulfuric acid to simulate conditions that may be encountered in real-world applications. To analyze the chemical alterations and elemental release on the gasket surface, FTIR and AAS were employed. The addition of DCP (dicumyl peroxide) to the curing process improved both the chemical resistance and mechanical strength of EPDM. After 800 hours of operation in the fuel cell, the optimized samples showed no changes in weight or hardness. These findings contribute to enhancing the durability of gaskets, ultimately improving the efficiency and longevity of PEM fuel cells.

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1 Introduction

Energy-efficient techniques and renewable energy sources are vital for reducing environmental pollution, combating climate change, and ensuring a sustainable future. Polymer electrolyte membrane (PEM) fuel cells play a key role in clean energy technologies, offering high efficiency and zero-emission power generation for stationary power systems, transportation, and portable devices [1]. The compact design, rapid start-up capability, and scalability of PEM fuel cells make them promising alternatives to traditional fossil fuel-based energy systems. However, the widespread adoption of PEM fuel cells faces significant technological challenges, with the development of durable and reliable gaskets being a key concern [2,3]. Gaskets in PEM fuel cells are essential components that seal and separate hydrogen, oxygen, and cooling fluids, all while withstanding harsh operational conditions, such as chemical exposure, mechanical stress, and temperature fluctuations [4–7].

Factors such as material degradation, insufficient sealing under cyclic loads, and restricted long-term durability constrain the performance and longevity of PEM fuel cells [8, 9]. Resolving these challenges necessitates creative material solutions and sophisticated to produce gaskets with improved reliability and efficiency, thereby facilitating the wider adoption of fuel cell technology in modern energy systems [10]. Tan et al. [11, 12] conducted several studies on fuel cell gaskets, examining the chemical stability and mechanical properties of EPDM rubber under fuel cell operational conditions. The experiments were carried out in a chemical solution at two different temperatures. Through chemical and mechanical tests, such as FTIR and DMA, they observed changes in the chemical characteristics and physical behavior of the rubber before and after exposure. The results indicated minimal chemical changes to the rubber surface and negligible alterations in its physical or mechanical properties after 35 weeks in the fuel cell environment. In a separate study, the mechanical and chemical durability of silicone rubber under fuel cell operating conditions was investigated. Experiments were conducted at 60 °C and 80 °C, using techniques such as ATR-FTIR and atomic absorption spectroscopy, along with dynamic assessments. revealed minimal chemical changes on the silicone rubber surface over time, along with an increase in hardness and elastic modulus. Additionally, EPDM and fluoroelastomer rubbers were evaluated under similar conditions, with a focus on mechanical properties such as hysteresis, elastic modulus, energy dissipation, and hardness. The results showed that fluoroelastomer exhibited dimensional and morphological changes, while EPDM demonstrated superior reliability in the fuel cell environment. Lin and associates [13] examined the chemical degradation and dynamic response of five distinct elastomer types: fluorosilicone rubber (FSR), liquid silicone rubber (LSR), EPDM, copolymer resin (CR), and fluororubber (FKM) under the operating conditions of PEMFC. The findings indicated that fluorosilicone and EPDM exhibited superior chemical stability, while liquid silicone rubber and resin experienced breakage and significant color changes. Regarding weight alterations, resin and LSR displayed similar weight reduction, whilst EPDM and FKM showed slight weight increase, and FSR displayed minimal weight fluctuation. Mechanical evaluations indicated that resin, LSR, and EPDM were more suitable for PEMFC sealing, with EPDM ultimately recognized as the superior elastomer. Moreover, resin and liquid silicone demonstrated breaking in the simulated fuel cell environment, resulting in weight loss of up to 45%. The results indicate that EPDM exhibited superior dynamic-mechanical and chemical stability compared to other elastomers in the fuel cell environment.

Choi et al. [14] investigated the stress relaxation characteristics of EPDM rubber in fuel cell operating conditions. Experiments were conducted in a fuel cell environment with deionized water at varying temperatures, applying different strain levels to the rubber. The findings revealed that the stress-strain curve of EPDM exhibited linear behavior up to 25% strain. The relaxation modulus was found to be time-dependent, independent of strain. Additionally, the study determined that water had a significant impact on the performance of EPDM rubber in fuel cell conditions. Choi et al. [15] investigated the mechanical aging and sealing characteristics of thermoplastic vulcanizates (TPVs) as sealing materials for vehicle fuel cells. The study aimed to assess the viability of TPVs as substitutes for conventional sealing materials and to enhance their durability and performance in extreme environments. The findings indicated that TPVs preserved their sealing efficacy under extended mechanical stress and thermal cycling. Quantitative data demonstrated that the degradation rate of TPVs was lower than that of traditional elastomers, making them a viable option for automotive fuel cell applications.

Shen et al. [16] examined the influence of gas permeability on the sealing efficacy of PEMFC stacks, with a primary focus on the impact of gas diffusion, particularly hydrogen and oxygen, through sealing materials and its influence on sealing integrity. The findings revealed that increased gas permeability accelerates seal deterioration, weakening both the sealing force and overall efficacy. As a result, higher gas permeability leads to reduced sealing effectiveness, causing leaks and a subsequent decline in fuel cell efficiency. The research emphasized the necessity of enhancing sealing materials to tackle these issues. In a follow-up study, Shen et al. [17] enhanced the hardness and tensile properties of EPDM rubber by employing a layered structure. They vulcanized the rubber with various fillers arranged in an alternating layered configuration and conducted comprehensive testing to assess the material's performance. The results indicated that, in comparison to the conventional construction, the multilayer design reduced tensile strength and compression set, while increasing hardness. Notably, hardness improved as the number of layers increased, which contributed to enhanced dimensional stability of the fuel cell seal.

