DUPONT™ VAMAC® ETHYLENE ACRYLIC ELASTOMER

VMX5000 SERIES PRE-COMPOUNDS

Introduction
VMX5000 Series Pre-Compounds for Improved Heat Resistance

The VMX5000 series of Vamac® pre-compounds offer superior performance for demanding applications requiring high heat resistance.

Until the introduction of the VMX5000 series, AEM compounds relied on fillers like carbon black or silica to provide strength and stiffness for a finished article. These fillers, however, accelerated oxidative degradation. VMX5000 series pre-compounds eliminate this problem by utilizing a novel filler system that actively extends the life of AEM articles exposed to hot air. Thus, finished parts based on VMX5000 series pre-compounds last up to three times longer at any given temperature compared to AEM compounds containing conventional fillers. Compounds based on the VMX5000 series are also lighter, with up to 15% lower specific gravity.

The improved heat ageing performance of VMX5000 series pre-compounds benefits automotive applications such as turbocharger hose and molded air ducts, with specific advantages for seals and gaskets applications. Compounds made with VMX5000 grades exhibit significantly improved compressive stress relaxation properties in air, as well as in long term compression set measurements.

While VMX5000 series pre-compounds may be extended with the addition of AEM elastomer, plasticizer or small amounts of conventional filler like carbon black, in some cases no additional filler may be required. VMX5000 compounds also provide a route to bright colored finished articles having superior physical properties and heat ageing resistance compared to mineral filled AEM compounds.

VMX5000 Series Product Range

As shown in Table 1, the VMX5000 series grades are available in a range of viscosities, suitable for molding, and extrusion applications. VMX5315 and VMX5394 are preferred for steam autoclave cure. VMX5394 low swell grade contains higher methyl acrylate content for better fluid resistance.

Table 1 - **Vamac® Pre-Compounds for High Heat Resistance**

Grade	ML (1+4) at 100 °C	Tg (by DSC) °C[1]	Density, g/cc	Key Feature
VMX5015	67	-30	1.07	Compression molding pre-compound[2]
VMX5020	53	-30	1.07	Injection molding pre-compound[2]
VMX5315	70	-30	1.07	Extrusion, steam autoclave curable pre-compound
VMX5394	70	-24	1.09	Low swell, steam autoclave curable pre-compound

[1] Tg of compounds with Vamac® may be extended typically – 10°C lower with the addition of plasticizer.

[2] Not suitable for steam autoclave cure.

VMX5000 series products are available in bale form, and the natural color is opaque creamy white to light pink. Bales are packaged in 23kg units with a blue strippable wrap in individual boxes. The strippable wrap must be completely removed prior to using the product. A full pallet will hold thirty individual boxes with a net weight of 690kg.

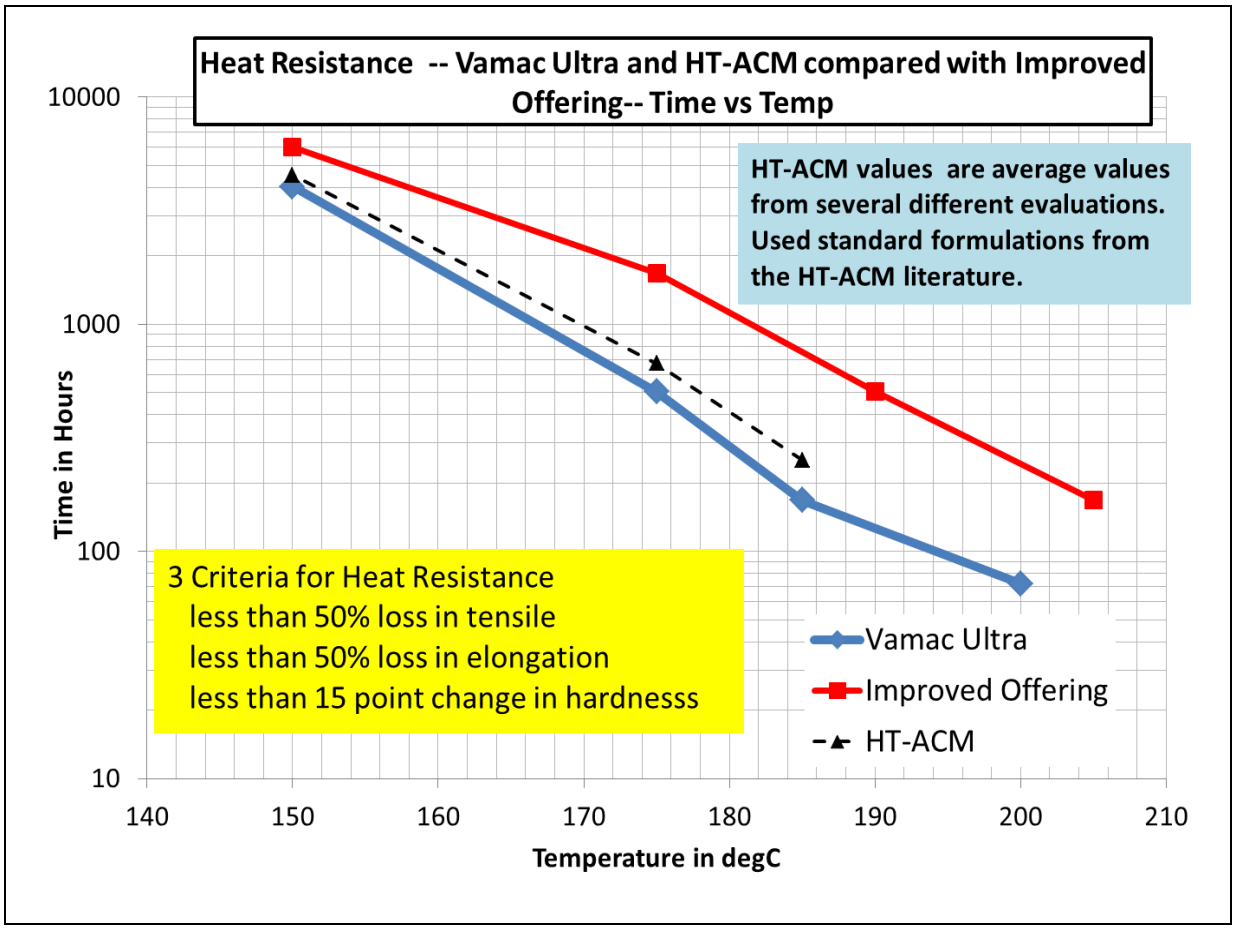
Handling Precautions

Because Vamac® VMX5000 series pre-compounds may contain small amounts of residual methyl acrylate monomer, adequate ventilation should be provided during storage and processing to prevent worker exposure to methyl acrylate vapor. Additional information may be found in the respective Vamac® 'VMX5000' product Safety Data Sheet (SDS), and bulletin, Safe Handling and Processing of Vamac® (VME-A10628), available on the DuPont website.

