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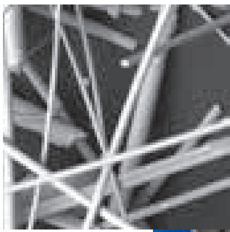
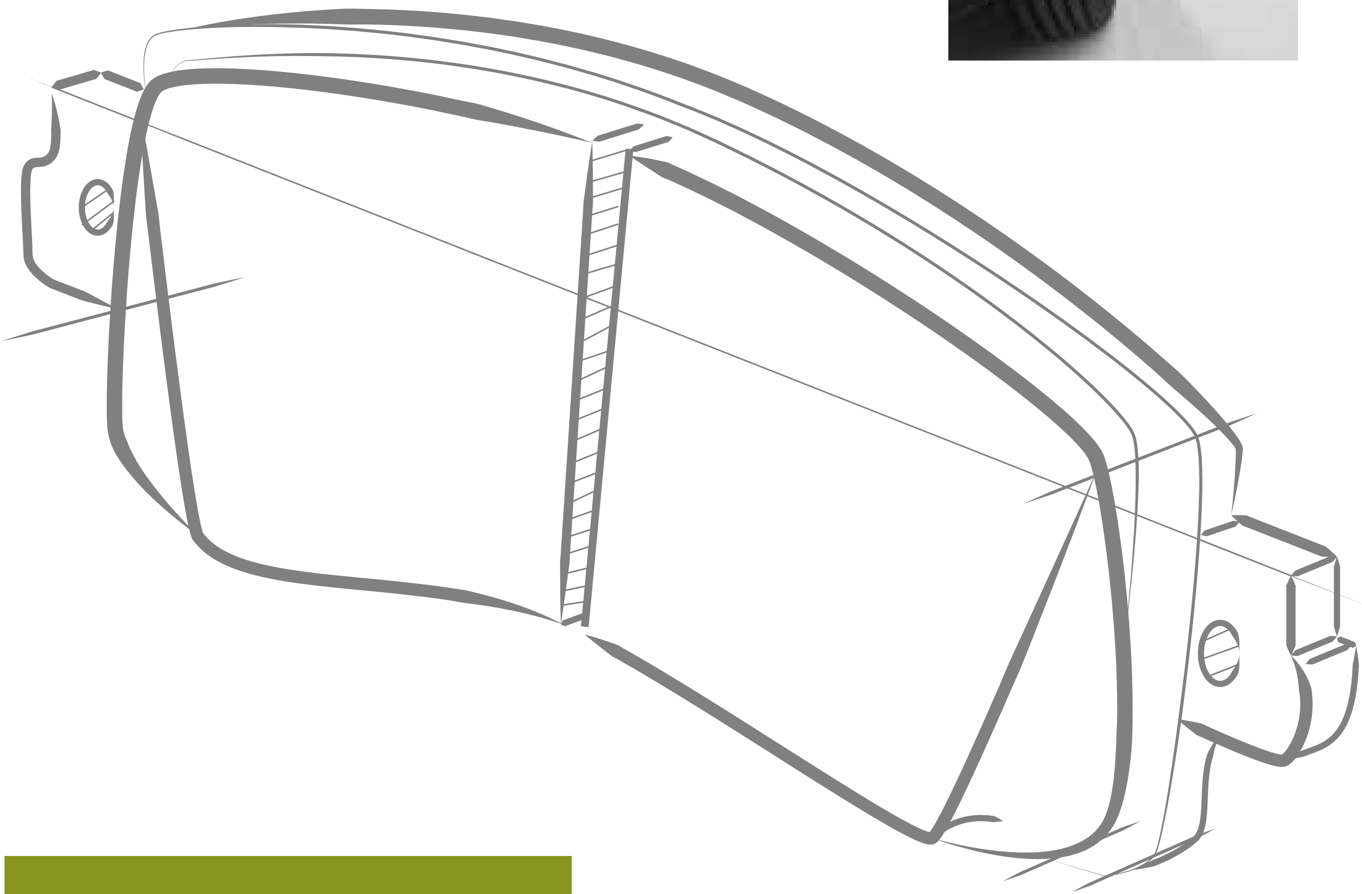
Functioning mechanism of white mineral fibres in friction applications

Technical Paper





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Bio-Soluble Chemical Composition For Complementary mineral fibres: An Enhanced Tribologic Effect And Its Influence On Disc Wear

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ABSTRACT

Environmental and financial factors are leading developments in the automotive industry and friction materials are no exception. Different organizations around the globe are increasing their attention on fine dust emissions. End users are more and more focused on comfort and cost due to global economic conditions.

Two of these factors are directly related to each other: comfort and fine dust. They are the result of tribologic mechanisms resulting from pad and disc wear. These mechanisms linked to friction performance are the consequence of the interaction between friction material surface and disc surface. This interaction forms the third body layer and extensive studies have been carried out on this.

This paper describes a detailed characterization of a new group of developed fibres. This new family of fibres has been specially engineered to offer an enhanced friction material surface reinforcement due to the specially designed aspect ratio. It has also been designed to maintain the most stable third body layer development to keep boosting friction level. Disc wear can be reduced thanks to its special chemical composition. The paper offers an explanation of the role of fibres in friction and it presents a proposal for a functioning mechanism in friction materials. Friction efficiency, wear and noise have been tested in a NAO copper-free formulation.

The paper demonstrates how - by using these new fibres - it is possible to increase the friction level without affecting wear and it explains the mechanism behind this. This offers an alternative to enhance friction performance or to reduce wear and dust emissions. This study shows how these fibres can improve wear (dust emissions) and noise as a cost effective alternative to current commercial products. The paper addresses three industrial challenges: wear, comfort and cost.

INTRODUCTION

In recent years there has been an increased interest in the environmental impact from brake pads [1-34]. Pad and disc wear are identified as one of the main sources of dust emissions into the environment [34-44]. Dust emission issues are related to the amount, size and chemical composition of powder released from cars during braking.

The chemical composition of brake debris depends partially on the raw materials introduced in the formulation used to produce them. Brake debris is the result of wear produced by friction. Friction coefficient is a relevant technical characteristic of brake pads. It is important to know the chemical and physical properties of the raw materials used in order to relate these properties to friction performance. It is also important to use non-hazardous materials for the formulation in order to guarantee the health and safety of workers on the production site. The use of safe materials for the production of brake pads reduces the risk of releasing dangerous fine dust into the environment. Raw materials need to be chemically stable under different temperature conditions. The starting point to understand dust emission reduction is pad and disc wear.

In order to reduce the powder released into the environment, car producers are requesting friction material manufacturers to develop friction materials with longer life cycles. The specific challenge is to develop friction materials with a friction level capable of stopping vehicles in any condition and able to maintain the same friction stability for as long as possible without compromising disc wear. At the same time the friction material needs to perform well from the noise vibration and harshness (NVH) point of view. It has been proven that these conditions are not unconnected as an increase in disc wear usually results in higher noise generation [35-44].

When trying to relate these technical needs into an industrial trend, there seems to be a need to develop non-asbestos organic (NAO) materials with a friction level higher than the typical commercially available materials, or low metallic/low steel materials with a better NVH performance than those commercially available. Whatever the approach for such a development, the focus point is a stable friction level and reduced disc wear (the former results in noise generation).

If dust production and noise generation are linked, the target for developments should be to understand how to improve friction stability and where this stability comes from. Literature studies have demonstrated that friction performance depends on the interaction between friction material surface and disc surface [45-61]. The tribologic interaction generated by these surfaces results in the generation of an intermediate and continuously evolving layer between them. This layer is responsible for the friction level and is generated by pad and disc wear. Different studies have focused on the analysis and characterization of this generated layer; third body layer, transfer film or flow film are typical names for this.

In order to work properly, the third body layer needs chemical, thermal and mechanical stability. Its formation and development are linked to the friction material formulation and specific circumstances during braking. Different mechanisms can lead to the formation of such a layer and this paper focuses on the different ways mineral fibres can contribute to some of them. With specific reference to the new generation of NAO materials, the formation of the third body layer is no longer guaranteed by copper. One reason for this is that copper had an important role in NAO material friction stability due to its low temperature ductile behavior that helped to form the third body layer between the disc and pad surface. Copper free-materials need different mechanisms to perform properly.