In a related study, Wang et al. [18] explored the chemical properties of SR (silicone rubber) in the context of fuel cells under two different types of compressive loading. Surface morphology analysis showed that fracture formation led to increased surface roughness and a decrease in smoothness. ATR-FTIR and XPS analyses revealed changes in the surface chemistry of the rubber due to the degradation of crosslinks and specific chemical bonds under acidic conditions and temperatures ranging from 60 to 80 °C. The findings identified that the acid concentration within the fuel cell and the applied loading force were the two most significant factors influencing the chemical stability and degradation of silicone rubber. Qiu et al. [19] identified various frequently utilized elastomers for fuel cell sealing and conducted both chemical and mechanical evaluations. The materials studied included SR, FR, nitrile rubber (NBR), and EPDM. The results showed that the applied compression rate had a significant impact on the tensile properties. Among the materials tested, SR exhibited the lowest mechanical stability, while EPDM displayed the highest. Although SR demonstrated the best heat resistance, elevated temperatures led to a reduction in the modulus of all the elastomers.

Yang and associates [20] investigated diverse fabrication techniques, structural configurations, and durability factors of sealing materials employed in PEMFCs. The main goal was to develop innovative materials and methods that could improve the durability and sealing efficacy of fuel cells. Key findings revealed that composite materials and multilayer configurations significantly improved the mechanical properties and degradation resistance of seals. The study concluded that seals made from structural composites outperformed traditional single-material seals in terms of performance and longevity. Wu et al. [21] studied silicone rubber in a fuel cell environment at low temperatures, starting at −20 °C, and investigated its degradation and stabilization through multiple heat cycles. The results showed a strong correlation between the number of thermal cycles and the increase in silicone rubber hardness, along with a significant reduction in sample weight. Chemical analysis supported these findings, revealing changes in the surface chemistry and the formation of fissures on the rubber sample's surface. Zhou et al. [22] developed an accelerated testing methodology to assess the longevity of SR seals in PEMFC systems. The primary aim was to replicate extreme fuel cell system conditions, including high temperatures and humid environments, within a shortened timeframe. The results revealed significant deterioration of silicone rubber after prolonged exposure, characterized by increased hardness and swelling. They suggested that the long-term durability of these seals could be improved by modifying their composition or structure.

Shi et al. [23] investigated fabrication methods, structural design, and durability evaluations of enhanced sealing materials in PEMFC. Their main objective was to assess the performance of different sealing materials under fuel cell conditions, particularly in response to temperature, pressure, and humidity. The results highlighted that sealing materials must show strong resistance to aging, mechanical stress, and chemical degradation to ensure long-term effectiveness. Silicone seals demonstrated exceptional durability under fuel cell operating conditions. Im and Jeoung [24] examined the characteristics of Ethylene Propylene Diene Monomer (EPDM) seals in PEMFC, concentrating on the implementation of an alternating multilayer structure to improve the hardness and compression set of these seals. The results demonstrated that the multilayer configuration markedly boosted both hardness and compression set, leading to better sealing efficacy under high-temperature cycling conditions.

Xiaohuo et al. [25] concentrated on forecasting the sealing force of elastomeric materials employed in PEMFCs under thermal cycle conditions. The main objective was to develop a model that could estimate changes in sealing force overtime due to repeated thermal expansion and contraction. The key finding revealed that elevated temperature cycles lead to a reduction in sealing force, potentially causing leaks. A quantitative analysis resulted in a model that forecasts the decline in sealing force, aiding in the selection of materials that improve sealing efficacy. In a 2024 investigation, Xiaohuo et al. [26] assessed the sealing efficacy of EPDM seals for PEMFCs. The objective was to analyze the performance of EPDM seals under the standard operating circumstances of PEM fuel cells, which involve high humidity and temperature variations. The primary findings revealed that whereas EPDM seals offer superior initial sealing efficacy, they deteriorate over time due to material aging. The study presented accurate quantitative data on the deterioration rate, indicating that the long-term efficacy of EPDM seals could enhance their overall performance. It focused on sealing in fuel cells using EPDM rubber, exploring its structure and curing formulation to meet performance criteria under fuel cell operating conditions. This research is novel in two key aspects: (i) the investigation of the curing formulation of EPDM using dicumyl peroxide at different concentrations, and (ii) the assessment of the mechanical properties and chemical characteristics of various substances using an ADT solution. The research also examines current rubbers utilized in fuel cells, assessing their chemical, mechanical, and degrading capabilities, with a particular focus on surface characteristics. The findings are compared with previous studies to validate their scientific and practical relevance. Additionally, the study emphasizes reverse-engineering optimal commercial rubbers to develop scalable formulations for mass production and examines the impact of vulcanization techniques on rubber performance in fuel cells.