Improved Heat Resistance

Vamac® VMX5000 series pre-compounds offer significantly improved heat resistance over conventional carbon black filled AEM or HT-ACM. Characterization of temperature rating as a function of retention of properties in static heat ageing is shown in Figure 1. Stress-Strain property and Shore A hardness change are given as time versus temperature for the specified property retention criteria.

Figure 1 – **Temperature Rating**



Comparing VMX5000 series to black filled AEM or HT-ACM, a significant increase in temperature rating is achieved.

- 6 weeks – from 167°C to 182°C rating (+15°C)
- 3 weeks – from 175°C up to 190°C rating (+15°C)
- 1 week – from 185°C up to 205°C rating (+ 20°C)

Likewise, when the temperature is held constant, there is a significant increase in performance lifetime.

- 160°C – from 1800 hours up to 3600 hours (2 x)
- 175°C – from 504 hours up to 1680 hours (3.3 x)
- 185°C – from 168 hours up to 750 hours (4.5 x)

Improved Sealing Performance

Industry standard tests for sealing performance include compression set (CS) and compressive stress relaxation (CSR). Results of these tests for many elastomers, including AEM, can depend on sample geometry. When tested in air, a test specimen with a high surface area to volume ratio (like a D214 o-ring) experiences greater oxidation, and therefor, greater degradation of sealing properties than large specimen like an ASTM D395 type 1 button. Because many seals have small sealing beads, CS and CSR tests using large specimens can mask performance issues that may arise from in-service oxidation.

The improved heat ageing performance of VMX5000 pre-compounds therefore has significant benefit on long term compression set resistance, especially when tested using ISO buttons, or D214 o-rings. Figure 2 shows compression set results for 60 Shore A hardness compounds of VMX5020 / Vamac® Ultra IP blends with either carbon black (15phr) or red pigment (for colored compound), compared to a conventional carbon black filled Vamac® Ultra LS compound.

While all the compounds perform about equally when testing ISO buttons at 168 hours/170°C, the VMX5000 compound outperforms the black-filled Ultra LS compound when the test time extends to 1008 hours, or when the specimen is switched to a D214 O-ring under conditions of 168 hours/180°C. Note the VMX5000 series compounds can tolerate small amounts of filler added for color or increasing hardness (typically by less than 10 points Shore A) without adversely affecting compression set or hot air aging properties.

Figure 2 – **Long Term Compression Set Resistance**

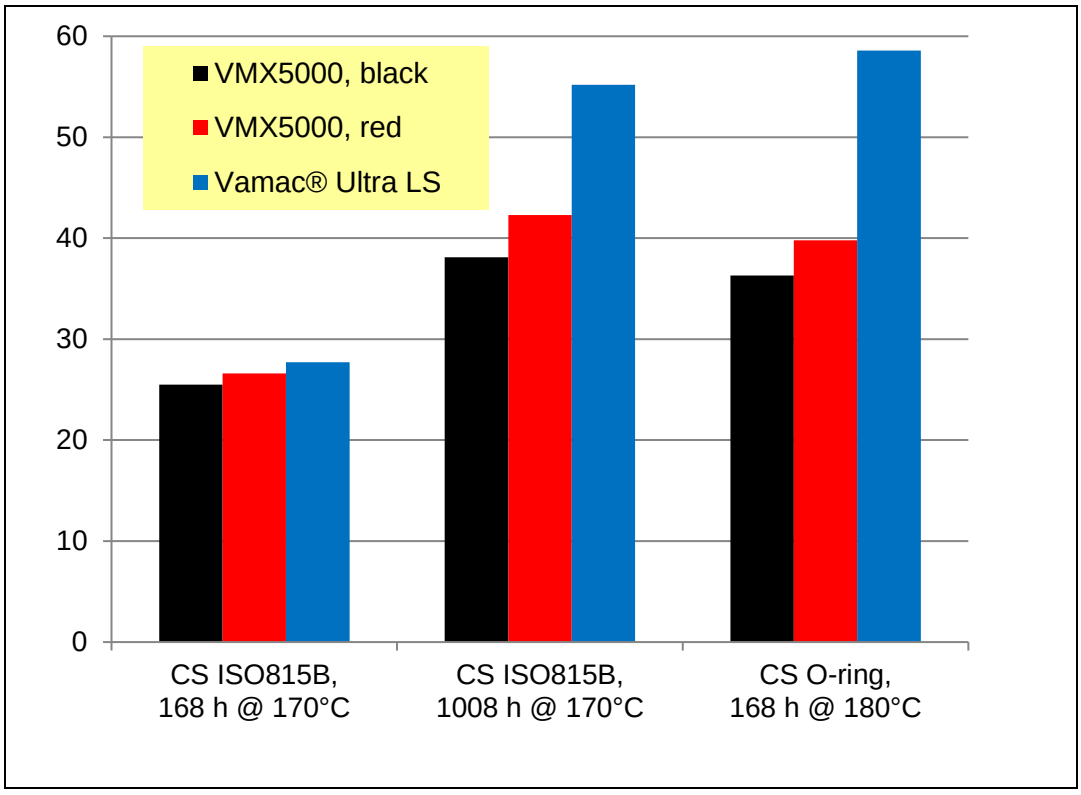
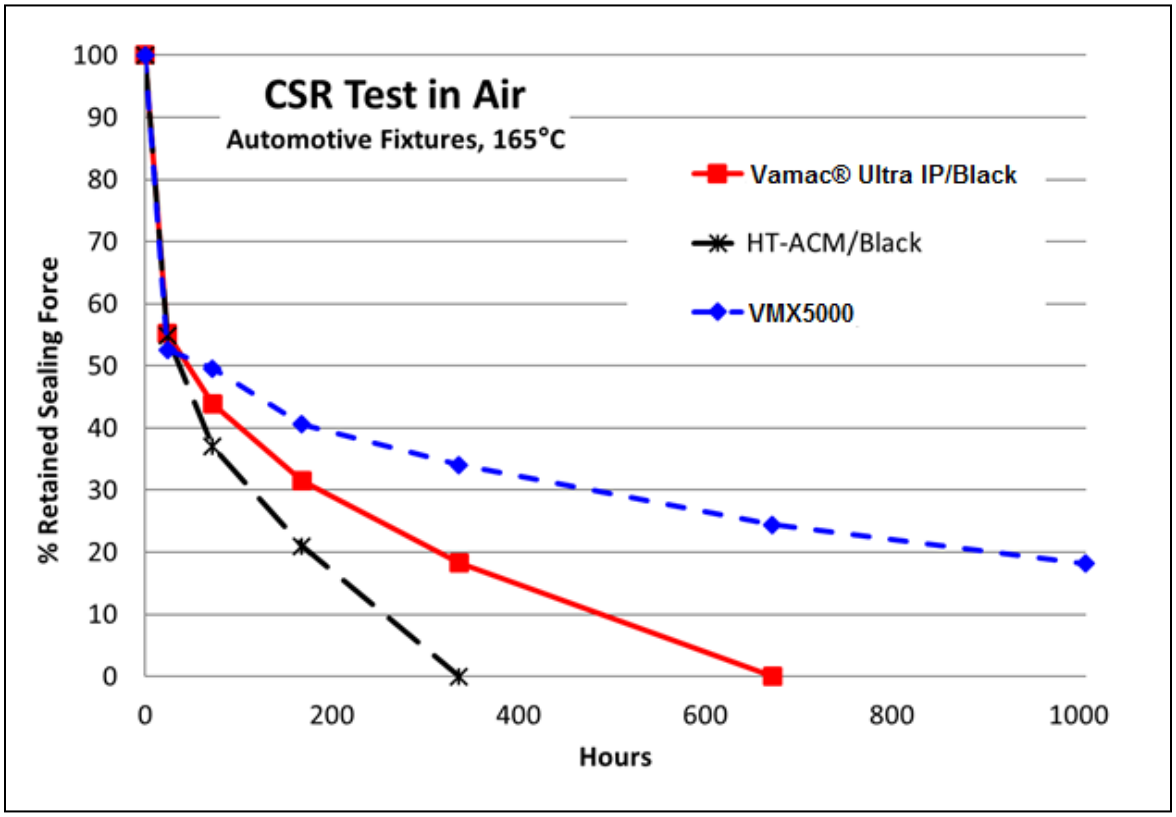