In this paper two different third body layer formation mechanisms are proposed:

a) A mechanical effect due to the load-bearing property of fibres acting as anchoring point as proposed in [62]
b) An accumulation effect of long lasting third body layers in the network produced by fibre nests in the friction material surface.

Three bio-soluble mineral fibre grades have been studied to prove the effect of these two mechanisms. This paper shows the functioning mechanism of these fibres and the result in friction efficiency and noise. However, they also play a role in the sliding contact between the friction material surface and the disc during braking. The combination of third body layer formation and sliding contact results in three different friction performances that offer the brakes industry an alternative to current products. Each one of the developed fibres enhances a different property and the selection of the right fibre to be used depends upon the specific formulation. The use of these newly developed fibres results in reduced disc wear and therefore improved NVH performance.

MINERAL FIBRES DESCRIPTION

The newly developed products are certified bio-soluble mineral fibres due to their specific chemical composition. They are produced using a combination of sustainable volcanic rocks and man-made briquettes. The end product has a certified chemical composition. The raw materials are melted in a furnace at a temperature of approximately 1500 °C. The homogeneous melt flows down on a spinning wheel forming long fibres and very small droplets called shot. The spun fibres are collected and in a second production step the shot is removed and the fibre length is adjusted under controlled circumstances, resulting in three new different bio-soluble fibre grades. Bio-solubility is one of the key characteristics for the unicity of these mineral fibres. Figure 1 shows an image of spun mineral fibres.

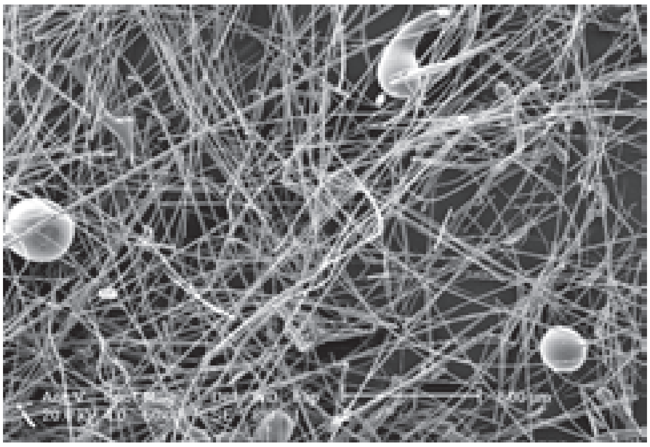

Figure 1. SEM image of mineral fibres before shot removal

The bio-solubility of fibres makes this product suitable and safe for use in friction materials. The bio-solubility is proven to be very high and hence the bio-persistency is very low. The fibres were tested by the independent institutes Fraunhofer and RCC. These independent measurements confirmed that these mineral fibres are highly bio-soluble and are exonerated from any hazardous classification. Table 1 shows the measured chemical composition of the proposed mineral fibres.

Component	Chemical analysis [wt%]
SiO_2	39.8
Al_2O_3	19.0
TiO_2	0.5
Fe_2O_3	0.8
CaO	32.8
MgO	5.2
Na_2O	1.2
K_2O	0.4
P_2O_5	0.2
M_nO	0.1

Table 1. Measured chemical composition of tested fibres

As a result of the special chemical composition, these new fibres show a reduced surface hardness. Apart from the effect of fibres in the friction material, they also interact with the disc by adding a local friction coefficient in the sliding contact area. This friction coefficient is somehow related to the specific material hardness. In comparison to other commercially available products, this newly developed fibre family is found to be softer in the interaction with the disc.

Table 2 shows the results of hardness characterization by means of a nanomechanical test system. It is a high-resolution nanomechanical test instrument that performs nano-scale quasi-static indentation by applying a force to an indenter tip while measuring tip displacement into the specimen. During indentation, the applied load and tip displacement are continuously controlled and/or measured, creating a load-displacement curve for each indent. From the load-displacement curve, nanohardness and reduced elastic modulus values can be determined by applying the Oliver and Pharr method and a pre-calibrated indenter tip area function and a pre-determined machine compliance value.

Sample	H [GPa]	HV [kgf/mm²]	Hardness [Mohs]
Other bio-soluble fibres	7.25	685	5.5
New bio-soluble fibres	2.06	195	3.5

Table 2. Average Vickers and Mohs Hardness converted from Nanohardness for all specimens

As a result of the reduced hardness, it has been proved that these new fibres have a softer interaction with the metallic disc, resulting in reduced disc wear [62].The interesting characteristic of these fibres is the special combination of low hardness due to their chemical composition, and their physical properties due to the special production process. Appendix 3 shows images of the hardness nanoindentation results.

In order to emphasize and differentiate the two third body layer formation mechanisms, the physical characteristics of the fibres have been specially designed to be different in length (as a result in aspect ratio). Table 3 shows the characteristics of samples A, B and C.

Fibre property	A	B	C
Fibre length (avg.) [µm]	127	303	505
Diameter (num. avg.) [µm]	4.0	4.0	4.0
Aspect ratio [L/D]	31	76	125
Shot content > 125µm [%wt]	0.11	0.10	0.12
Specific density [g/cm³]	2.71		
Colour [visual]	Off-white		

Table 3. Overview of measured fibre properties for samples A, B and C

INSTRUMENTS AND TEST PROCEDURES

Fibre length and fibre diameter measurements were performed using a Carl Zeiss Axioskop 2 with an AxioCam digital camera for image processing.

For shot measurements a Hosokawa Alpine 200LS-N air jet sieve was used with sieves of 45, 63 and 125 µm.

The chemical composition of the mineral fibres was determined using a XRF-Axios EP 264 spectrometer for X-ray fluorescence analysis.

Microscope images were taken in a Phenom Pro scanning electronic microscope (SEM).

The instrument that was used to perform the nanoindentation tests is a Nanomechanical Test System manufactured by Hysitron, Inc. To obtain the nanohardness and modulus values, 10 indents, sufficiently spaced were made on the apex of each of the fibres. Loads of 800 and 2000 µN were used. All indents were performed by in-situ Scanning Probe Microscopy (SPM) imaging. Mohs Hardness was determined using Mineral Hardness Conversion [63].

Efficiency and NVH performances were evaluated using a Horiba dynamometer according to SAE J2522 and SAE J2521 procedures, respectively. The pads were scorched, but did not contain an anti-noise shim, slot or chamfer. The brake system used for tests was the front brake of a VW Golf (WVA21974), using a ventilated disc and inertia of 65 kg.m².

A Krauss machine was used for wear testing as a function of temperature. Temperature block tests were carried out at 150 °C, 300 °C and 500 °C adapted from the SAE J2707 wear procedure.

SAMPLE PREPARATION

A NAO/metal-free formulation was used to investigate the impact of fibres on the third body layer formation and its influence on friction and noise performance. All fibres were introduced in the same friction material formulation at the same volumetric rate. A more precise description of the formulation is given in table 4.

Mixing took place in two stages using a multiple blade, high-speed, vertical MTI laboratory mixer (speed 2000 RPM). In the first stage, the aramid fibres and mineral fibres were dispersed by mixing the fibres with graphite and fillers for two minutes. In the second stage, the remaining raw materials were added to the mixture for an additional two minutes of mixing time.

Component	Volume [%]
Novolac resin	16
Aramid fibres	5
Solid lubricants	11
Friction dust/ rubber crumb	10.5
Potassium titanates flake form	17.5
Abrasives	11
Lapinus® mineral fibres	8
PROMAXON®-D	5.5
Fillers	15.5
Total	100

Table 4. Metal free NAO formulation used for the investigation

The pads were processed in a positive mould for five minutes under a pressure of 290 kg/cm^2 at 160 °C. After hot moulding, the pads were cured for four hours at a constant temperature of 210 °C. All the materials were ground in order to achieve a flat surface and acclimatized for 24 hours at 23 °C and 50% relative humidity afterwards. Three different friction materials were then produced under the circumstances described above with fibre samples A, B and C.