2 Materials and Methods

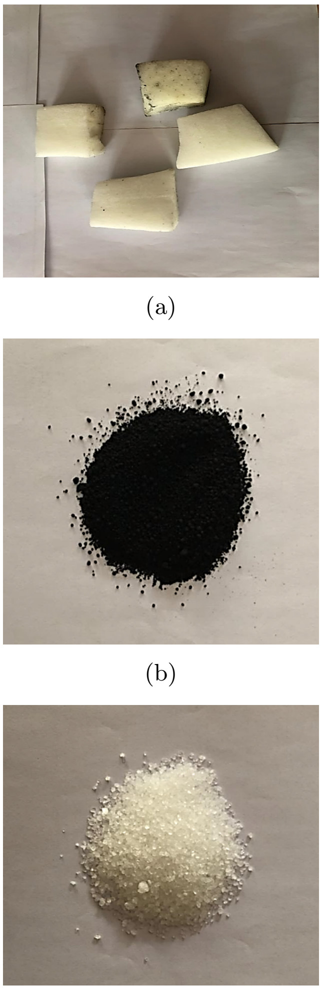
2.1 Materials and fabrication

In this study, ethylene-propylene-diene monomer (EPDM, KEP270) was selected as the base elastomer due to its favorable chemical resistance, mechanical stability, and sealing performance under fuel cell operating conditions. The EPDM was supplied by KUMHO Polychem (Seoul, South Korea). To achieve effective crosslinking and enhance the mechanical properties of the gasket material, dicumyl peroxide (DCP) with a purity exceeding 98% was used as the curing agent. The DCP was obtained from Sinopharm Chemical Reagent Co., Ltd. (Beijing, China). A detailed overview of the material composition and processing parameters is provided in Figure 1.

Table 1. Composition of materials utilized for curing rubber.

Sample	Raw Rubber (phr)	Dicumyl Peroxide (phr)	Carbon Black (phr)
EP2	100	2	20
EP3	100	3	20
EP4	100	4	20

The EPDM-based gasket compounds were prepared using a two-roll milling machine (Santam®, Tehran, Iran) with a friction ratio of 1 : 1.25. Mixing was conducted at room temperature following the ASTM D3568 standard to maintain consistency in formulation. Initially, EPDM rubber was softened for two minutes under a nip gap of 2 mm, while the rolls rotated at 40 RPM. Dicumyl peroxide (DCP) and carbon black N550 were then sequentially added to the mixture to promote crosslinking and enhance the mechanical properties of the material. The total mixing duration was 50 minutes, during which cold water was circulated through the milling machine to prevent premature curing and maintain process stability. The curing process was carried out at 168 °C and a pressure of 13.8 MPa to achieve optimal crosslinking and structural integrity. The final prepared samples, illustrated in Figure 2, were subsequently subjected to mechanical and sealing performance evaluations.



(a)

(b)

(c)

Fig. 1. Raw materials employed in the production of EPDM rubber: (a) pure EPDM polymer, (b) carbon black N550, and (c) dicumyl peroxide (DCP) as the curing agent.

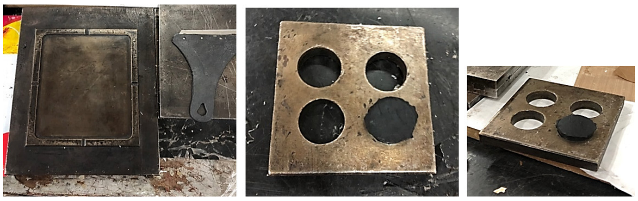


Fig. 2. Compounded EPDM material after mixing in the milling machine: (rubber disc molds prepared for hardness and compression set tests).

2.2 Testing methods

Polymers and advanced elastomers have demonstrated extensive applicability in high-performance industries, including aviation, aerospace, and sports equipment, due to their superior mechanical properties, chemical resistance, and durability. Among these materials, Advanced Polymer Materials (APMs) have gained significant attention in aerospace engineering, particularly in structural components for aircraft and space exploration missions [27]. The continuous advancements in APMs have been driven by NASA's space transportation programs, alongside their long-standing utilization in military and governmental aviation sectors. With the rapid evolution of plastic and rubber manufacturing technologies, many of these innovations have foundsecondary applications, including in commercial markets and renewable energy systems [28, 29]. In particular, the integration of high-performance elastomers in fuel cell technologies has become a critical area of research, given their essential role in improving the durability and efficiency of key components. The following sections offer a comprehensive analysis of the mechanical and chemical performance of elastomeric materials designed specifically for fuel cell applications. The experiments and evaluations conducted provide valuable insights into their suitability for sealing applications, their longevity under operational conditions, and the potential improvements they can bring to fuel cell performance.

Hardness is a key indicator of rubber elasticity, with lower hardness generally corresponding to greater flexibility 262626. It is defined as a material's resistance to permanent indentation under specific conditions and applied force. In elastomers, hardness can be classified into two types: inherent hardness, determined by polymer composition, and process-induced hardness, influenced by manufacturing conditions [30]. Hardness measurement in elastomers is typically done using two standard units: Shore Durometer and International Rubber Hardness Degree (IRHD). The Shore Durometer includes multiple scales, with Shore A commonly used for rubbers and Shore D for plastics. This parameter is critical in fuel cell gaskets, as it directly affects sealing force and compression. Excessive sealing force may lead to plastic deformation in sensitive components, such as the membrane and gas diffusion layer (GDL), while insufficient force can increase contact resistance, leading to higher resistive losses.