Figure 3 shows compressive stress relaxation testing of ISO buttons in hot air for carbon black filled compounds of Vamac® Ultra IP, HT-ACM, and a VMX5000 compound containing 2phr N550 carbon black for color. The superior oxidative stability of the VMX5000 compound results in dramatically improved CSR performance.

Figure 3 – **CSR in Hot Air**



Compounding VMX5000 Series Pre-Compounds

VMX5000 series compounds optimally contain about 20% lower Diak™1 levels than conventional AEM compounds, and use 4-aminodiphenylamine (ADPA) as the anti-oxidant. The preferred diarylamine anti-oxidants for carbon black or silica filled AEM compounds, like IPPD or Naugard® 445, do not perform as well in the VMX5000 series.

Table 2 shows starting point recipes where the amount of VMX5000 series pre-compound is set so that the compound comprise 100phr total AEM. As desired, additional AEM polymer may be added along with the VMX5000 pre-compound to adjust hardness or cure speed. Vamac® Ultra HT, Ultra IP, and GXF are suitable diluents. Vamac® Ultra IP provides faster curing. For compounds that may be steam autoclave cured, VMX5315 or VMX5394 are recommended.

Table 2 –**Starting Recipes for VMX5000**

Ingredient (phr)	75 ShA hose	60 ShA gasket
VMX5000 Grade	181.8	118
AEM (diluent)		36
Diak™1	0.5 to 0.6	0.6 to 1.0
Vulcofac® ACT-55	1	0 to 2
Alcanpoudre® DBU-70		0 to 2
Armeen® 18D	0.5	0 to 0.5
Stearic Acid	0 to 0.5	0 to 0.5
ADPA*	0.5 to 1.5	0.5 to 1.5
Plasticizer**	2 to 5	0 to 0.5
Vanfre® VAM	1	1
Carbon Black	2	2

* 4-aminodiphenyl amine, is available from ChemSpec or Safic Alcan as ADPA

** Alcanplast® PO80, TegMer® 812, or similar

Fatigue resistance is optimized at 0.55phr or less of Diak™ 1, and ISO compression set is optimized at 0.8phr. VW compression set improves up to and beyond 1.0phr, although heat resistance worsens at Diak™1 levels greater than 1.0phr.

Use at least 1phr accelerator, noting that Vulcofac® ACT-55 is a weaker accelerator than Alcanpoudre® DBU-70. Better release and faster cure may be achieved for molded compounds using 1.5 to 2phr DBU-70.

ADPA is the preferred anti-oxidant for VMX5000 pre-compounds, and also provides added scorch protection along with Armeen® 18D. For bright compounds, staining diaryl amine AO like ADPA or Naugard® 445 are not desirable.

Low volatile plasticizers may be used up to 10phr, depending on the low temperature requirements.

Low levels of carbon black (any type) may be used as a colorant without negatively impacting properties.

For compounds of Vamac® with conventional non-black inorganic fillers such as silica, clay or calcium carbonate, physical properties and rheology are inferior to carbon black filled compounds in terms of processing, and compression set.

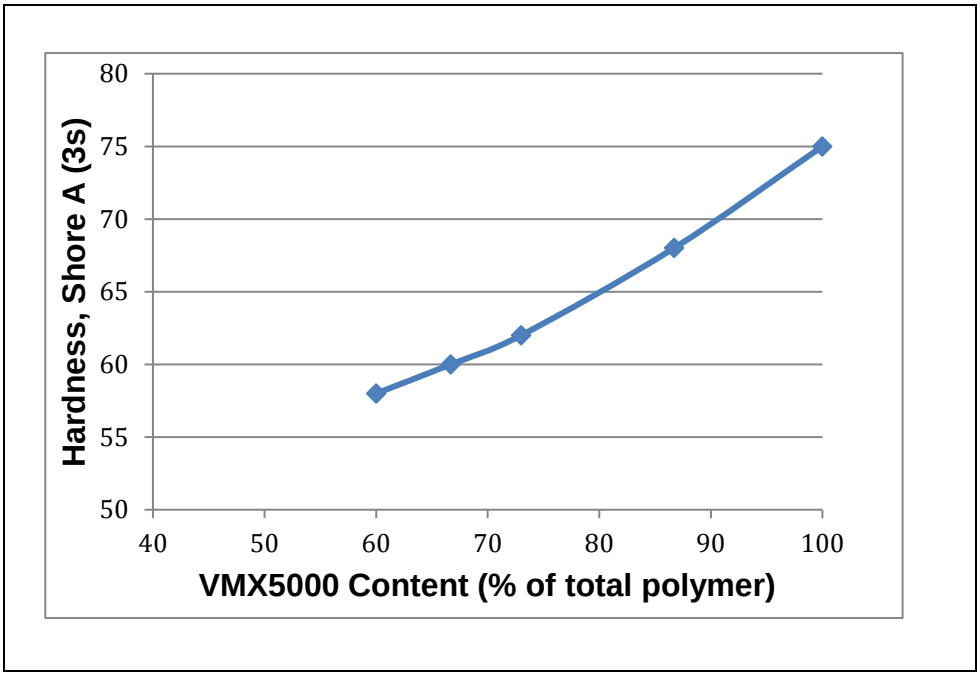
The VMX5000 pre-compounds already contain a non-black filler system, and exhibits excellent properties for heat ageing, and compression set. This makes the VMX5000 series suitable for use of AEM in colored compounds for differentiation of parts and optical control. While non-staining anti-oxidants, like Irganox® 1010 and Ultranox® 626, may be used with VMX5000, ADPA is preferred for the best heat resistance. The ADPA will darken with oxidation.