Fibre length/sample	Friction material
Short, sample A	FA
Medium, sample B	FB
Long, sample C	FC

Table 5. Friction materials produced with different fibre lengths

TEST RESULTS

The physical properties and friction performances of the 3 samples were evaluated. Table 6 shows the results for density, porosity and hardness. Hardness measurements were carried out at 10 different points on the friction material surface. Fibre length shows no influence on hardness and density.

Friction material	Density [g/cm³]	Porosity [%]	Hardness [HRS]
FA	2.23	16.1	74 stdev 3
FB	2.22	17.8	72 stdev 6
FC	2.19	20.3	76 stdev 5

Table 6. Physical macrometric properties of friction materials

Figure 2 shows the relation between porosity and fibre length. As the three proposed fibres have the same diameter, the change in aspect ratio is directly related to the fibre length. The graph also shows the relation between aspect ratio and porosity.

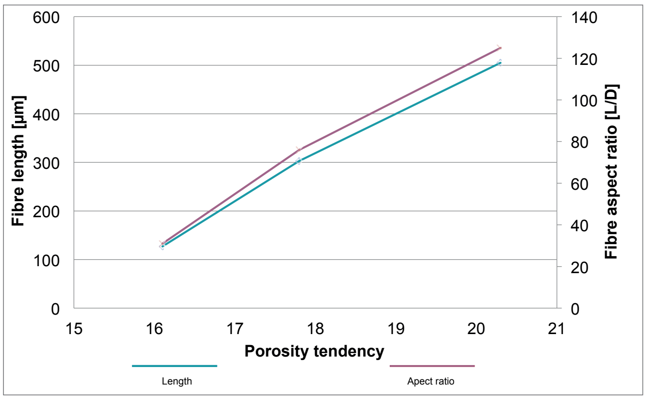

Figure 2. Relation between porosity of the friction material and fibre aspect ratio (L/D). Left "y" axis is fibre length and right "y" axis is aspect ratio

An efficiency test was carried out with the three friction materials produced. Figure 3 shows a comparison between the summary of the AK-Master test results for samples FA, FB and FC.

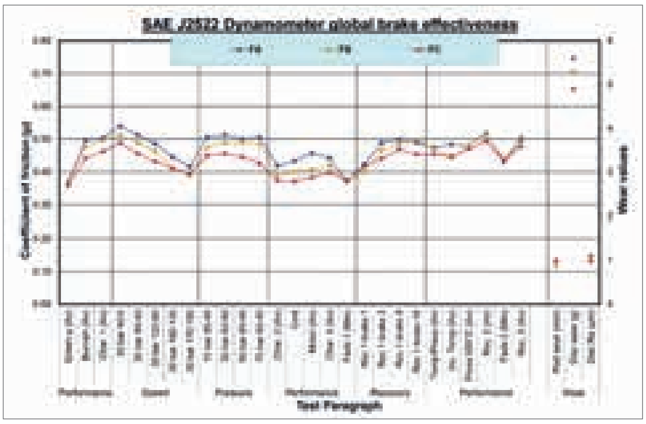

Figure 3. AK-Master efficiency summary comparison

Appendix 1 shows the three complete AK-Master results. Despite the fact that the three efficiency results have the same profile, the friction level shown by each of the three friction materials is different. For these formulations the tendency shows an increase in friction level with the decrease in fibre length. At the same time, the stability of the friction level is much higher with the increase in fibre length (aspect ratio). It is interesting to mention here the difference between the results and not the specific results. As an attempt to demonstrate stability, table 7 shows the values of minimum, average and maximum friction level of the three AK-Master tests.

Friction material	Nominal µ	Minimum µ	Maximum µ	Maximum ∆µ
FA	0.47	0.37	0.54	0.17
FB	0.45	0.37	0.51	0.14
FC	0.43	0.37	0.49	0.12

Table 7. AK-Master nominal, minimum and maximum friction levels

It is shown that due to fibre length there is an effect on friction material porosity. The combination of different porosities and different fibre length influences the friction level with a specific tendency. At the same time, disc wear shows an interesting and clear tendency.

There seems to be a relation between friction stability and disc wear. Table 8 shows the disc wear values after the AK-master test.

Friction material	Disc wear [g]	Fibre length [µm]	Aspect ratio
FA	5.6	127	31
FB	5.3	303	76
FC	4.9	505	125

Table 8. Disc wear results

Disc wear and porosity are both related to fibre length, also friction stability and friction level. There is a clear different mechanism of functioning between short and long fibres

As already mentioned in the introduction, several papers have demonstrated the relation between disc wear and noise.

An NVH test was carried out with two of the three friction materials produced. In order to emphasize the differences due to length, only the short and long fibre samples (FA and FC) were tested. Figures 4 and 5 show the noise results for the two friction materials with no shim, no chamfers and no slots.

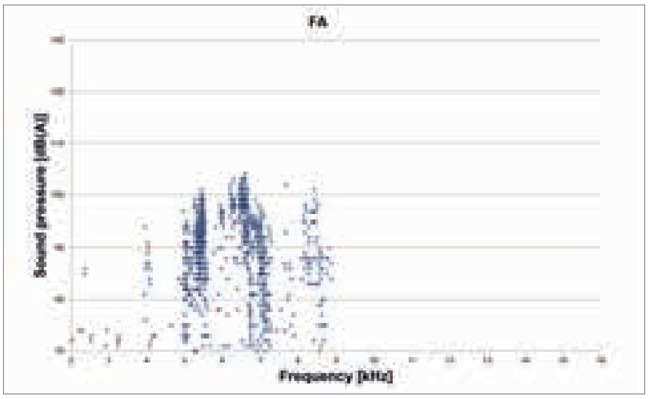

Figure 4. Noise events measured during NVH test for sample FA

Although the number of noisy occurrences is high, as in the case of efficiency tests, the relevance of these data is not the result itself, but the difference in results between the two friction materials.

The sole variation between them is the length of the fibre (and as a consequence porosity) so improvements from one result to the other can be attributed to an effect due to the fibre length.

Table 9 shows the relative difference between the number of noisy occurrences between samples FA and FC.

Friction material	Relative percentage of noisy stops [Sample result / FA noisy stops *100]	Fibre length [µm]
FA	100	127
FC	57	505

Table 9. Relative difference of noisy stops

Appendix 2 also shows the cumulative percentage of noise events, the percentage of noise events as a function of frequency and as a function of intensity. These clearly show that not only the number of noisy stops changes, but also the frequencies and intensities of the occurrences.

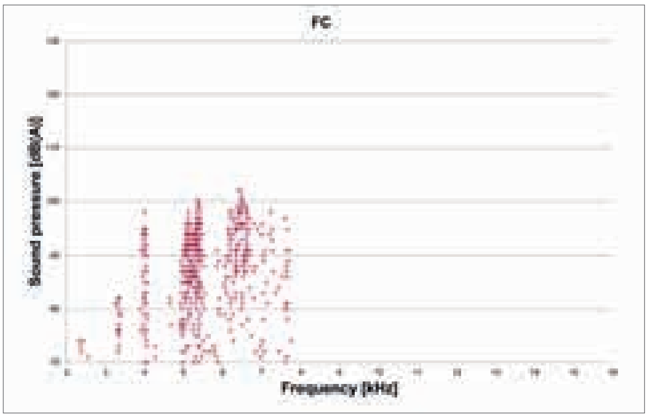

Figure 5. Noise events measured during NVH test for sample FC

The longer fibre shows overall a better friction and noise performance. The friction level is lower, but more stable and stability seem to be related to a reduction in vibration generation. The relation between vibration generation and friction stability can be linked to wear, in particular disc wear.

Under completely different braking circumstances, wear was evaluated at different temperature blocks. The intention is to verify if reduced pad and/or disc wear is actually linked to the length of the fibre.

Table 10 shows the pad and disc wear results for each friction material at three different temperature blocks. Roughness was also evaluated as vibrations are generated in the interface between disc and friction material. In general damaged surfaces generate more vibrations.

Once wear variations have been verified, it is important to focus on the cascade of consequences.