Another crucial factor is the variation in hardnessunder operating conditions, which indicates the seal's long-term durability. Greater fluctuations in hardness over time suggest reduced gasket longevity in fuel cells. In this study, hardness was measured following the ASTM D2240 standard using the Shore A method. Test samples had a minimum thickness of 6 mm, and measurements were taken at three different points on separate specimens. A force of 800 N was applied to ensure precise hardness evaluation. In this study, a durometer was utilized to measure the hardness of elastomers following the Shore A standard method. The device assesses the hardness of the rubber at various points on the samples by applying a specified force under controlled conditions. To ensure high measurement accuracy, three distinct pieces with a minimum thickness of 6 mm were employed.

All materials, due to their molecular structure, have a limited capacity to endure tensile and compressive stresses. In fuel cell applications, gaskets primarily experience compressive stresses, making it crucial to calculate the stress applied to the gasket and compare it with the material's maximum permissible stress before compression. Tensile strength is closely related to hardness and represents the maximum stress an elastomer can withstand before undergoing permanent deformation. This property is typically measured in units of Psi or MPa. The tensile strength of an elastomer is highly influenced by the stretching capability of its crystalline structure under tension. To determine tensile strength, the ASTM D412 standard is commonly followed. In this test, samples are prepared in a dumbbell shape, ensuring consistency with the standard. The tensile strength test proceeds with the preparation of three dumbbell-shaped samples, followed by the adjustment of the testing machine's stretching speed according to the standard's specifications. The samples are then subjected to tensile testing using a universal tensile machine, and the tensile strength values are recorded. Finally, the average tensile strength of the three samples is calculated and reported as the final result. This testing was carried out using a 2-ton universal tensile machine manufactured by Santam®. The compression set test evaluates the ratio of elasticity to viscosity in an elastomer under compressive forces. Elastomers with larger polymer chains typically exhibit better resistance to compressive loading, as their higher energy storage capacity enhances elasticity. Compression set refers to an elastomer's ability to return to its original dimensions or retain its elastic properties after prolonged compression. According to ASTM D395 (ISO 815) standards, two methods are defined for conducting the compression set test. The first method, the constant force method (A), applies a constant force using a compressive spring during the test. The second method, the constant strain method (B), maintains a 25% strain on the specimen using a spacer of a specific thickness. It is important to note that the results from these two methods are not directly comparable, and the method used should be clearly indicated in the results. In this study, the constant strain method was applied. Disc-shaped samples were prepared following the standard's dimensions. For smaller disc samples, the spacer thickness was ±0.5 mm for a 4.5 mm disc, while for larger discs, the spacer thickness was ±0.5 mm for a 9.5 mm disc. The compression set test mechanism was designed and fabricated according to the specified requirements of the standard.

The compression set test mechanism, as shown in Figure 3, consists of two steel plates with dimensions of 10 cm × 10 cm × 2 cm, and two rods with thicknesses of 4.5 mm and 9.5 mm, respectively. The applied pressure on the samples was maintained for durations of either 20 or 70 hours. In this study, the disc-shaped samples were subjected to pressure for 70 hours. Before applying the compressive force, the initial thickness of the samples was measured. After the specified compression time and subsequent release of the pressure, the samples were allowed to rest at room temperature for 30 minutes to stabilize. Once stabilized, their final thickness was measured. The compression set of the elastomer is calculated as the percentage difference between the final thickness and the initial thickness. To ensure reliability, three samples were evaluated for each test. The average of two samples was used to determine the compression set of the elastomer.

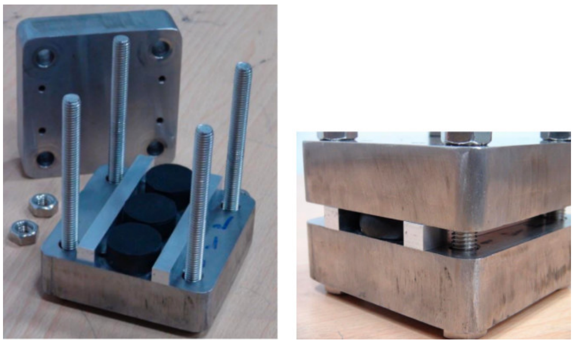


Fig. 3. Tensile strength test used in this research.

When an elastomer is subjected to constant strain, the force required to maintain that strain typically decreases over time, a phenomenon known as compressive stress relaxation. On the other hand, when the elastomer is under constant stress, its deformation increases over time, which is referred to as creep. Stress relaxation testing, according to ASTM D6147-97 and ISO 3384 standards, can be performed using two different methods. Method A involves compressing the sample at the test temperature and measuring the sealing force at the same temperature. This method is particularly useful for evaluating sealing performance at high temperatures. In Method B, the compression occurs at the test temperature, but the sealing force is measured at ambient temperature (23 °C). This method is ideal for assessing sealing performance under fluctuating temperature conditions. This test evaluates the elastomer's elastic properties under pressure at elevated temperatures. Greater changes in the material's properties correspond to higher relaxation values, indicating more significant stress relaxation. The test setup consists of two flat plates with a maximum surface roughness of 0.6 μm. The test duration is set for 168 hours, with pressure reaching its maximum value within 30 seconds. A furnace is used to maintain a constant temperature throughout the test. The first force measurement is taken 30 minutes after the test begins, and three samples are tested simultaneously. The average values are then used to calculate the elastomer's compressive stress relaxation behavior.

