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Fachverband Fluidtechnik im VDMA e. V. Lyoner Str. 18
50628 Frankfurt am Main
Germany

Phone +49 69 6603-1513
E-Mail maximilian.baxmann@vdma.eu

Internet www.vdma.eu/fluid

Sealing Material 2030: Why Formulation, Consistency and Application Data Determine Seal Performance

Dipl. Ing. Timo Richter, Dipl. Ing. Bernhard Richter
OPR Group GmbH, Großbottwar, Germany

Material designations such as EPDM, HNBR or FKM describe an elastomer family, but they do not determine the actual performance of a seal. Polymer architecture, fillers, plasticisers, protective systems and crosslinking can produce markedly different long-term, low-temperature and media behaviour within the same family. This paper illustrates the effect using quantitative examples. HNBR formulations with comparable glass-transition indicators can show compression-set values of approximately 10% or 85% at -15 °C, while peroxide cured EPDM O-rings tested for two weeks at 150 °C can range from approximately 50% to 95%. The resulting uncertainty cannot be resolved by standard datasheets alone, because these usually focus on basic and short-term properties. The paper therefore proposes three requirements for "Sealing Material 2030": application-oriented high-performance formulations, transparent formulation and process consistency, and compound-specific data for service-life assessment, finite-element analysis, permeation and media resistance. A practical implementation route based on independently available formulations, controlled mixing licences and an expandable data package is outlined using OPR Elastolabs as an example.

1 Introduction

A designation such as EPDM 70, NBR 70 or HNBR 70 provides an important first classification, but it is not a complete performance specification. Within a single elastomer family, polymer grade, molecular architecture, fillers, plasticisers, protective agents and the crosslinking system can be varied over a wide range. Consequently, two compounds carrying the same family designation and hardness can behave very differently in long-term use, at low temperature or in contact with a medium.

This issue has become more relevant as the market for comparatively simple elastomer seals, including O-rings, has been exposed to strong cost and globalisation pressure. The associated focus on economical processing is understandable, but it can reduce the technical margin available in the application if the compound is insufficiently specified. Where technical support and compound expertise are weakened, the user may receive a material that meets a short datasheet while leaving a substantial part of the available performance potential unused.

The central question is therefore not whether one or two additional values should be added to a conventional datasheet. The more important question is which formulation-specific information is required to describe and verify seal performance under the actual operating conditions. Examples include data for finite-element analysis (FEA), low- and high-temperature recovery, permeation in gases, long-term media resistance and service-life curves that can be combined with the temperature history of an application.

This paper develops the argument in three steps. First, it explains why the formulation is a primary performance lever and illustrates the magnitude of the effect using HNBR and EPDM. Second, it discusses why formulation and process consistency are necessary for reproducible properties. Third, it outlines how conventional datasheets can be extended by an application-oriented material database. These three elements form the proposed concept of "Sealing Material 2030".

2 The Formulation as a Performance Lever

2.1 Polymer selection

The design space for an elastomer compound is exceptionally broad. A polymer supplier commonly offers more than 20 grades within one polymer family and, in individual cases, considerably more than 50. The grades can differ in monomer composition, average molecular weight, molecular-weight distribution, degree of branching and the arrangement of side groups. For EPDM, for example, the ethylene, propylene and diene content can be varied. These parameters influence cold flexibility, media and ageing resistance, dynamic behaviour and other properties that are visible to the seal user.

The processor evaluates a partly different set of characteristics. Relevant factors include viscosity, the relationship between viscous and elastic response, scorch behaviour, reversion, green strength, tack and storage stability [1]. The polymer grade therefore affects both the eventual application properties and the robustness and cost of manufacturing. Optimising one side without understanding the other can produce an apparently efficient compound that is less capable in service.

2.2 Fillers, plasticisers and protective systems

Polymer selection is only the first level of formulation design. Fillers, plasticisers, ageing-protection systems and processing aids are available in similarly broad varieties. Their type, purity and concentration can alter stiffness, thermal and oxidative ageing, volume change, gas permeability and low-temperature response. A formulation may also contain ingredients already introduced through an oil-extended polymer grade, which means that the complete compound must be considered rather than the nominal polymer alone.