Formulating for Different Hardness Level

VMX5000 series pre-compounds contain filler level for a hardness of approximately 75 Shore A after vulcanization. To achieve lower hardness levels, unfilled Vamac® AEM polymer must be added to dilute and reduce the overall filler level. Figure 4 exhibits a profile of hardness range between 55 to 75 Shore A (3 sec) for VMX5015 / Vamac® Ultra IP blends in a compound formulation and curative package typical for a sealing application. Further modification can be achieved by changing curative, supplemental filler, and plasticizer level. Dilution of VMX5000 pre-compounds may be extended to provide compounds of low hardness level (37 to 47 Shore A) with relatively good properties, and processing, which is difficult to achieve with conventional black filled compounds.

Figure 4 – **AEM Blends with VMX5000 Series for Lower Hardness Compounds**

Example (%): VMX5015 = 73%, Vamac® Ultra IP = 27%, ADAP = 0.93%, Stearic Acid = 0.33%, Vanfre® VAM = 0.67%, Diak™ 1 = 0.67%, Alcanpoudre® DBU-70 =1.33% for a hardness (3s) of 62 Shore A.



Higher hardness compounds (>75 Sh A) may be achieve with addition of supplemental filler.

Compound Comparison of Four VMX5000 Grades (65-70 Shore A)

The following tables compare the four VMX5000 grades versus a black filled Vamac® Ultra LS compound. Two variations of red colored compounds with VMX5020 are included. The later compound is a blend of VMX5020, and Vamac® Ultra LS with higher Diak™ 1 level.

Table 3 – **Compound Formulation for Comparison of All Four VMX5000 Grades**

Compound Ingredient (phr)	Vamac® Ultra LS Reference	VMX 5015	VMX 5020	VMX 5315	VMX 5394	VMX 5020, red	VMX 5020 / Ultra LS, red
Vamac® Ultra IP	100	17.5	17.5	17.5	17.5	17.5	
Vamac® Ultra LS							17.5
Vamac® VMX5015		150					
Vamac® VMX5020			150			150	150
Vamac® VMX5315				150			
Vamac® VMX5394					150		
Alcanpoudre® ADPA 75		1.5	1.5	1.5	1.5	1.5	1.5
Naugard® 445	2						
Armeen® 18D PRILLS	0.5						
Stearic Acid	2	0.5	0.5	0.5	0.5	0.5	0.5
Vanfre® VAM	1	1	1	1	1.5	1	1
Ultrasil® VN2						10	10
Alcanpoudre® A1100 70						0.25	0.25
Ferroxide 214 M						1.5	1.5
Spheron™ SOA (N550)	20						
Corax® N772	50						
MT Thermax® Floform N990		20	20	20	20		
Alcanplast® PO 80	10	7	7	7	7	7	7
Diak™ 1	1.4	0.9	0.9	0.9	0.9	0.8	0.9
Vulcofac® ACT-55	2	2	2	2	2	2	2

Mooney viscosity of the VMX5020 injection molding compound is the lowest among the 5000 series. MDR MH is relatively lower, and cure times are longer generally for the lower swell, higher methyl acrylate containing VMX5394 grade.

Table 4 – Comparison Study Rheology

Rheology	Vamac® Ultra LS Reference	VMX 5015	VMX 5020	VMX 5315	VMX 5394	VMX 5020, red	VMX 5020 / Ultra LS, red
Mooney Viscosity ML 1+4 at 100°C (ISO 289-1:2005)							
Initial Mooney [MU]	70.8	87.0	70.7	99.9	93.7	89.7	89.8
Final Mooney [MU]	49.2	56.2	45.6	57.1	54.6	47.5	49.8
Slope [lg M/g s]	-0.609	-0.653	-0.605	-0.586	-0.61	-0.667	-0.553
Intercept Mooney [MU]	13.5	13.6	11.8	15.1	14.2	11.6	14.0
MDR cure rate 15 minutes at 180°C, arc 0.5° (ISO 6502:1999)							
ML [dNm]	0.65	0.69	0.52	0.82	0.64	0.54	0.65
MH [dNm]	16.45	15.03	12.40	14.94	13.37	13.28	12.19
Ts1 [min]	0.62	0.78	0.84	0.77	0.90	0.90	0.92
Ts2 [min]	0.86	1.03	1.14	1.02	1.23	1.24	1.30
T10 [min]	0.76	0.89	0.90	0.87	0.98	0.99	0.98
T50 [min]	2.46	2.58	2.56	2.62	3.06	3.00	3.10
T90 [min]	7.66	7.25	6.69	7.47	8.53	8.02	8.56
T95 [min]	9.99	9.18	8.53	9.43	10.57	10.02	10.63
Tan delta at ML	1.108	1.101	1.077	0.963	1.078	1.167	0.954
Tan delta at MH	0.009	0.045	0.047	0.038	0.041	0.047	0.049
Peak rate [dNm/min]	6	6	5	6	5	5	4
Mooney Scorch 45 min at 121°C (ISO 289-2:1994)							
Initial Mooney [MU]	27	41	30	37	40	29	32
Minimum Mooney [MU]	17	20	17	21	18	17	19
Ts1 [min]	5.6	8.3	6.6	7.0	7.9	7.0	6.0
Ts2 [min]	7.0	9.9	7.8	8.2	9.5	8.2	6.9
T5 [min]	10.2	13.7	10.2	10.8	13.1	11.1	8.6
T10 [min]	13.7	17.4	12.6	13.4	16.6	14.0	10.6
T35 [min]	25.0	35.2	32.2	26.3	39.8	26.4	24.1
Point rise at 30 min		31.5	33.9		28.6		

Table 5 – **Comparison Study Original Properties**

Original Properties	Vamac® Ultra LS Reference	VMX 5015	VMX 5020	VMX 5315	VMX 5394	VMX 5020, red	VMX 5020 / Ultra LS, red
Compression molding 10 minutes at 180°C / Post-cure 4 hours at 175°C							
Hardness (ISO 7619-1:2004)							
Hardness Shore A, 3s	71.9	65.7	64.4	64.7	66.8	66	65.2
Hardness Shore A, 1s	73.5	67.9	66.2	66.9	68.9	67.7	67.2
Tensile Properties (type 2) at 23°C							
Tensile Strength [MPa]	19.0	17.4	13.4	19.8	15.1	11.5	10.6
Elongation at Break [%]	270	240	238	262	243	184	201
Modulus at 10 % [MPa]	0.67	0.58	0.52	0.56	0.58	0.56	0.55
Modulus at 25 % [MPa]	1.29	1.05	1.00	1.01	1.16	1.05	1.00
Modulus at 50 % [MPa]	2.4	2.1	1.9	2.0	2.3	1.9	1.8
Modulus at 100 % [MPa]	6.1	5.8	4.9	5.5	5.4	5.0	4.6
Modulus at 200 % [MPa]	14.8	15.1	12.0	15.1	13.0		10.7
Trouser Tear, Propagation Direction: Mill (ISO 34-1:2004)							
Tear Strength - type A	5.5	2.6	2.9	3.9	3.0	2.6	2.8
Tg [°C]	-36.0	-35.0	-34.4	-35.0	-28.0	-33.8	-33.9

Tensile Properties T2 at 150°C (ISO 37:2005, Cor 1 2008)							
Tensile Strength [MPa]	6.3	6.0	5.3	6.4	5.9	3.9	3.8
Elongation at Break [%]	110	179	146	151	153	112	114
Modulus at 10 % [MPa]	0.57	0.40	0.36	0.41	0.40	0.38	0.36
Modulus at 25 % [MPa]	1.17	0.82	0.74	0.83	0.85	0.77	0.73
Modulus at 50 % [MPa]	2.25	1.58	1.41	1.63	1.69	1.45	1.35
Modulus at 100 % [MPa]	5.7	3.7	3.3	3.8	3.8	3.5	3.2

The conventional carbon black reference AEM compound exhibits more hardening, and greater loss of properties than the VMX5000 compounds.