Chemical resistance refers to the ability of a material to maintain its stability when exposed to a specific environment. This is assessed by evaluating changes in the material's physical and chemical properties, such as weight, hardness, tensile strength, and other relevant characteristics. The process starts by measuring the material's initial properties before subjecting it to the test environment. After a set exposure period, the material's properties are re-measured. The extent of any changes indicates the material's compatibility with the environment. Minor changes suggest the material is compatible, while significant changes imply incompatibility. According to ASTM D471, elastomeric samples are immersed in a specific fluid for a predetermined period. After this exposure, any changes in the material's dimensions, weight, and other physical properties (excluding hardness) are measured and recorded as a percentage of the initial values. Once removed from the fluid, the samples are rinsed with distilled water to remove any acidic contamination. The samples are then placed at room temperature for two hours to allow for stabilization. After this period, their properties are measured again. A critical parameter assessed in this test is the weight change of the samples. To evaluate this, rubber discs are weighed before being placed in the test fluid, and their weight is remeasured after the exposure period.

A crucial characteristic of an effective gasket in fuel cell applications is its ability to maintain chemical stability when exposed to operational environments. In fuel cells, the gasket is subjected to acidic, oxidative, and humid conditions, which can influence its stability. The ability of the gasket to maintain its chemical composition under these conditions is critical for its performance. Any changes in the chemical composition can lead to alterations in the material's properties, reduced sealing performance, and even degradation of other fuel cell components.

Certain elements, such as calcium, magnesium, and particularly silicon, are highly reactive in the fuel cell environment. These elements may detach from the gasket's surface and dissolve into the surrounding solution, potentially compromising the gasket's performance. Additionally, materials from other fuel cell components could also detach and interact with the gasket, further altering its composition. Spectroscopic techniques are useful for identifying and analyzing these chemical changes in both the gasket and other fuel cell components. Spectroscopy involves the study of material properties by examining the light, sound, or particles emitted, absorbed, or scattered by the material. In this study, two types of spectrometers were employed to analyze the chemical properties of the gasket. Atomic Absorption Spectroscopy (AAS) was used to measure the transfer of elements, such as magnesium and calcium, from the gasket to the acidic environment. Changes in their concentrations were assessed before and after the experiment. Fourier Transform Infrared Spectroscopy (FTIR) was used to evaluate any alterations in the gasket's chemical composition, which can reveal its chemical stability and possible structural changes under test conditions. FTIR results are presented as graphs where the horizontal axis represents the wavelength (cm^{-1}), and the peaks correspond to unique chemical bonds between atoms. The intensity of these peaks indicates the concentration of specific bonds. Significant chemical reactivity between the gasket material and the acidic environment may result in a decrease or disappearance of certain peaks, reflecting the degradation or changes in the material's structure. Both AAS and FTIR analyses were performed at the Razi® Metallurgy Laboratory under standard testing conditions.

Changes in the surface quality of the gasket can serve as a significant indicator for evaluating its suitability and performance in fuel cell operational conditions. Chemical reactions between the gasket and other fuel cell components may lead to the detachment of elements from the gasket's surface or the introduction of new elements, both of which can alter the surface properties. These surface changes are closely linked to the chemical and physical properties of the gasket. In other words, alterations in surface quality can provide insights into the reactivity of the gasket material in its operational environment. The extent and intensity of these changes are directly related to the gasket's material reactivity. Surface quality changes are studied using microscopy techniques. Initially, high-magnification imaging (at the micrometer level) of the gasket's surface is conducted before it is exposed to the fuel cell environment. This imaging procedure is repeated at regular intervals to track changes over time. The images obtained are compared to analyze how the gasket's surface evolves under the various test conditions. In this series of experiments, the properties of selected materials are examined in a simulated acidic environment under two different temperature conditions. The acidic environment used in this study consists of a mixture of sulfuric acid (H_2SO_4) and hydrofluoric acid (HF), with the specific composition ratio outlined in Table 2.

Table 2. Composition of the simulated acidic environment with sulfuric acid and hydrofluoric acid used for material property tests under two different temperature conditions.

Material	Concentration/Property
Sulfuric acid (H_2SO_4)	98% → 1 M
Hydrofluoric acid (HF)	48% → 10 ppm
Reagent grade water	18 MΩ
pH	< 1

Although the pH value in real fuel cell conditions is around 3.5 to 5, an attempt was made to bring the test results closer to real conditions by creating a stronger acidic environment and reducing the test duration. The tests were conducted at two different temperatures: room temperature (23 °C) and 80 °C in an oven. The selection of 80 °C was aimed at stimulating the operating temperature of the fuel cell and examining the effect of temperature on the reaction rate between the sealant and the acid. The elastomer properties were measured before the test began and recorded as the initial values. At regular intervals, the elastomer properties were re-measured, and their changes compared to the initial values were calculated. The properties of the elastomers examined in these tests include hardness, compression set, tensile strength, weight changes, Fourier-transform infrared spectroscopy (FTIR) and atomic absorption spectroscopy (AAS), and surface appearance changes of the sealant. The purpose of these tests was to evaluate the durability of each selected material in an environment similar to that of a fuel cell. The tests were conducted at 80 °C for 800 hours, with samples placed in an oven. Two interim sampling points were taken: the first sample after 400 hours and the second

400 hours after the first sample.

3 Results

Figure 4 depicts the many types of rubber samples prepared post-production, categorized by their curing formulation and physical state, presented as sheets, discs, and dumbbells. These samples are utilized for diverse mechanical assessments and the evaluation of physical characteristics. The various forms were created to evaluate the influence of curing formulations and production conditions on the characteristics of the rubbers in distinct molds.