Fibre length increase → Friction material porosity increase

Fibre length increase → Friction level decrease

Fibre length increase → Friction level stability increase

Friction level stability increase → Disc wear decrease

Disc wear decrease → Vibration generation decrease

The correlation of results indicates that there is actually a very direct relation between friction stability, wear and noise. If the analysis is taken back to the mechanism of friction generation and correlated to the third body layer, it is very clear that the different fibres generate different conditions for the third body layer formation and it is only due to the fibre length

150 °C			
Friction material	Pad wear [g]	Disc wear [g]	Disc roughness [µm]
FA	4	3.9	1.45
FB	3.8	3.6	1.08
FC	3.8	3.1	1.06
300 °C			
Friction material	Pad wear [g]	Disc wear [g]	Disc roughness [µm]
FA	3.8	2.1	1.94
FB	3.6	2.0	1.83
FC	2.9	1.8	1.81
500 °C			
Friction material	Pad wear [g]	Disc wear [g]	Disc roughness [µm]
FA	11.7	7.8	3.95
FB	11.3	7.4	4
FC	11	6.7	3.55

Table 10. Wear test results at three temperatures 150 °C, 300 °C and 500 °C for samples FA, FB and FC

Table 11 shows clearly that fibre length also influences pad and disc wear. The longer the fibre length, the lower the wear.

Friction material	**Total pad wear [g]**	**Total disc wear [g]**
FA	19.5	13.8
FB	18.7	13.0
FC	17.7	11.6

Table 11. Total pad and disc wear

It is very interesting to note the significant difference in disc roughness associated with fibre length. Long fibres affect the disc surface roughness less than short fibres. This observation, in combination with the results of efficiency, noise and wear, suggest that the proposed different mechanisms of third body layer formation mentioned on page two could be involved:

a) A mechanical effect due to load bearing property of fibres acting as an anchoring point for short fibres
b) An accumulation effect of long lasting third body layers in a network produced by fibre nests in the friction material surface for long fibres
c) A combination of a and b for medium fibres

DISCUSSION

Mineral fibres have already been discussed previously and the mechanism of formation of third body layer has been explained. Nevertheless the explanation was based only on one of the two formation mechanisms this paper suggests.

The mechanism is shown in figure 6 and it is aligned with the well-known theory of third body layer formation starting from anchoring points. Fibres function as primary plateaus due to their anchoring effect and they allow other raw materials to form secondary plateaus.

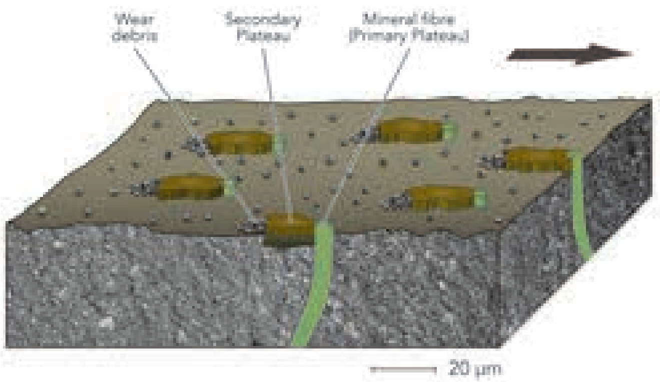

Figure 6. Mechanism of third body layer formation, suggesting fibres act as anchoring point. The arrow indicates the direction of rotation of disc

The alternative formation of third body layer suggested in this paper is related to the accumulation of wear debris in the surface porosity. Long fibres create porosity spots. These spots are not normal porosity spots like the common porosity created by the gases generated during the phenolic resin crosslinking. Fibre spots are actually nests and these nests are anchored to the friction material. Figure 7 shows an image of a new friction material surface showing some localized porosity. Note the difference between surface porosity generated by short (FA) and long (FC) fibres.

FA surface **FC surface**

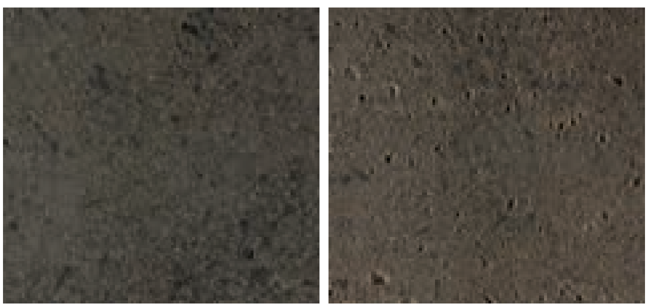

Figure 7. Friction materials FA and FC surfaces. FC surface shows surface porosities generated by long mineral fibres. Surface is new and before porosity is filled with wear debris

When taking a closer look at these porosities it is clear that they are formed due to fibres folding in on themselves. Folding fibres are achieved only with medium and long fibres; the longer the fibre, the easier it is to produce this effect. Figure 8 shows a SEM image of these pores after the friction material was produced, porosity is still empty as no wear debris has been generated yet.

The formation of porosity due to fibres folding suggests that the fibre "agglomeration" actually generates empty space or pores. This empty space is then filled with fine debris produced during the interaction of friction material and disc surface. Just as in the case of the secondary plateaus formation, raw materials such as potassium titanate, calcium silicate or graphite are milled down by the sliding forces.

Figure 8 is a schematic representation of the suggested mechanism.

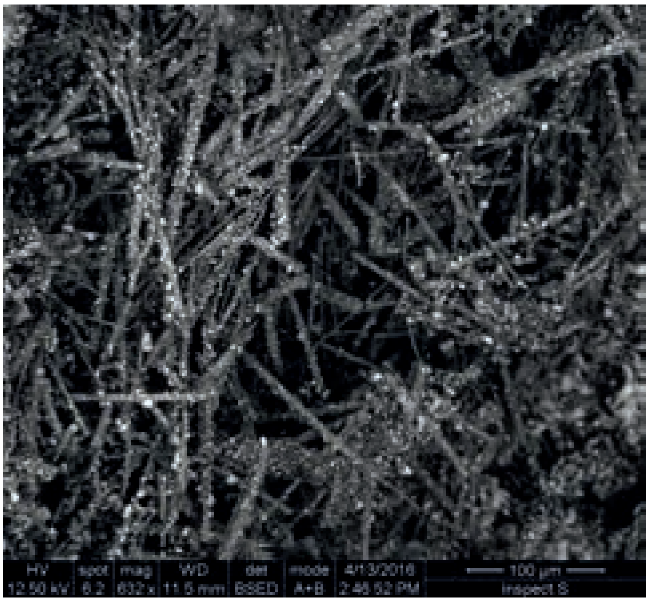

Figure 8. SEM image of porosity formed by long fibres (FC)

Porosities actually represent an alternative to trap wear debris. When sliding friction generates fine dust coming from the friction material and disc surfaces, the small generated particles can be trapped in the pores as if they were in a nest.

Once wear debris is trapped, it becomes a secondary area of contact. The difference between this debris accumulation and the typical secondary plateaus of the well-known third body layer is that this contact area is not a layer, but a body trapped in a nest-like structure.

In this case debris does not compact in front of a fibre acting as an anchoring point, but it is accumulated in the empty spaces of the porosity generated by the fibre nest. The fibre nest changes from being an empty space and becomes a deep long-lasting three dimensional third body nest (2L3D- double L three D). This 2L3D will last longer than normal secondary plateaus.

The final effect is an increase of sliding contact area and a stabilization of the friction level resulting in a reduction of wear debris and vibration production.

Figure 9 shows an electronic microscope image of a third body nest. This image was taken after friction material FC was subject to a AK-Master test. Empty pores were not visible anymore and when looking at the surface under the electronic microscope, it was clear that 2L3D structures were filled with wear debris.