Table 6 – **Comparison Study Heat Ageing**

Heat Ageing	Vamac® Ultra LS Reference	VMX 5015	VMX 5020	VMX 5315	VMX 5394	VMX 5020, red	VMX 5020 / Ultra LS, red
Heat Ageing 1008 hours at 150°C							
Hardness Shore A, 3s	74.0	66.3	65.0	68.8	66.9	65.1	64.7
Delta Hardness	2.2	0.6	0.4	3.6	-1.0	-0.7	-0.7
Tensile Strength [MPa]	16.6	12.4	9.3	15.5	12.9	10.1	10.1
Delta TS [%]	-12.6	-28.9	-30.8	-21.7	-14.8	-12.3	-5.2
Elongation at Break [%]	230	216	222	214	203	217	226
Delta Elong. [%]	-14.8	-10.0	-6.7	-18.3	-16.5	17.9	12.4
Modulus at 50 % [MPa]	3.0	2.3	2.0	2.3	2.5	2.4	2.0
Delta 50% [%]	23.4	11.2	4.7	15.3	11.4	25.0	8.3
Modulus at 100 % [MPa]	6.8	5.5	4.8	6.1	6.0	4.9	4.9
Delta 100% [%]	11.7	-5.6	-2.3	10.8	11.7	-2.0	7.9
Modulus at 200 % [MPa]	14.9	12.0	9.2	14.6	12.8	9.9	9.6
Delta 200% [%]	0.9	-20.2	-22.8	-3.5	-1.8		-10.5
Heat Ageing 1008 hours at 175°C							
Hardness Shore A, 3s	93.3	61.8	62.6	63.9	63.5	62.5	63.5
Delta Hardness	21.4	-3.8	-1.8	-1.3	-3.5	-3.2	-1.9
Tensile Strength [MPa]	9.4	12.1	11.4	9.1	12.7	9.9	9.1
Delta TS [%]	-50.5	-30.2	-15.0	-54.3	-16.1	-14.3	-13.9
Elongation at Break [%]	37	175	158	128	185	140	127
Delta Elong. [%]	-86.3	-27.1	-33.6	-51.2	-23.9	-23.9	-36.8
Modulus at 50 % [MPa]		1.6	1.7	1.7	1.8	1.4	1.6
Delta 50% [%]		-24.8	-13.1	-13.3	-22.4	-26.0	-11.1
Modulus at 100 % [MPa]		5.2	5.6	5.9	5.2	5.4	5.8
Delta 100% [%]		-10.1	14.8	6.9	-3.9	8.4	27.5

Long term compression set at 160 to 170°C are lower for the VMX5000 compounds, and is less impacted over time when cooled in the clamps compared to the black reference AEM compound. Compression set for the lower swell VMX5394 (higher methyl acrylate) pre-compound is highest among the VMX5000 series.

VW compression set can be made lower than what is shown for this study using higher Diak™ 1. VMX5015, and VMX5315 are shown best among the VMX5000 series in VW compression set.

Table 7 – **Comparison Study Compression Set**

Compression Set	Vamac® Ultra LS Reference	VMX 5015	VMX 5020	VMX 5315	VMX 5394	VMX 5020, red	VMX 5020 / Ultra LS, red
Compression Set – type B (ISO 815-1:2008)							
70 hours / 150°C [%]	21.5	22.6	25.1	21.2	23.3	28.0	30.5
504 hours / 160°C [%]	49.1	41.1	40.6	41.2	48.1	45.3	48.0
1008 hours / 160°C [%]	58.0	45.0	44.8	47.7	55.5	49.3	52.9
504 hours / 170°C [%]	52.3	47.9	47.1	49.3	58.1	51.3	53.9
504 hours / 180°C [%]	56.3	54.2	54.0	54.8	66.7	56.0	60.5
Compression Set – type B (ISO 815-1:2008), cooled in clamps for 2h							
24h / 150°C [%]	22.7	30.6	32.8	28.5	33.8	36.4	37.3
1008h / 150°C [%]	58.7	53.6	53.5	53.2	60.3	59.0	61.5
Compression Set VW (PV 3307:2004-08), 72 hours at 23°C							
at 5 seconds [%]	24.8	35.6	45.0	36.1	46.2	47.0	48.1
at 30 minutes [%]	8.4	7.5	9.4	7.7	9.7	10.5	10.3
Compression Set VW (PV 3307:2004-08), 22 hours at 150°C							
at 5 seconds [%]	46.2	60.5	69.7	58.6	67.4	73.8	71.8
at 30 minutes [%]	30.1	32.8	40.3	32.0	36.3	46.8	45.7
Deflection [%]	51	50	49	50	50	50	49

Table 8 – **Comparison Study Fluid Ageing with Oil**

Fluid Ageing: Reference and Engine Oil	Vamac® Ultra LS Reference	VMX 5015	VMX 5020	VMX 5315	VMX 5394	VMX 5020, red	VMX 5020 / Ultra LS, red
Ageing 1008 hours at 150°C, Aeroshell Oil Diesel Ultra, 5W-30							
Compression Set – type B (ISO 815-1:2008), cooled in clamps for 2h							
CSet, 1008h / 150°C [%]	46.6	51.3	48	49.3	62.8	52.8	58.8
Hardness Shore A, 3s	72.5	62.0	60.2	63.9	69.4	63.2	63.1
Delta Hardness	0.8	-3.8	-4.1	-1.1	2.5	-2.7	-2.1
Tensile Strength [MPa]	13.5	15.3	12.2	18.7	15.1	11.8	12.5
Delta TS [%]	-28.9	-12.2	-9.1	-5.7	-0.1	2.5	17.6
Elongation at Break [%]	139	174	173	183	218	154	154
Delta Elong. [%]	-48.5	-27.5	-27.3	-30.2	-10.3	-16.3	-23.4
Modulus at 25 % [MPa]	1.8	1.1	1.0	1.1	1.7	1.1	1.1
Delta 25% [%]	37.2	1.0	3.0	12.9	43.1	1.0	13.0
Modulus at 50 % [MPa]	3.5	2.5	2.2	2.6	3.3	2.2	2.4
Delta 50% [%]	44.8	18.9	13.1	33.7	43.9	15.6	31.5
Modulus at 100 % [MPa]	9.1	7.1	5.8	7.6	7.8	6.4	6.9
Delta 100% [%]	49.8	22.9	19.8	37.5	45.1	26.9	49.6
Weight Change [%]	3.8	5.4	4.4	5.0	0.9	5.6	3.8
Volume Change [%]	6.7	7.4	6.1	7.0	1.7	7.7	5.5