Fig. 4. Rubber sheets, discs, and dumbbells after production, categorized by curing formulation and physical state.

The samples' hardness was assessed following the designated standard, as detailed in the preceding section. Table 3 illustrates that an increase in the amount of curing agent correlates with a heightened density of polymer chain crosslinking within the rubber structure. This caused a decrease in the elasticity of the polymer chains, subsequently leading to an increase in the hardness of the samples. Furthermore, the experiment demonstrated that following an 800-hour exposure of the rubbers to the simulated ADT solution, no notable alteration in the hardness of the samples was detected. The consistent hardness signifies that the mechanical properties of the rubber remain largely unchanged throughout the simulated fuel cell environment.

Table 3. Hardness characteristics of the rubbers before and after the ADT test.

Sample	Before ADT	400 hours ADT	800 hours ADT
EP2	63	62	59
EP3	66	65	64
EP4	67	67	66

The rheometer is an essential device utilized to assess the curing properties of rubber compounds. The apparatus functions by positioning a rubber specimen between two circular plates, thereafter applying heat and rotating force to the specimen. During this phase, the rubber raw materials, coupled with the curing agent and additives, initiate the curing process. As time advances, chemical curing events transpire, resulting in the formation of links between polymer chains. This leads to an augmentation in the necessary torque. The procedure persists until the torque stabilizes, indicating the conclusion of the curing process. The point at which the curve stabilizes signifies the appropriate curing duration for the sample, serving as an essential reference for producers in the creation of rubber products.

Table 4. Rheometric curing characteristics of the rubbers.

Sample	Tc 90 (minutes)	MH (dN.m)	ML (dN.m)	Q (%)
EP2	26.29	16.11	2.68	24.8
EP3	22.68	20.65	2.81	20.7
EP4	21.7	21.12	2.93	19.17

The rheometric results indicate that an increase in curing agent concentration leads to a rise in maximum torque (MH) and a decrease in curing rate (%Q). This signifies an enhancement in the curing process and a decrease in the rubber preparation duration. Table 4 illustrates that Tc 90, MH, ML, and Q% denote the minimum torque, maximum torque, the duration to achieve 90% curing, and the curing percentage, respectively. The compression set is a critical metric for assessing the alterations and displacement of elastomeric chains in rubber subjected to force loading. This feature was evaluated for all three samples, as illustrated in Figure 5.

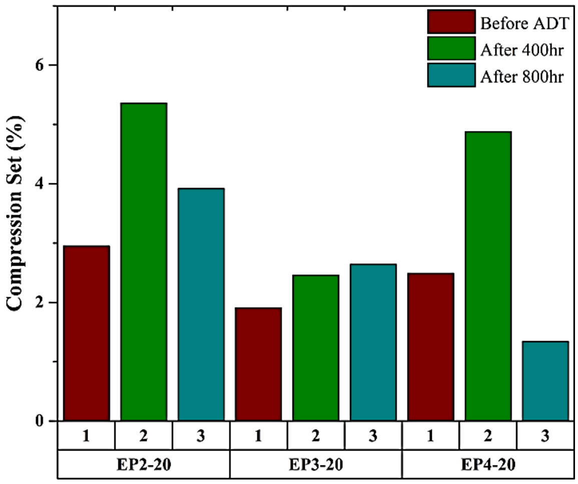


Fig. 5. Compression set values of the samples before and after the ADT test.

In the fuel cell environment, the solution's acidity may cause the degradation of crosslinks and bonding within the rubber structure. Following 800 hours of exposure to the simulated ADT environment, a general rise of around 2 to 3 percent in the compression set of the samples was noted. The compression set for sample EP2, prior to the ADT test, was determined to be 2.95%. Following the simulation of the fuel cell environment, the compression set rose by merely 2.41%, attaining a total of 5.36%. For sample EP3, the initial compression value was 1.91%, which increased to 2.46% upon exposure to the simulated environment. This sample exhibited a reduced compression set relative to both Danabaspar EPDM and silicone rubber. Ultimately, sample EP4 had an initial compression set of 2.49%, which escalated to 4.88% post-test. Observations indicated that employing Dicumyl Peroxide (DCP) as a curing agent, which establishes shorter bond lengths than sulfur curing agents, markedly diminished the compression set of the rubbers. This characteristic significantly improves the efficacy of sealing in polymer electrolyte membrane (PEM) fuel cells. The negligible alterations in the compression set upon exposure to the fuel cell environment underscore the enhanced stability of these rubbers.

The weight variation of the seal samples was assessed, revealing no weight change and indicating remarkable stability in both mass and appearance. Figure 6 illustrates that in the EP2 sample, following 800 hours of exposure to the ADT solution, the proportion of weight change diminished relative to the first phase of the experiment (400 hours). The weight alteration and decrease amounted to 1.02%. The EP3 and EP4 samples, demonstrating an elevated level of crosslinking and curing, saw a more significant weight shift and reduction during the second phase of the test. The weight decrease in these samples was 0.93% for EP3 and 0.29% for EP4. The disparities suggest that rubbers with more robust crosslinks are more influenced by the ADT environment. The negligible alterations in weight and appearance noted in the EPDM rubbers are ascribed to the establishment of strong crosslinks and resilient chemical connections among the polymer chains. This attribute demonstrates the exceptional strength and longevity of these seals, rendering them appropriate for application in rigorous fuel cell conditions.