The effects can be beneficial or detrimental depending on the application. Ageing-protection agents can improve resistance to heat, oxygen and autoxidation. Plasticisers can support processing and low-temperature flexibility, but they may evaporate or be extracted by the operating medium; the associated mass and volume loss can impair long-term sealing behaviour. Filler contaminants such as metal salts can be particularly critical in water service because they may promote oxidative degradation and depolymerisation.

2.3 Crosslinking and the processing-performance trade-off

The crosslinking system, including accelerators and additional chemicals, adds another decisive design level. It determines the network formed during vulcanisation and therefore influences compression set, heat resistance, media resistance and dynamic recovery. The selected system must also be matched to the intended manufacturing process, such as injection or compression moulding, and to the attainable vulcanisation state of the finished part.

During the past three decades, the market for elastomer seals has increasingly changed from a seller's to a buyer's market. This has encouraged formulations that are easier and more economical to process. Such optimisation does not automatically degrade application properties. Where the required performance is protected by meaningful specifications, or where the compound is developed jointly by supplier and user, a balanced compromise can be achieved. The risk is greatest where the compound is selected mainly by price and a small set of short-term values.

Even a change from a high-viscosity to a low-viscosity polymer grade can significantly impair long-term compression-set and compression-stress-relaxation behaviour. The implication for demanding applications is clear: compound design is not a secondary procurement detail. It is part of the functional design of the sealing system.

3 Quantified Effects Within a Single Elastomer Family

3.1 HNBR: heat resistance and low-temperature recovery

Model formulations show how strongly hydrogenated nitrile butadiene rubber (HNBR) performance can change when the degree of saturation, the fillers and the crosslinking system are modified. Using a criterion of 50% relative change in elongation at break, the permissible temperature for 1,000 h can range from approximately 125 °C to 155 °C [2]. For an application at approximately 100 °C, this corresponds to a service-life difference by a factor of about five to ten between a partially saturated HNBR with roughly 80% saturation and a highly saturated grade with more than 99% saturation.

The low-temperature example is equally significant. HNBR compounds with comparable differential scanning calorimetry (DSC) glass-transition indicators of approximately -30 °C can nevertheless show compression-set values of approximately 10% or 85% at -15 °C, depending on whether the selected polymer is amorphous or crystalline [3]. A single DSC indicator therefore does not fully describe the recovery behaviour relevant to a compressed seal. The polymer selection also has a strong influence on ozone resistance.

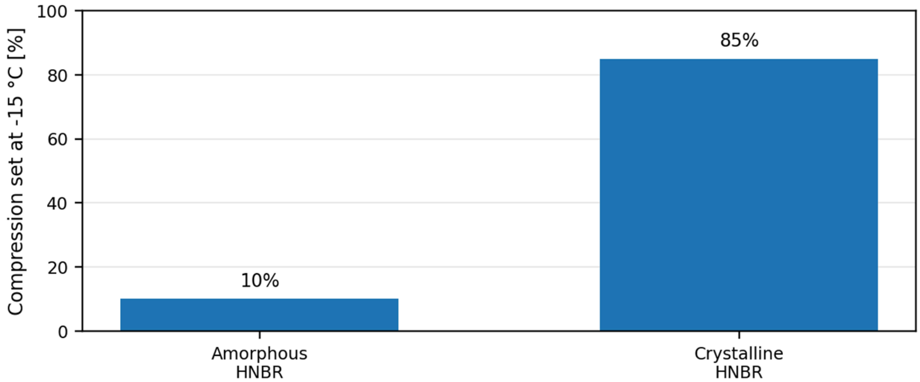

Figure 1: Formulation-dependent low-temperature compression set of HNBR compounds with comparable DSC cold indicators [3].