Ageing 1008 h, 150°C, Lubrizol OS 206304							
Compression Set – type B (ISO 815-1:2008), cooled in clamps for 2h							
CSet, 1008h / 150°C [%]	31.1	36.0	38.2	53.7	53.5	41.3	48.4
Hardness Shore A, 3s	67.9	58.6	57.8	60.6	65.4	59.2	59.3
Delta Hardness	-3.9	-7.1	-6.6	-4.6	-1.6	-6.6	-5.9
Tensile Strength [MPa]	17.3	15.4	12.4	16.8	15.4	10.6	11.3
Delta TS [%]	-8.8	-11.2	-7.1	-15.4	1.8	-7.6	6.6
Elongation at Break [%]	173	181	188	179	180	147	151
Delta Elong. [%]	-35.9	-24.6	-21.0	-31.7	-25.9	-20.1	-24.9
Modulus at 25 % [MPa]	1.4	0.8	0.9	1.0	1.4	0.9	0.9
Delta 25% [%]	10.1	-20.0	-13.0	-5.9	17.2	-10.5	-10.0
Modulus at 50 % [MPa]	3.1	2.0	1.9	2.3	2.9	2.1	2.0
Delta 50% [%]	29.3	-2.4	1.6	19.4	25.9	7.3	11.1

Modulus at 100 % [MPa]	8.5	6.4	5.5	7.2	7.2	6.2	6.1
Delta 100% [%]	40.0	11.3	12.8	30.2	33.6	22.9	33.0
Weight Change [%]	9.3	11.7	11.2	11.4	5.6	11.7	9.5
Volume Change [%]	13.9	14.7	14.0	14.5	7.2	14.9	12.5

Table 9 – Comparison Study Fluid Ageing with 10% FAM-B

Fluid Ageing: Reference Oil + 10% FAM-B	Vamac® Ultra LS Reference	VMX 5015	VMX 5020	VMX 5315	VMX 5394	VMX 5020, red	VMX 5020 / Ultra LS, red
Fluid ageing 168 hours at 150°C in Lubrizol® OS 206304 +10% FAM-B (ISO 1817:2011) in Autoclave							
Hardness Shore A, 3s	59.8	55.2	52.4	55.7	59.3	52.8	52.5
Delta Hardness	-12.1	-10.6	-12.2	-9.5	-7.6	-12.9	-12.4
Tensile Strength [MPa]	13.2	14.0	10.5	16.5	14.1	8.6	8.0
Delta TS [%]	-30.3	-19.3	-21.5	-16.8	-6.6	-25.2	-25.0
Elongation at Break [%]	190	193	195	206	219	145	149
Delta Elong. [%]	-29.6	-19.6	-18.1	-21.4	-9.9	-21.2	-25.9
Modulus at 10 % [MPa]	0.3	0.3	0.3	0.3	0.5	0.3	0.3
Delta 10% [%]	-49.3	-41.4	-44.2	-39.3	-19.0	-42.9	-40.0
Modulus at 25 % [MPa]	0.9	0.8	0.7	0.7	1.0	0.7	0.7
Delta 25% [%]	-32.6	-28.6	-35.0	-26.7	-13.8	-33.3	-30.0
Modulus at 50 % [MPa]	2.1	1.7	1.4	1.7	2.1	1.6	1.5
Delta 50% [%]	-13.0	-17.0	-24.6	-12.8	-7.9	-18.2	-17.7
Modulus at 100 % [MPa]	6.2	5.1	4.1	5.2	5.3	4.8	4.3
Delta 100% [%]	2.3	-12.0	-16.1	-5.3	-1.9	-5.0	-6.6
Modulus at 200 % [MPa]			10.9	15.4	13.0		
Delta 200% [%]			-8.7	1.9	-0.6		
Weight Change [%]	12.5	12.4	11.8	12.2	6.6	14.6	12.6
Volume Change [%]	20.2	17.7	17.0	17.5	10.2	20.5	17.9

Table 10 – **Comparison Study Fluid Ageing with Blow-By Condensate**

Fluid Ageing: Blow-By Condensate	Vamac® Ultra LS Reference	VMX 5015	VMX 5020	VMX 5315	VMX 5394	VMX 5020, red	VMX 5020 / Ultra LS, red
Fluid ageing 24 hours at 120°C in Blow-By Condensate (ISO 1817:2011), in Autoclave							
Hardness Shore A, 3s	69.1	62.8	59.8	62.1	60.3	64.4	61.8
Delta Hardness	-2.6	-2.9	-4.3	-3.1	-6.6	-1.4	-3.4
Tensile Strength [MPa]	14.5	12.9	11.6	13.6	13.0	10.8	9.5
Elongation at Break [%]	253	239	238	255	247	208	194
Modulus at 50 % [MPa]	2.3	1.6	1.5	1.5	1.7	1.5	1.4
Modulus at 100 % [MPa]	5.8	3.7	3.5	3.6	4.0	3.7	3.6
Weight Change [%]	0.6	5.2	5.8	4.9	5.3	NaN	NaN
Volume Change [%]	0.7	6.1	6.9	6.0	6.4	NaN	NaN

Drying - Blow-By Condensate, BMW - GS 97018							
Hardness Shore A, 3s	70.1	66.8	63.9	65.2	66.4	66.5	66.5
Delta Hardness	-1.8	1.2	-0.5	0.0	-0.6	0.7	1.3
Tensile Strength [MPa]	18.5	16.6	13.9	17.9	14.5	11.5	12.4
Elongation at Break [%]	259	238	235	251	230	199	196
Modulus at 50 % [MPa]	2.6	2.0	1.7	2.0	2.1	1.9	2.0
Modulus at 100 % [MPa]	6.9	4.9	4.3	5.0	5.1	4.7	5.2
Weight Change [%]	-0.2	0.1	0.1	0.1	0.2	-0.5	-0.6
Volume Change [%]	0.0	0.0	0.2	0.1	0.2	-0.8	-0.9

Table 11 – **Comparison Study of Fluid Ageing with AdBlue®**

Fluid Ageing: AdBlue® (32% Urea Solution in Water)	Vamac® Ultra LS Reference	VMX 5015	VMX 5020	VMX 5315
Fluid ageing 168 hours at 130°C in Adblue® (registered trademark of BASF) ISO 1817:2011, in Autoclave				
Hardness Shore A, 3s	61.8	65.4	60.9	64.4
Delta Hardness	-10.1	-0.3	-3.5	3.2
Tensile Strength [MPa]	18.3	12.7	11.8	12.9
Delta TS [%]	-3.3	-27.0	-11.7	-35.0
Elongation at Break [%]	202	343	386	339
Delta Elong. [%]	-25.2	42.9	62.2	29.4

Modulus at 50 % [MPa]	2.9	2.4	2.0	2.8
Delta 50% [%]	23.0	18.0	5.2	43.4
Modulus at 100 % [MPa]	8.3	4.5	3.4	4.8
Delta 100% [%]	36.7	-22.9	-29.6	-13.1
Weight Change [%]	33.1	25.0	29.1	29.4
Volume Change [%]	35.8	24.9	29.3	29.5

Higher Hardness Compounds – 70 to 80 Shore A

Formulating VMX5000 pre-compounds with additional filler allows for producing higher hardness compounds. The following study is made to further show the effect of carbon black filler type and level on VMX5015, and VMX5020 compounds, and compared with conventional black-filled AEM compounds for applications like bonded piston seals.