The FTIR analysis results for the samples showed that the main bonds in the rubber were fully established, with peaks corresponding to C−H, $C-H_2$, $C-H_3$, C−O, and C=O bonds observed. Additionally, after exposing the samples to the ADT solution, the O−H peak, which appeared as a broad shoulder at a wavenumber of 3337 $\mathrm{cm^{-1}}$, was detected due to the presence of sulfuric and hydrofluoric acids in the simulated solution. This peak appeared weakly. As shown in Figure 7, no significant chemical changes or release of hazardous chemicals, particularly elements such as $\mathrm{Mg_2}^+$, $\mathrm{Ca_2}^+$, $\mathrm{S_2}^-$, and other materials that could negatively affect the fuel cell efficiency, were observed.

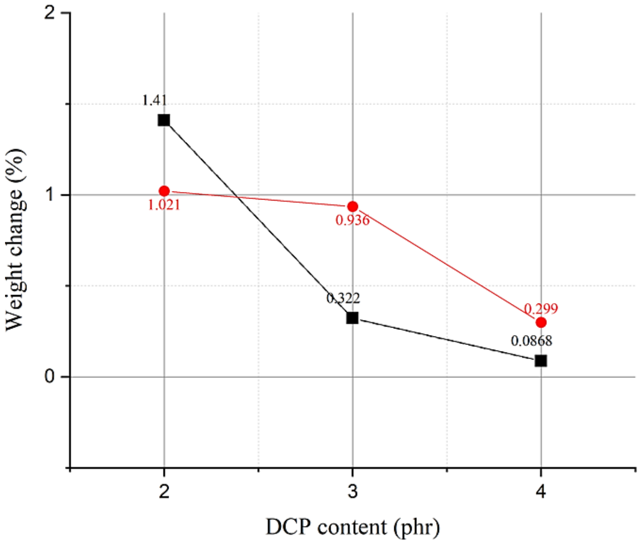
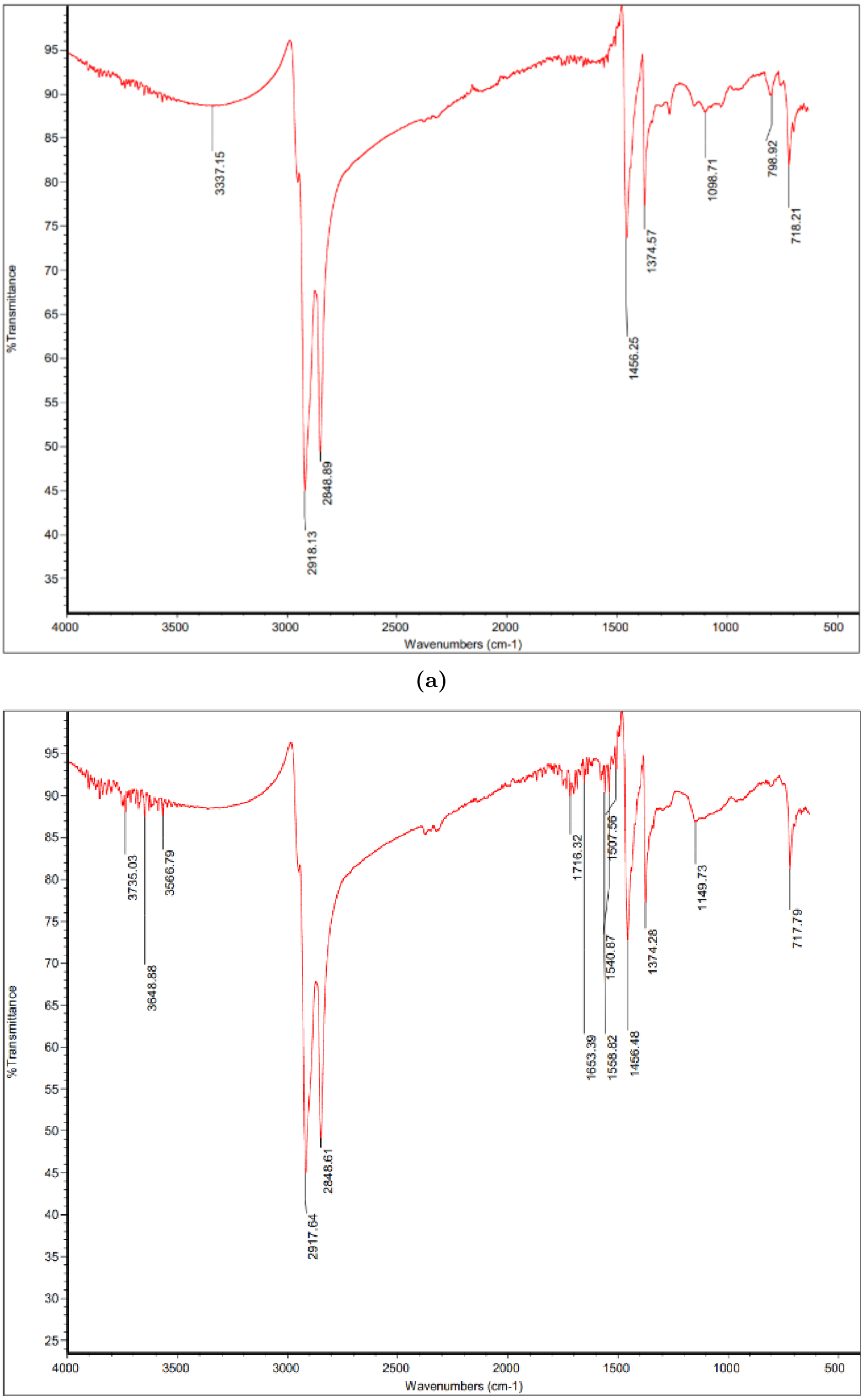


Fig. 6. Percentage weight changes of the seals after 400 hours (black lines) and 800 hours (red lines).