3.2 EPDM: crosslinking, morphology and long-term compression set

Ethylene propylene diene monomer rubber (EPDM) demonstrates several formulation effects at the same time. The crosslinking system should be specified when the compression-set potential of EPDM is to be used. In the examples discussed here, peroxide curing enables substantially better compression-set performance than a sulphur-based system. However, specifying peroxide curing alone is not sufficient to define the long-term behaviour.

A comparative measurement on EPDM O-rings illustrates the remaining spread. Although the finished parts achieved an appropriate short-term value of less than 30% after 24 h at 150 °C, the compression set after two weeks at 150 °C ranged from approximately 50% to 95% [4]. A short acceptance test can therefore screen out insufficient vulcanisation while still failing to reveal large compound-related differences in longer exposure.

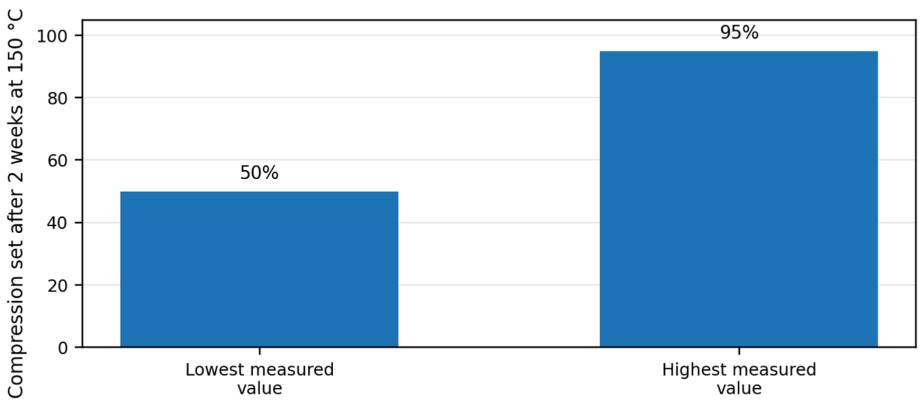

Figure 2: Range measured on EPDM O-rings after two weeks at 150 °C despite acceptable short-term compression-set values [4].

Polymer morphology and composition also affect the cold limit. An amorphous EPDM grade with an ethylene content of approximately 45-55% showed a compression set of 20% at -10 °C, while a crystalline EPDM grade containing approximately 65-75% ethylene showed 90% under the same stated temperature condition [5]. High diene and/or ethylene contents can also restrict heat resistance and cold flexibility.

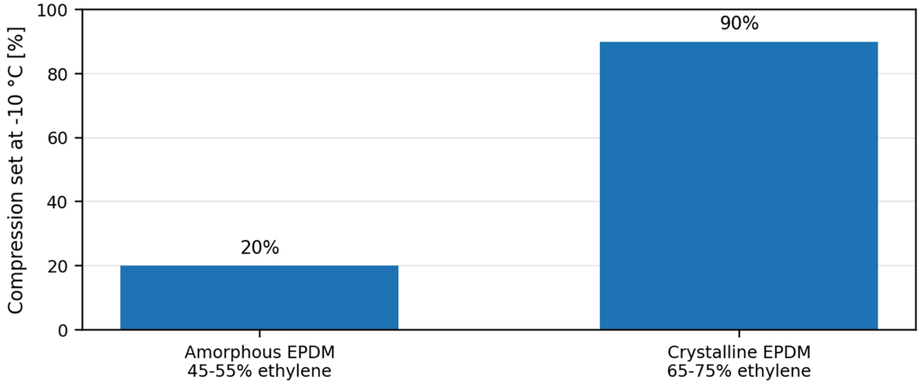

Figure 3: Influence of EPDM morphology and ethylene content on low-temperature compression set [5].

Additional formulation variables reinforce the effect. Ageing-protection systems influence resistance to heat, oxygen and autoxidation. Plasticisers may evaporate or be washed out, and the resulting shrinkage can reduce the long-term functional reserve. Fillers can shorten service life in water if impurities promote oxidative chain degradation. The EPDM designation therefore covers a broad performance range rather than a single technical level.