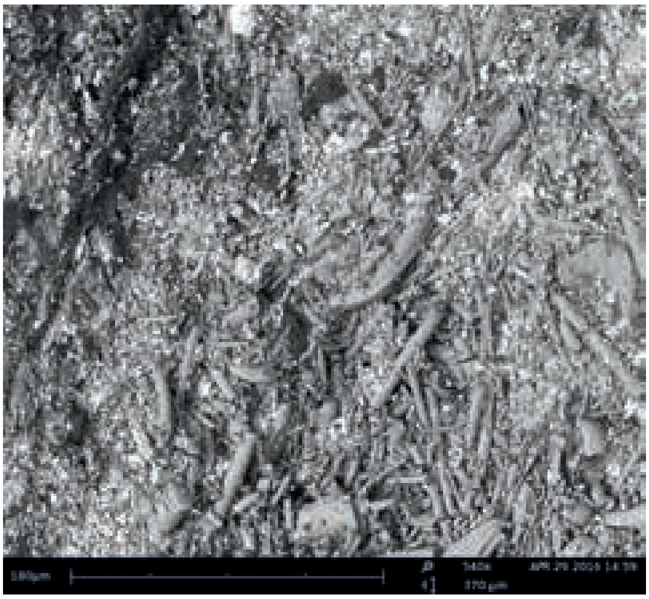

Figure 9. Third body nest located in the surface of the friction material FC after AK-master test

CONCLUSION

The proper formation of the third body facilitates the reduction of wear debris production and therefore results in an improvement in NVH behavior for friction materials. Friction materials with a more stable friction level generate less wear debris.

The formation of third body can be achieved by two mechanisms:

a) Third body layer promoted by the use of short mineral fibres acting as anchoring points and facilitating the compaction of wear debris into secondary plateaus.
b) Third body nest by the use of long mineral fibres acting as porosity generation and facilitating the accumulation of wear debris in available reinforced nests – 2L3D.

In both cases the effect is an increase of the sliding contact area. Depending on the kind of application and formulation, the need for short or long fibres is suggested. A combination of long and short fibres could also help to achieve the required friction level and stability.

The three newly developed mineral fibres offer the two possibilities of third body formation; each product has been specially designed to be used in a different application or formulation style. Short, medium and long mineral fibres were developed using a new bio-soluble chemistry and they can be used to support the development of NAO metal-free friction materials.

Formulators have now an alternative to achieve the industry goals by obtaining a friction material with longer life and stable friction level. It is expected that these specially engineered fibres will complement future formulations in reducing wear and therefore also wheel dust and dust emissions.

The newly developed product represents a cost-effective alternative to ceramic fibres.

REFERENCES

1. Figi R., Nagel O., Tuchschmid M., Lienemann P., Gfeller U., Bukowiecki N. 2010. “Quantitative analysis of heavy metals in automotive brake linings: A comparison between wet-chemistry based analysis and in-situ screening with a handheld X-ray fluorescence spectrometer”. Analytica Chimica Acta 676: 46-52
2. Thorpe A., Harrison R.M.. 2008. “Sources and properties of non-exhaust particulate matter from road traffic: A review”. Science of the Total Environment 400: 270-82
3. Atkinson R.W., Fuller G.W., Anderson H.R., Harrison R.M., Armstrong B. 2010. “Urban Ambient Particle Metrics and Health A Time-series Analysis”. Epidemiology 21: 501-11
4. Gietl J.K., Lawrence R., Thorpe A.J., Harrison R.M.. 2010. “Identification of brake wear particles and derivation of a quantitative tracer for brake dust at a major road”. Atmospheric Environment Journal 44: 141-46
5. Harrison R. 17th Transport and Air Pollution Symposium and 3rd Environment and Transport Symposium 2009.
6. Harrison R.M., Beddows D.C.S., Dall’Osto M. 2011. “PMF Analysis of Wide-Range Particle Size Spectra Collected on a Major Highway” Environmental Science & Technology 45: 5522-28
7. Harrison R.M., Jones A.M., Gietl .J, Yin J.X., Green D.C.. 2012. “Estimation of the Contributions of Brake Dust, Tire Wear, and Resuspension to Nonexhaust Traffic Particles Derived from Atmospheric Measurements” Environmental Science & Technology 46: 6523-29
8. Kumar P., Pirjola L., Ketzel M., Harrison R.M.. 2013. “Nanoparticle emissions from 11 non-vehicle exhaust sources - A review”. Atmospheric Environment Journal 67: 252-77
9. Pant P., Harrison R.M.. 2013. “Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review”. Atmospheric Environment Journal 77: 78-97
10. Abu-Allaban M., Gillies J.A., Gertler A.W., Clayton R., Proffitt D. 2003. “Tailpipe, resuspended road dust, and brake-wear emission factors from on-road vehicles”. Atmospheric Environment Journal 37: 5283-93
11. Gadd J., Kennedy P. 2003. “Preliminary examination of organic compounds present in tyres, brake pads and road bitumen in New Zealand”. Prepared for Ministry of Transport, New Zealand, Infrastructure Auckland 2003
12. Garg B.D., Cadle S.H., Mulawa P.A., Groblicki P.J., Laroo C., Parr GA. 2000. “Brake wear particulate matter emissions”. Environmental Science & Technology 34: 4463-69
13. Matějka V., Lu Y., Matějková P., Smetana B., Kukutschová .J, et al. 2011. “Possible stibnite transformation at the friction surface of the semi-metallic friction composites designed for car brake linings”. Applied surface science 258: 1862-68
14. Peikertová P., Vaculík M., Filip P., Kukutschová J. “Raman microspectroscopy as a tool for characterization of brake wear debris”. Procedding Nancon 23. - 25. 10. 2012, Brno, Czech Republic, EU
15. Kwak J.H., Kim H., Lee J., Lee S.. 2013. “Characterization of non-exhaust coarse and fine particles from on-road driving and laboratory measurements”. Science of the Total Environment 458: 273-82
16. Furuta N., Iijima A., Kambe A., Sakai K., Sato K.. 2005. “Concentrations, enrichment and predominant sources of Sb and other trace elements in size classified airborne particulate matter collected in Tokyo from 1995 to 2004”. Journal of Environmental Monitoring 7: 1155-61
17. Iijima A., Sato K., Yano K., Tago H., Kato M., et al. 2007. “Particle size and composition distribution analysis of automotive brake abrasion dusts for the evaluation of antimony sources of airborne particulate matter”. Atmospheric Environment Journal 41: 4908-19
18. Riediker M., Cascio W.E., Griggs T.R., Herbst M.C., Bromberg P.A., et al. 2004. “Particulate matter exposure in cars is associated with cardiovascular effects in healthy young men”. American Journal of Respiratory and Critical Care Medicine169: 934-40
19. Riediker M., Devlin R.B, Griggs T.R., Herbst M.C., Bromberg P.A., et al. 2004. “Cardiovascular effects in patrol officers are associated with fine particulate matter from brake wear and engine emissions” Particle and Fibre Toxicology 1: 8977-1
20. Riediker M., Gasser M., Perrenoud A., Gehr P., Rothen-Rutishauser B.. 12th International ETH-Conference on Combustion Generated Nanoparticles 2008: 23-25.
21. Zhao J.Y., Lewinski N., Riediker M.. 2015. “Physico-Chemical Characterization and Oxidative Reactivity Evaluation of Aged Brake Wear Particles” Aerosol Science and Technology 49: 65-74
22. Sanders P.G., Xu N., Dalka T.M., Maricq M.M.. 2003. “Airborne brake wear debris: Size distributions, composition, and a comparison of dynamometer and vehicle tests” Environmental Science & Technology37: 4060-69
23. Cha S., Carter P., Bradow R.L.. 1983. “Simulation of automobile brake wear dynamics and estimation of emissions”, SAE Technical Paper
24. Williams R.L., Muhlbaier J.L.. 1982. “Asbestos brake emissions”. Environmental research 29: 70-82
25. Yang W., Peters J.I., Williams R.O., 3rd. 2008. “Inhaled nanoparticles--a current review”. International journal of pharmaceutics 356: 239-47