The tensile strength test was employed to assess the rubbers' resistance to tension and to determine the Young's modulus and stiffness of the samples prior to and following exposure to the fuel cell environment. As shown in Figure 8, sample EP2 demonstrated the greatest strain and registered the highest force at the failure location. Moreover, sample EP4, exhibiting the highest level of crosslinking and curing density, displayed the best resistance to strain. The failure strain values for the samples were 3.5, 2.6, and 2.34 for EP2, EP3, and EP4, respectively.

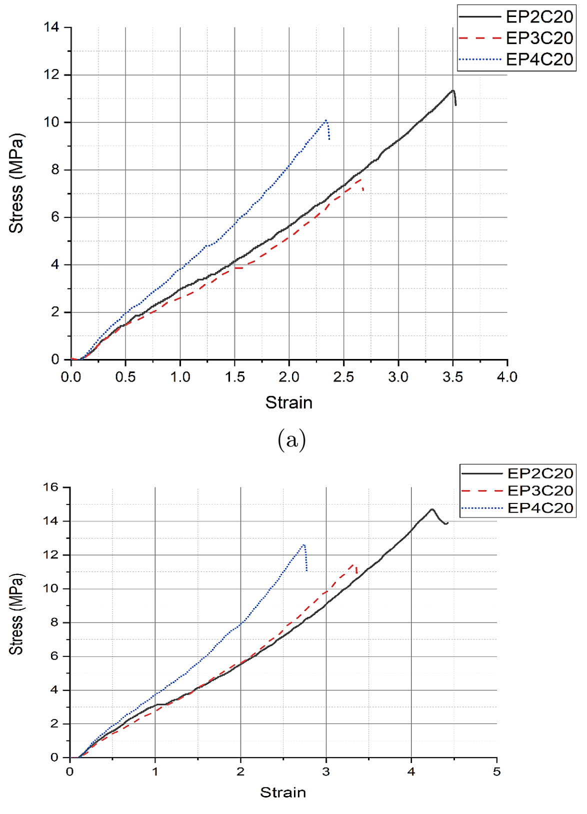
The tensile strength, strain at failure, and 300% modulus (a standard metric for representing the modulus of elastomers at 3% strain) were computed and analyzed prior to and during immersion in the ADT solution, with the findings displayed in Table 5. This table indicates that as the curing degree of the rubbers increased, the strain at failure fell, along with a reduction in their elastic and tensile properties. The strain diminished from 3.51 to 2.34. As anticipated, the Young's modulus was greatest for sample EP4; however, because the rubber failed before to achieving 3% strain, the value is not documented in Table 5. The rubber's behavior transitioned from elastomeric to a more elastic condition, resulting in enhanced resistance to stretching. Additionally, the tensile strength of the samples exhibited a proportionate decline. The tensile strength diminished from 11.33 MPa to 10.07 MPa. Over the course of 800 hours of exposure to the fuel cell operational environment, all samples demonstrated a proportional increase in strain at break, tensile strength, and 300% modulus. The environmental acidity resulted in an elevated crosslink density of the polymer chains in the rubbers.



(a)

(b)

Fig. 7. Infrared spectrum of EP2; (a) before ADT testing, (b) after ADT testing.



(a)

(b)

Fig. 8. Stress-strain curves of the rubbers; (a) before ADT, (b) after 400 hours of exposure to the ADT environment.

Table 5. Mechanical properties of the stress-strain test for the rubbers before and after simulating the fuel cell environment.

Sample	Modulus 300% before ADT (MPa)	Modulus 300% after ADT (MPa)	Tensile Strength before ADT (MPa)	Tensile Strength after ADT (MPa)	Strain at Break
EP2	3.08	3.35	11.33	14.76	3.51
EP3	-	3.37	7.57	10.18	2.65
EP4	-	-	10.07	10.18	2.34

4 Conclusion and Summary

This study examines elastomeric EPDM seals' mechanical stability, chemical resistance, and long-term durability in fuel cell-like circumstances. Hardness changed little after prolonged exposure to simulated acidic degradation test (ADT) conditions, demonstrating mechanical integrity and flexibility. Curing agent concentration increases crosslink density, boosting curing efficiency and processing time, according to rheometric studies. After 800 hours of compression set testing, EPDM samples' elasticity increased, preventing permanent deformation. Weight change experiments showed minimal mass loss in very acidic environments, supporting EPDM seals' chemical resistance. AAS and FTIR confirmed the elastomers' chemical endurance. The robustness of the PEM fuelwas confirmed by FTIR spectra showing negligible structural breakdown and AAS showing no elemental leaching. Prolonged contact did not alter surface morphology, supporting our findings. EPDM elastomers demonstrate strong potential as PEM fuel cell gasket materials due to their mechanical performance, chemical stability, and rigorous operating conditions. Further research should focus on enhancing the heat stability and degradation resistance of EPDM formulations to extend the lifespan and effectiveness of fuel cell sealing applications.

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