3.3 Implications for material selection

The HNBR and EPDM examples provide the central didactic message of this paper: the elastomer family is a starting point, not the final selection criterion. Comparable hardness or even comparable glass-transition indicators do not guarantee comparable recovery, ageing or service-life behaviour. The decisive information is the combination of the specific formulation, the vulcanisation state, the test method and the exposure history.

For the user, this means that supplier changes and material substitutions cannot be evaluated reliably by family designation and a few initial values alone. The property that limits seal function must be identified first. A compound-specific test or model can then be selected to measure that property under conditions that are technically connected to the application.

4 Transfer to NBR, CR, FKM and FFKM

The principle is not limited to HNBR and EPDM. Significant formulation-related differences occur throughout the main elastomer families. Table 1 summarises the variables and consequences described in the source manuscript. The table is not intended as a complete compatibility guide; it shows why the polymer-family name alone cannot represent the full performance profile.

Table 1: Examples of formulation variables and application consequences in further elastomer families

Family	Important formulation variables	Potential application consequences
NBR	Acrylonitrile (ACN) content, plasticiser level, sulphur crosslinking and ozone-protection concept.	Low ACN supports cold flexibility; high ACN reduces permeation. Plasticiser contents of up to about 20% may become critical. Sulphur curing can introduce corrosion concerns, and insufficient ozone resistance may limit use.
CR	Polymer type, including mercaptan-modified and thiuram- or sulphur-modified grades, together with the selected plasticiser.	The polymer type can strongly affect compression set. Polymer and plasticiser selection influence crystallisation and therefore long-term and low-temperature behaviour.
FKM	Polymer viscosity and crosslinking system; standard bisphenol-cured grades versus specialised, often peroxide-cured grades.	Polymer viscosity can influence long-term behaviour. Special grades can provide improved cold flexibility, hot-water resistance or acid resistance, including systems without metal oxides as acid acceptors.
FFKM	Polymer architecture, crosslinking system, fillers, metal oxides and application-specific adaptations.	Large differences can occur in high- and low-temperature behaviour and in resistance to aqueous media and acids. Further adaptations are possible for high-pressure service or individual semiconductor-process steps.

This overview demonstrates why a high-performance sealing solution cannot be created by choosing the nominally most resistant polymer family alone. The formulation must be aligned with the dominant failure mechanism, and the relevant compromise between processing and application behaviour must be made explicit. This leads to the first requirement of the proposed concept: high-performance formulations for high-tech applications.

5 Formulation and Process Consistency

5.1 Why identical designations do not guarantee identical behaviour

Once a capable formulation has been developed, the user still needs confidence that its performance will remain available over time. A supplier's material designation can be linked to one defined formulation, but it does not have to be. Even where a defined formulation exists, changes may be made in response to processing requirements, raw-material availability or a reassessment of substances with potential health or environmental relevance.

Whether such changes must be communicated depends on the contractual agreements, the specified properties and the applicable requirements. A formally agreed initial-sample or approval process can create a higher degree of commitment. Many users with medium or small quantities, however, purchase on the basis of a standard material designation and an informative datasheet. In that situation, an unchanged designation does not necessarily prove that the formulation and long-term behaviour are unchanged.

The problem is reinforced by the nature of typical datasheets. Their values are normally measured on standard test pieces, whereas the user receives finished parts with a specific geometry and vulcanisation history. A short-term value on the datasheet may therefore remain within range even when a formulation change affects the long-term property that controls the application.

5.2 A practical hierarchy of consistency

The term "consistency" becomes clearer when it is separated into four levels. Each level answers a different question and provides a different degree of protection for the user.

Table 2: Proposed levels of consistency for elastomer sealing materials

Level	**What is controlled**	**Practical meaning for the user**
1. Designation consistency	The commercial name or material code remains unchanged.	Useful for ordering, but by itself it does not prove an unchanged formulation or long-term property profile.
2. Property consistency	Defined datasheet and, where agreed, finished-part values remain within specified limits.	Provides an observable acceptance window; the protection is limited to the selected tests and test durations.
3. Formulation consistency	Raw materials, grades and quantity ranges are controlled, and defined changes are documented or communicated.	Improves traceability and reduces the risk of hidden changes to properties not covered by the standard datasheet.
4. Process consistency	Mixing, moulding and vulcanisation conditions are controlled together with the formulation.	Supports reproducible properties in the finished part and links compound capability to actual seal production.