26. Hou L., Wang S., Dou C., Zhang X., Yu Y., et al. 2012. “Air pollution exposure and telomere length in highly exposed subjects in Beijing, China: a repeated-measure study” Environmental International Journal 48: 71-7
27. Tanner P.A., Ma H.L., Yu P.K.N.. 2008 “Fingerprinting metals in urban street dust of Beijing, Shanghai, and Hong Kong” Environmental Science & Technology 42: 7111-17
28. Yue W., Schneider A., Stozel M., Ruckerl R., Cyrys J., et al. 2007. “Ambient source-specific particles are associated with prolonged repolarization and increased levels of inflammation in male coronary artery disease patients”. Mutation Research - Fundamental and Molecular Mechanisms of Mutagenesis 621: 50-60
29. Mathissen M., Scheer V., Vogt R., Benter T.. 2011. “Investigation on the potential generation of ultrafine particles from the tire-road interface” Atmospheric Environment Journal 45: 6172-79
30. Hagino H., Oyama M., Sasaki S. 2015. “Airborne brake wear particle emission due to braking and accelerating”. Wear 334: 44-48
31. Wik A., Dave G. 2009. “Occurrence and effects of tire wear particles in the environment - A critical review and an initial risk assessment” Environmental Science and Pollution Research International, 157: 1-11
32. Chan D., Stachowiak G. 2004. “Review of automotive brake friction materials” Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 218: 953-66
33. Grigoratus T., Martini G., 2015. “Brake wear particle emissions: a review”. Environmental Science and Pollution Research International. 22: 2491-2504.
34. Wahlström, J., Söderberg, A., and Olofsson, U., “Simulation of Airborne Wear Particles from Disc Brakes,” SAE Technical Paper 2009-01-3040, 2009, doi:10.4271/2009-01-3040.
35. Rhee, S., “Influence of Disc Metallurgy on the Wear of Friction Materials in Automotive Brakes,” SAE Technical Paper 710247, 1971, doi:10.4271/710247.
36. Sriwiboon, M., Tiempan, N., Kaewlob, K., and Rhee, S., “Influence of Formulation and Process Modifications on Brake Friction, Wear and Squeal: Low-Copper NAOs and Importance of Disc Wear,” SAE Technical Paper 2014-01-2482, 2014, doi:10.4271/2014-01-2482.
37. Kim, S., Lee, S., Park, B., and Rhee, S., “A Comprehensive Study of Humidity Effects on Friction, Pad Wear, Disc Wear, DTV, Brake Noise and Physical Properties of Pads,” SAE Technical Paper 2011-01-2371, 2011, doi:10.4271/2011-01-2371
38. Coyle, J., Tsang, P., and Johnson, T., “The Effect of Disc Metallurgy on Brake Performance and Wear Resistance,” SAE Technical Paper 830533, 1983, doi:10.4271/830533.
39. Lee, S., Jeong, J., Kim, S., Kim, S. et al., “Brake Squeal and Disc Metallurgy Variability: Importance of Disc Wear,” SAE Technical Paper 2014-01-2491, 2014, doi:10.4271/2014-01-2491.
40. Rhee, S., Jacko, M., and Tsang, P., “The Role of Friction Film in Friction, Wear, and Noise of Automotive Brakes,” SAE Technical Paper 900004, 1990, doi:10.4271/900004
41. Sriwiboon, M., Tiempan, N., Kaewlob, K., and Rhee, S., “Brake Squeal and Wheel Dust vs. Disc Wear: No-Copper, Low-Copper and High-Copper NAOs,” SAE Int. J. Mater. Manf. 9(1):112-117, 2016, doi:10.4271/2015-01-2660.
42. Rhee, S. and Thesier, P., “Effects of Surface Roughness of Brake Drums on Coefficient of Friction and Lining Wear,” SAE Technical Paper 720449, 1972, doi:10.4271/720449
43. Lee, S., Kim, S., Kim, S., and Rhee, S., “Characterization of Disc Wear Particles Transferred to the NAO Pad Surface: Brake Squeal,” SAE Technical Paper 2015-01-2684, 2015, doi:10.4271/2015-01-2684.
44. Kikudome, T., Yoshida, Y., and Unno, M., “The Influence of Brake Wear Debris Chemical Properties on Wheel Dust,” SAE Technical Paper 2009-01-3020, 2009, doi:10.4271/2009-01-3020.
45. Santamaria Razo, D., Decrock, J., Opsommer, A., Fabré, M. et al., “PROMAXON® D in NAO Non Steel Disc Pad Formulations: the Importance in the Third Body Layer and its Effect on Brake Noise,” SAE Int. J. Mater. Manf. 9(1):158-170, 2016, doi:10.4271/2015-01-2678.
46. Majcherczak, D., Dufrenoy, P., Berthier, Y.,Tribological, thermal and mechanical coupling aspects of the dry sliding contact”, Tribology International, 40: 834-843, 2007, doi:10.1016/j.triboint.2006.08.004.
47. G.P. Ostermeyer, M. Muller, “Dynamic interaction of friction and surface topography in brake systems”, Tribology International, 39, 370–380, 2006
48. W. Osterle, H. Kloß, I. Urban, A.I. Dmitriev, “Towards a better understanding of brake friction materials”, Wear, 263, 1189-1201, 200
49. M. Eriksson, S. Jacobson, “Tribological surfaces of organic brake pads”, Tribology International, 33, 817–827, 2000.
50. Oesterle, W. and Urban, I., “Third Body Formation on Brake Pads and Discs,” SAE Technical Paper 2004-01-2767, 2004, doi:10.4271/2004-01-2767.
51. Oesterle, W. and Dmitriev, A., “Some Considerations on the Role of Third Bodies during Automotive Braking,” SAE Int. J. Passeng. Cars - Mech. Syst.7(4):1287-1294, 2014, doi:10.4271/2014-01-2490.
52. Ostermeyer, G. and Merlis, J., “Effective Simulation of the Boundary Layer of an Entire Brake Pad,” SAE Technical Paper 2015-01-2664, 2015, doi:10.4271/2015-01-2664.

53. Polak, A., Grzybeck, J., and Pytko, S., "Friction Processes in Disc Brake – Brake Pad Couple," SAE Technical Paper 2002-01-1484, 2002, doi:10.4271/2002-01-1484.
54. Griffen, C., "Effects of Brake Pad Boundary Contact Surfaces on Brake Squeal," SAE Technical Paper 2011-01-2355, 2011, doi:10.4271/2011-01-2355.
55. Dufrénoy, P. and Brunel, J., "Thermal Localizations in Friction Brakes," SAE Technical Paper 2008-01-2568, 2008, doi:10.4271/2008-01-2568.
56. Thuresson, D., "Thermomechanical Analysis of Friction Brakes," SAE Technical Paper 2000-01-2775, 2000, doi:10.4271/2000-01-2775.
57. Van Halteren, A., "Fundamentals of Heat Transmission Applied to Automotive Brakes," SAE Technical Paper 380148, 1938, doi:10.4271/380148.
58. Lange, J. and Ostermeyer, G., "The Effect of Metal Pickup to the Friction Interfaces," SAE Technical Paper 2011-01-2348, 2011, doi:10.4271/2011-01-2348.
59. Wilkening, L., Paul, H., and Ostermeyer, G., "Investigations on Tribological Memory Effects in Friction Materials," SAE Int. J. Passeng. Cars - Mech. Syst. 7(4):1264-1273, 2014, doi:10.4271/2014-01-2481
60. Ostermeyer, G., Bode, K., Stühler, G., Stenkamp, A. et al., "Tribological Aspects of Carbon Ceramic and Cast-Iron Brake Discs with Organic Pad Materials in Simulation and measurement," SAE Technical Paper 2009-01-3010, 2009, doi:10.4271/2009-01-3010.
61. Ostermeyer, G., Müller, M., Abendroth, H., and Wernitz, B., "Surface Topography and Wear Dynamics of Brake Pads," SAE Technical Paper 2006-01-3202, 2006, doi:10.4271/2006-01-3202.
62. Persoon F., Tegels D., Santamaria Razo D.A., Kerssemakers A., "Bio-soluble mineral fibres: alternative chemical compositions and the effect in disc pad applications".
63. "Mineral Hardness Conversion Chart" IDEX Health & Science, LLC, http://www.cidraprecisionservices.com/mohs-conversion.html.

CONTACT INFORMATION

If you have any concerns, questions or suggestions and also for collaboration proposals or sample requests, please contact Diego Santamaria or Fernao Persoon.