Table 12 – **Compound Formulations with Added Carbon Black**

Compound Formulation	G	G / GLS	Ultra IP / GXF	Ultra IP / GLS	Ultra IP / Ultra LS	5015, FEF	5020, FEF	5020, SRF	5020, MT	5020, low MT, high DIAK
Vamac® G	100	50								
Vamac® GLS		50		50						
Vamac® Ultra IP			50	50	50					
Vamac® GXF			50							
Vamac® Ultra LS					50					
Vamac® VMX 5015						182				
Vamac® VMX 5020							182	182	182	182
Alcanpoudre® ADPA 75						1.5	1.5	1.5	1.5	1.5
Naugard® 445	2	2	2	2	2					
Armeen® 18D PRILLS	0.8	0.8	0.8	0.8	0.8					
Stearic Acid Reagent	2	2	2	2	2					
Vanfre® VAM	1	1	1	1	1	1	1	1	1	1
Spheron™ SOA (N550)	25	25	25	25	25	15	15			
Corax® N772	60	60	60	60	60			20		
MT Thermax® N990									25	15
Alcanplast® PO 80	10	10	10	10	10	7	7	7	7	7
Diak™ no 1	1.5	1.5	1.5	1.5	1.3	0.9	0.9	0.9	0.9	1.2

No scorch retarder was added to the VMX5000 compounds for this study. The addition of Armeen® 18D would reduce viscosity, lower scorch times, and slow cure speed.

Table 13 – **Higher Hardness Compounds, Rheology**

Rheology	G	G / GLS	Ultra IP / GXF	Ultra IP / GLS	Ultra IP / Ultra LS	5015, FEF	5020, FEF	5020, SRF	5020, MT	5020, low MT, high DIAK
Mooney, ML 1+4 at 100°C										
Initial Mooney [MU]	61.7	63.1	78.6	76.3	91.9	121.3	90.9	112.1	99.9	95.4
Final Mooney [MU]	42.7	41.2	55.1	54.0	62.3	76.8	60.3	60.7	58.6	53.7
MDR, 12 min, 180°C, arc 0.5°										
ML [dNm]	0.63	0.65	0.82	0.84	0.97	1.02	0.74	0.79	0.74	0.59
MH [dNm]	15.91	15.04	16.83	16.93	16.82	17.85	15.29	14.65	13.95	15.99
Ts1 [min]	0.58	0.56	0.64	0.55	0.58	0.76	0.80	0.82	0.81	0.90
Ts2 [min]	0.82	0.78	0.92	0.76	0.80	1.00	1.08	1.10	1.11	1.25
T10 [min]	0.70	0.66	0.81	0.68	0.71	0.94	0.94	0.92	0.91	1.09
T50 [min]	2.25	2.08	2.84	2.14	2.27	2.94	2.76	2.76	2.66	3.51
T90 [min]	6.67	6.85	8.06	6.93	7.17	8.20	6.86	7.03	6.69	8.86
Tan delta at MH	0.043	0.049	0.056	0.048	0.057	0.081	0.078	0.080	0.082	0.063
Peak rate [dNm/min]	6	6	5	7	6	6	5	5	5	4
Mooney Scorch 45 min at 121°C										
Initial Mooney [MU]	23	21	29	26	32	47	35	39	38	37
Minimum Mooney [MU]	16	15	19	19	22	27	22	23	22	20
Ts1 [min]	4.5	4.5	5.9	4.7	5.5	7.8	5.8	6.0	5.9	7.1
Ts2 [min]	5.6	5.4	7.3	5.7	6.8	9.4	6.7	6.8	6.7	8.2
T5 [min]	7.9	7.4	10.7	7.8	9.8	13.2	8.8	8.6	8.3	10.5
T10 [min]	10.5	9.7	14.9	10.4	13.3	17.7	11.0	10.6	10.2	13.2

Hardness of VMX5000 compounds may be adjusted by varying the addition of carbon black, and carbon black type. The VMX5000 series exhibit significantly lower IRHD hardness than conventional carbon black filled AEM compounds, especially VMX5020.

Table 14 – **Higher Hardness Compounds, Original Properties**

Original Properties	G	G / GLS	Ultra IP / GXF	Ultra IP / GLS	Ultra IP / Ultra LS	5015, FEF	5020, FEF	5020, SRF	5020, MT	5020, low MT, high DIAK
Compression Molding 10 minutes at 180°C, Post-cure 4 hours at 175°C										
Initial Specific Gravity [g/cm³]	1.27	1.28	1.27	1.28	1.28	1.12	1.12	1.13	1.14	1.12
Hardness Sh A, 1s	80.3	81.5	81.1	80.5	80.8	79.1	73.6	74.4	72.8	72.1
Hardness Sh A, 3s	79.3	80.4	80.1	79.8	79.7	77.7	72.0	72.8	71.1	70.6
Hardness IRHD (Method N, ISO48:2007)	79.5	79.5	80.7	80.0	79.8	74.9	68.2	68.9	67.0	67.5
Tensile properties (type 2) at 23°C, ISO 37:2005 Cor 1 2008										
Tensile Strength [MPa]	16.4	16.4	17.3	16.7	17.7	18.6	14.7	14.8	15.0	18.3
Elong at Break [%]	179	174	203	184	230	190	199	194	231	207
Mod at 10 % [MPa]	1.2	1.1	1.0	1.2	1.1	0.9	0.8	0.8	0.7	0.7
Mod at 25 % [MPa]	2.2	2.1	1.9	2.3	2.1	1.9	1.5	1.6	1.5	1.6
Mod at 50 % [MPa]	4.2	4.0	3.4	4.4	3.7	4.0	3.1	3.1	2.9	3.1
Mod at 100 % [MPa]	9.3	9.3	8.3	9.8	8.4	9.5	7.4	7.4	6.6	7.6
Tear strength type A - Trouser test pieces (Tear propagation direction: mill), ISO 34-1:2004										
Tear strength [kN/m]	5.4	4.2	4.8	5.6	5.2	5.7	4.0	3.5	4.2	4.4

Table 15 – **Higher Hardness Compounds, Compression Set**

Compression Set	G	G / GLS	Ultra IP / GXF	Ultra IP / GLS	Ultra IP / Ultra LS	5015, FEF	5020, FEF	5020, SRF	5020, MT	5020, low MT, high DIAK
Compression Set, ISO 815-1, type B										
70 h at 150°C [%]	26	31	24	27	25	25	27	27	33	25
504 h at 160°C [%]	49	52	49	49	50	43	44	42.	42	37
504 h at 170°C [%]	56	55	52	50	50	51	52	51	50	46
504 h at 180°C [%]	66	69	62	62	61	61	61	60	57	57