Defined formulation + controlled processing = reproducible property window

The formulation should therefore not be viewed in isolation from manufacturing. Even a stable compound can produce different finished-part behaviour if the degree of vulcanisation is insufficient or inconsistent. Conversely, monitoring only the finished-part hardness or a short compression-set test may not detect every formulation change. A transparent combination of formulation, process and property controls is the more robust approach.

This replaces the overly absolute statement "same material equals same formulation equals same properties" with a more technically defensible requirement: the same material designation should represent a defined and monitored formulation and process window, resulting in reproducible properties within agreed limits.

6 From Datasheets to Application-Specific Data

6.1 What a conventional datasheet can provide

A conventional elastomer datasheet remains useful. It commonly provides hardness, tensile strength, elongation at break and a compression-set value after 24 h or 72 h. Density may be included and can create a limited link to the compound composition. Low-temperature information such as a temperature retraction value at 10% recovery (TR10) or a DSC value is particularly helpful. Heat-ageing results, resistance tests in reference media such as IRM oil 903, and approvals for food, drinking water or gas applications can provide further orientation.

These values allow a first comparison between suppliers and help identify materials that meet a basic technical level. Agreeing suitable compression-set limits on finished parts can also reduce the risk associated with a supplier change. The datasheet should therefore not be discarded; its role should be understood as an entry-level description rather than a complete application model.

6.2 What is missing for design and service-life validation

The main limitations are test duration, test-piece geometry and the absence of compound-specific model data. Short tests do not necessarily reveal long-term compression set or compression-stress relaxation. A single cold indicator does not describe dynamic recovery over the complete temperature and frequency range. Reference-fluid results do not answer every question about the actual coolant, hydraulic fluid, engine oil, gas or pure oxygen used in the application.

Table 3: From a conventional datasheet to an application-oriented material database

Engineering question	**Typical datasheet contribution**	**Required compound-specific extension**
How long will a static seal retain sufficient restoring force?	Short-term compression set, usually after 24 h or 72 h.	Long-term compression-set or compression-stress-relaxation data and service-life curves with a defined failure criterion.
Will the seal recover at low temperature?	TR10 or a DSC glass-transition indicator, if available.	Dynamic mechanical analysis (DMA), multi-frequency data and an FEA-capable material model for the relevant temperature range.
Is a static gas seal suitable?	General polymer-family guidance and, occasionally, approvals.	Formulation-specific permeation coefficients for the relevant gas, temperature and pressure range.

Engineering question	Typical datasheet contribution	Required compound-specific extension
Will the material withstand the actual medium?	Short immersion tests in standard reference media.	Long-term resistance data in the actual coolant, oil, oxygen environment or other process medium.
Can supplier or batch changes be assessed?	A material designation and selected initial properties.	Traceable formulation, process and property controls together with agreed change-management criteria.

The proposed extension is therefore a database rather than merely a longer datasheet. It should connect the specific formulation to measured long-term properties, simulation parameters, permeation and media data. The database can grow step by step, provided that the underlying formulation remains defined and the validity range of each data set is stated.

6.3 A route from temperature profile to suitability assessment

For static seals whose service life is limited by ageing resistance, compound-specific service-life curves can be generated from compression-set tests [6]. The calculation becomes useful when the application owner defines a functional criterion, for example a compression set of 90%. A variable temperature profile can then be converted into an isothermal equivalent exposure and compared with the relevant service-life curve.

1. **Define the application profile.** Record the relevant temperatures and exposure times rather than relying only on a nominal maximum temperature.
2. **Define the limiting criterion.** Select the property and threshold that represent loss of function for the intended assessment, such as the stated 90% compression-set criterion.
3. **Generate the compound-specific curve.** Use long-term tests at several temperatures to describe the ageing behaviour of the actual formulation.
4. **Calculate the equivalent exposure.** Convert the application temperature history into an equivalent constant-temperature load using the formulation-specific relationship.
5. **Compare and document.** Assess whether the equivalent load remains within the validated service-life range and document the assumptions and limits of the result.