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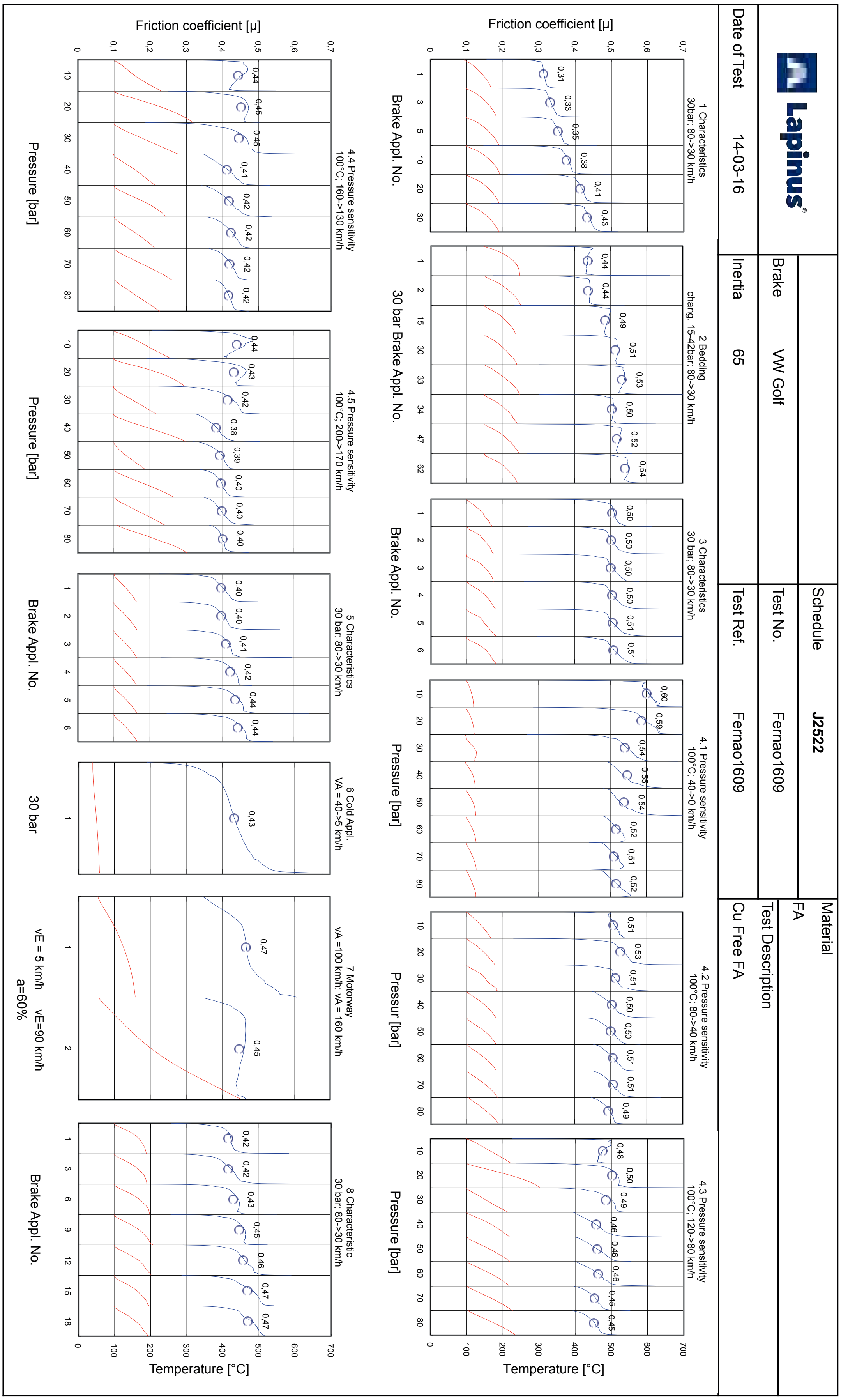
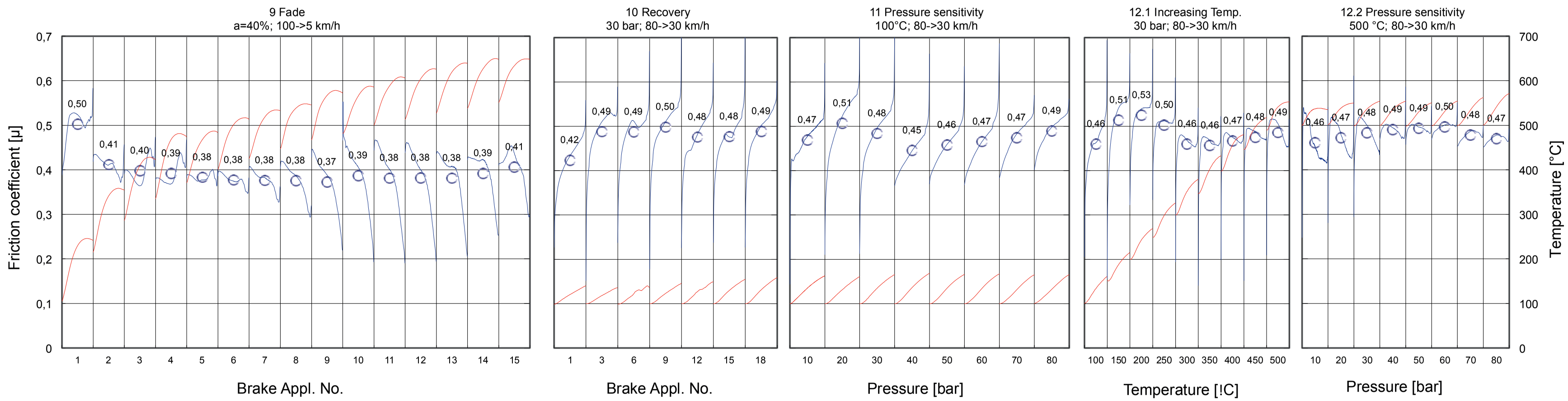
APPENDIX 1

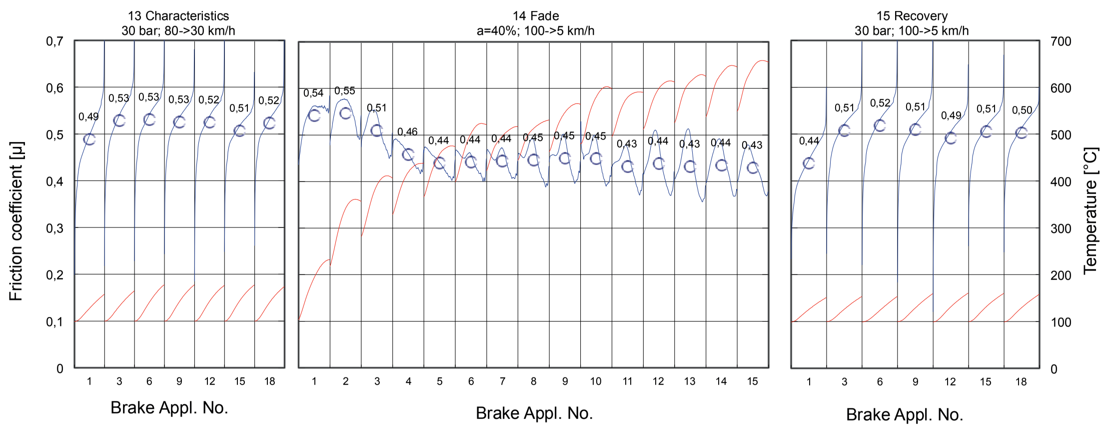
AK MASTER TEST RESULTS



Lapinus		Schedule	J2522	Material
	Brake	VW Golf	Test No.	Fernao1609
Date of Test 14-03-16	Inertia 65	Test Ref.	Fernao1609	Test Description: Cu Free FA