504 h at 190°C [%]	86	88	81	79	78	70	70	71	70	67
Compression Set, ISO 815-1:2008 (DBL 6038), plied – cooled in the clamps 2h										
1008 h at 150°C [%]	67	69	62	64	66	48	48	47	47	40

Compression Set VW (PV 3307:2004-08), 22h at 150°C										
after 5 sec. [%]	41	48	43	44	41	49	62	65	59	43
after 30 min [%]	31	35	29	36	28	28	38	40	33	26
Compression Set VW (PV 3307:2004-08), 72h at 23°C										
after 5 sec. [%]	28	32	25	28	31	36	43	45	42	26
after 30 min [%]	10	11	9	10	11	8	10	10	4	7

Six week air oven ageing of VMX5000 compounds show significantly less change in hardness, and loss in elongation than carbon blacked filled AEM compounds.

Table 16 – **Higher Hardness Compounds, Ageing**

Heat Ageing	G	G / GLS	Ultra IP / GXF	Ultra IP / GLS	Ultra IP / Ultra LS	5015, FEF	5020, FEF	5020, SRF	5020, MT	5020, low MT, high DIAK
Heat Ageing 1008 h at 150°C (ISO 188:2007)										
Hardness Shore A, 1s	85.4	88.6	85.5	87.0	85.9	77.5	74.0	73.8	72.5	72.9
Delta Hardness	5.2	6.8	4.6	6.5	5.3	-1.9	0.1	-0.7	-0.6	0.4
Tensile Strength [MPa]	14.2	13.6	14.9	13.6	15.2	10.0	8.1	9.0	9.0	8.9
Delta TS [%]	-13	-17	-14	-19	-14	-47	-45	-41	-38	-52
Elong at Break [%]	145	134	163	140	178	174	213	189	192	206
Delta Elong. [%]	-19	-23	-20	-24	-23	-8	7	-3	-17	0
Mod at 25 % [MPa]	3.2	3.5	2.7	3.4	2.9	1.8	1.5	1.5	1.4	1.3
Delta 25% [%]	43	65	45	47	38	-6	-5	-9	-7	-17
Mod at 100 % [MPa]	10.5	11.0	9.9	10.6	9.9	7.9	6.6	6.8	6.1	5.8
Delta 100% [%]	13	19	19	8	18	-16	-10	-8	-8	-23

Heat Ageing 1008 h at 175°C (ISO 188:2007)										
Hardness Shore A, 1s	97.0	96.5	97.2	97.0	95.4	74.3	71.2	70.1	69.2	69.3
Delta Hardness	16.8	14.9	16.1	16.5	14.0	-5.1	-2.3	-4.3	-3.7	-3.2
Tensile Strength [MPa]	0.22	0.22	1.23	0.09	0.17	13.4	12.4	12.1	10.2	10.3
Delta TS [%]	-99	-99	-93	-100	-99	-28	-16	-18	-32	-44

Elong at Break [%]	0	0	0	0	0	144	137	128	123	129
Delta Elong. [%]	-100	-100	-100	-100	-100	-24	-31	-34	-47	-38
Mod at 25 % [MPa]						1.0	0.94	1.04	0.84	0.85
Delta 25% [%]						-48	-39	-36	-43	-45
Mod at 100 % [MPa]						8.2	8.0	8.3	7.4	7.1
Delta 100% [%]						-13	8	12	11	-7

Table 17 – **Higher Hardness Compounds, Fluid Ageing**

Fluid Ageing	G	G / GLS	Ultra IP / GXF	Ultra IP / GLS	Ultra IP / Ultra LS	5015, FEF	5020, FEF	5020, SRF	5020, MT	5020, low MT, high DIAK
Fluid Ageing, 1008 h at 150°C in Petro Dexron® VI RDL 3434										
Hardness Shore A, 1s	81.5	86.9	80.1	86.3	84.1	71.7	68.4	68.1	67.2	68.1
Delta Hardness	1.3	5.4	-1.0	6.3	3.3	-7.4	-5.1	-6.3	-5.5	-4.4
Tensile Strength [MPa]	15.3	14.3	15.8	15.1	17.5	14.1	11.8	11.8	11.8	11.0
Delta TS [%]	-6.9	-12.8	-9.0	-9.6	-1.4	-24.5	-19.7	-20.4	-21.4	-40.0
Elongation at Break [%]	93	76	118	77	121	139	140	127	153	155
Delta Elong. [%]	-48.0	-56.3	-41.9	-58.2	-47.4	-26.8	-29.7	-34.5	-33.8	-25.1
Mod at 10 % [MPa]	1.3	2.0	1.2	2.0	1.7	0.6	0.5	0.5	0.5	0.5
Delta 10% [%]	16.5	87.2	16.8	65.0	48.3	-38.0	-34.6	-39.0	-32.9	-33.8
Mod at 100 % [MPa]			12.9		14.3	10.4	8.4	8.9	7.4	7.1
Delta 100% [%]			54.8		71.3	9.7	14.8	20.6	10.8	-6.1
Weight Change [%]	7.8	5.0	8.5	5.0	5.2	9.2	9.3	8.6	8.5	8.9
Volume Change [%]	11.4	7.4	12.5	7.6	7.9	11	11.5	10.7	10.8	10.2

Fluid Ageing, 1008 h at 150°C in Pentosin® FFL-5 LV										
Hardness, Shore A, 1 s	85	87.6	85.8	88.7	88.6	76.6	73.5	72.8	72.8	73.6
Delta Hardness	4.5	6.0	4.7	8.2	7.9	-2.7	0	-1.4	-0.1	1.0
Tensile Strength [MPa]	16.3	15.5	15.6	16.5	17.1	13.5	11.2	12.4	11.6	10.6
Delta TS [%]	-0.7	-5.5	-9.7	-0.8	-3.8	-27.5	-24.0	-16.2	-22.7	-42.0
Elongation at Break [%]	83	84	102	83	108	167	184	137	178	193
Delta Elong. [%]	-53.6	-51.7	-49.8	-54.9	-53.0	-12.1	-7.5	-29.4	-22.9	-6.8
Mod at 10 % [MPa]	2.3	2.5	1.9	2.8	2.2	0.7	0.7	0.8	0.6	0.6
Delta 10% [%]	99.1	127.5	91.1	129.2	93.0	-19.6	-9.0	-8.5	-12.3	-16.2

Mod at 100 % [MPa]				10.7	15.3	10.6	8.5	9.9	7.8	7.8
Delta 100% [%]				9.1	83.6	11.5	15.4	33.6	18.1	2.6
Weight Change [%]	4.4	2.3	4.5	2.8	1.6	5.9	4.9	6.2	5.5	6.3
Volume Change [%]	6.3	3.3	6.8	3.9	2.7	7.2	6.1	7.2	6.5	7.0

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