A parallel approach is available for low-temperature dynamics. FEA can be used to calculate deformation and recovery when the material model is based on DMA multi-frequency measurements [7]. The objective is not to replace physical testing, but to link formulation-specific measurements with the geometry and time-temperature conditions of the sealing system.

7 Three Requirements for "Sealing Material 2030"

The analysis can be condensed into three requirements. Together they describe a quality and data concept rather than a new polymer name.

1. **High-performance formulations for high-tech applications.** Compound design should be driven by the function and dominant failure mechanism of the application, not only by processing cost and a minimum short-term specification.
2. **Transparent formulation and process consistency.** The user should know which aspects of raw materials, formulation, mixing, moulding, vulcanisation and finished-part properties are controlled and how relevant changes are handled.
3. **Application-specific data as an extension of datasheets.** The material designation should be linked to long-term, low-temperature, simulation, permeation and media data that support selection and service-life assessment.

The three requirements are interdependent. Extensive data have limited long-term value if the formulation can change without traceability. A constant formulation is not sufficient if the processing window is uncontrolled. A perfectly controlled compound still provides no engineering advantage if the user has only a hardness value and a 24 h compression-set result. The performance benefit arises from their combination.

8 A Possible Implementation Route at OPR Elastolabs

8.1 From independent testing to compound development

The original business idea of O-Ring Prüflabor Richter, established approximately 30 years ago, was to counteract the loss of independent sealing expertise and technical support. This activity has developed into OPR Elastolabs, which accompanies users as an independent laboratory service provider, performs failure analyses, delivers advanced training up to an elastomer-expert course and offers dynamic testing of radial shaft seals (RWDRs).

The implementation concept described in the source manuscript extends this role to the development of high-quality elastomer formulations for seals and other demanding applications. The objective is to make selected high-performance formulations available independently of a single seal manufacturer while retaining suitability for established processing routes, including injection and compression moulding.

8.2 Controlled licences and an expandable data package

Before market introduction, each formulation is intended to be tested in detail for the properties that are important to its target applications. The user would receive an initial technical data package that is subsequently expanded as additional long-term, simulation, permeation or media data become available. This creates a direct link between a defined formulation and an evolving evidence base.

1. **Formulation development.** Select polymer, filler, protective system, plasticiser and crosslinking concept according to the target performance profile and processing method.
2. **Qualification.** Test the formulation beyond the minimum datasheet values and define the initial validity range of the data package.
3. **Controlled mixing licences.** Grant licences to compounders together with agreed criteria for monitoring formulation consistency.
4. **Optional process monitoring.** Where required, extend the control concept to the adequacy and consistency of vulcanisation at the seal processor.

This approach does not remove the need for application validation. It is intended to improve transparency, comparability and the technical basis for that validation. The resulting value proposition is therefore not simply a premium compound, but a defined combination of formulation, manufacturing control and application-relevant data.

9 Summary and Conclusion

The performance of an elastomer seal is determined by substantially more than the polymer-family designation and hardness. Polymer architecture, fillers, plasticisers, protective systems and crosslinking can create large differences within one family. The HNBR and EPDM examples show that these differences can affect permissible temperature, service life and low-temperature compression set by technically decisive amounts.

A robust selection process therefore requires three linked elements: a formulation designed for the application, a defined and monitored formulation and process window, and compound-specific data that extend beyond short-term datasheet values. Conventional datasheets remain useful for initial orientation, but they should be complemented by service-life curves, low-temperature material models, permeation coefficients and long-term media data where the application requires them.

In this sense, "Sealing Material 2030" is not the name of a new elastomer. It is an expanded quality and engineering concept in which formulation, consistency and data are treated as one system. Implemented consistently, this concept can provide users with a more reliable basis for material selection, supplier management, simulation and service-life assessment.

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