Material: FA

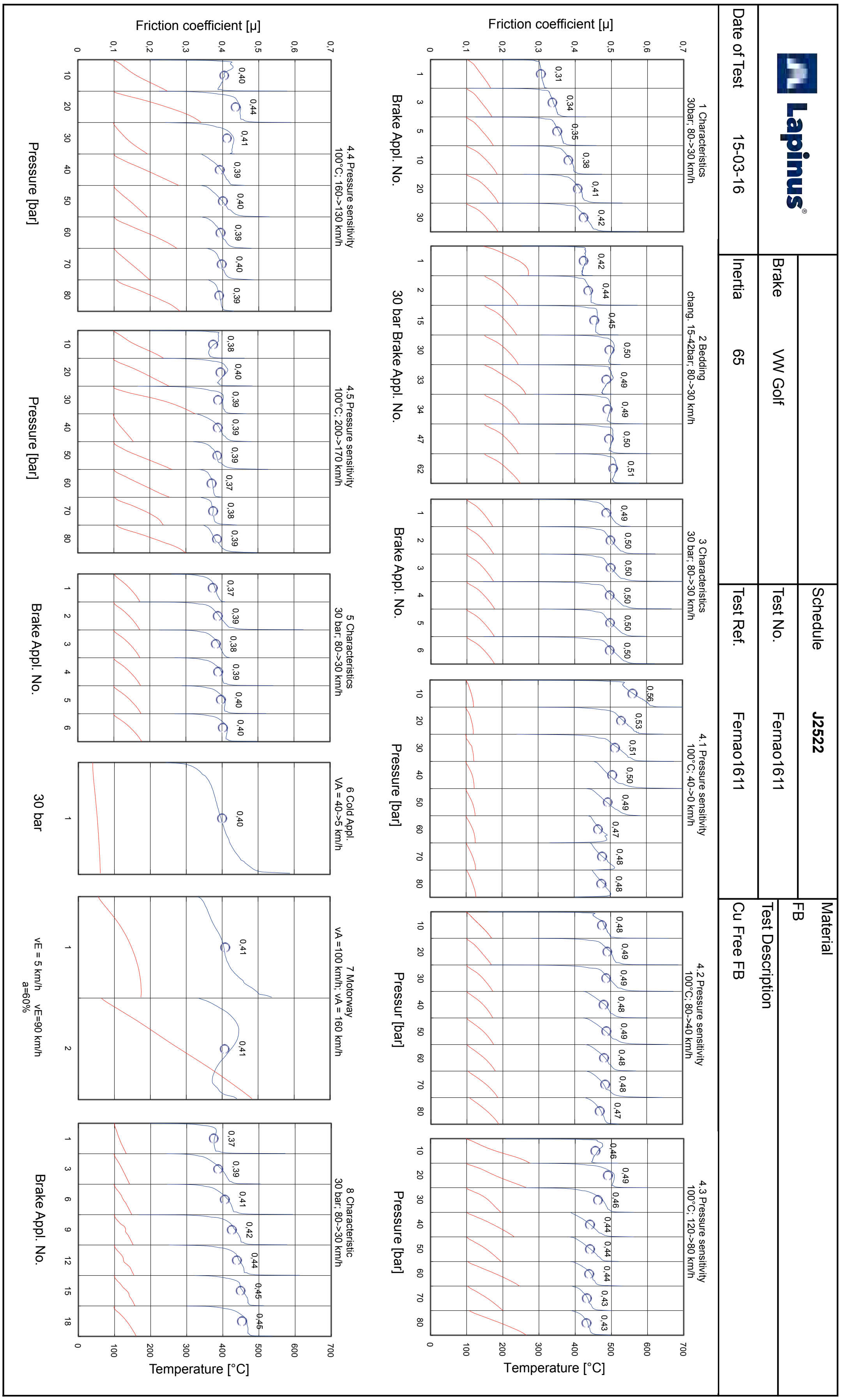




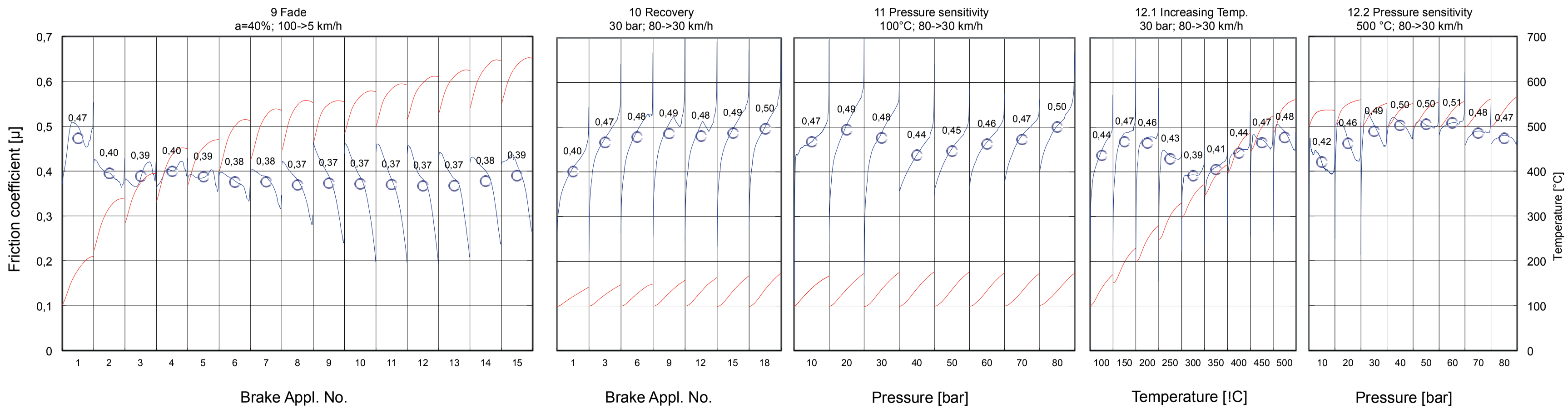
µ Values			Avg.	Min
operating	(3)	µ op =	0,51	
speed	(4.3)	µ 120 =	0,48	
speed	(4.5)	max =	0,41	
operating	(5)	µ op =	0,42	
40 C braking	(6)	µ 40 =	0,43	
motorway	(7)	µ mw =	0,45	
operating	(8)	µ op =	0,44	
1. Fade	(9)	µ f 1 =		0,37
operating	(10)	µ op =	0,48	
temperature	(12)	µ 500 =		0,46
operating	(13)	µ op =	0,52	
2. Fade	(14)	µ f 2 =		0,43
operating	(15)	µ op =	0,50	
		µ ave =	0,47	

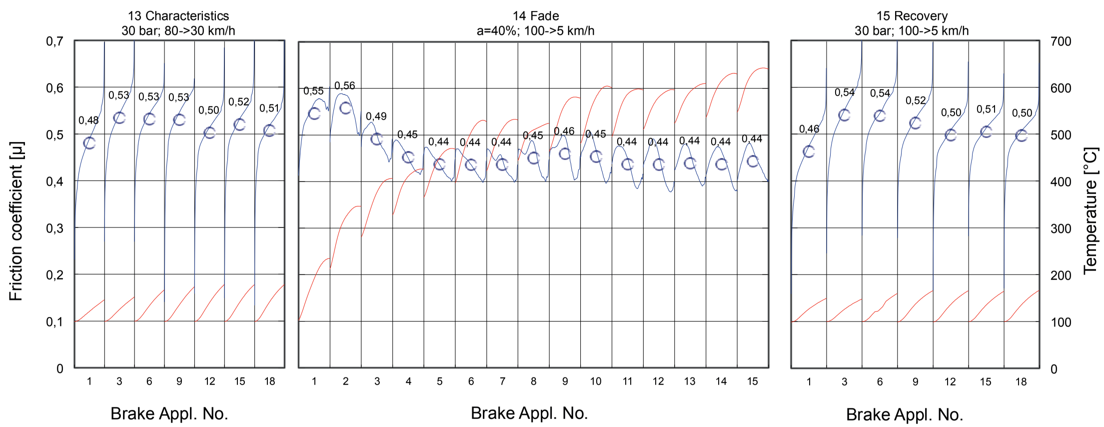
µ - 90 % (blue line)
µ - Average (circle)
t - Progress (red line)

Data sampled by UniTEST, a Software from FRÖHLICH & SCHADE GmbH, Germany, on a Krauss GmbH, Gemany, dynamometer


Lapinus
Schedule J2522
Material FB
Brake VW Golf
Test No. Fernao1611
Test Description
Date of Test 15-03-16
Inertia 65
Test Ref. Fernao1611
Cu Free FB
Friction coefficient [μ]
Temperature [°C]
1 Characteristics 30bar; 80->30 km/h
Brake Appl. No.
2 Bedding chang. 15-42bar; 80->30 km/h
30 bar Brake Appl. No.
3 Characteristics 30 bar; 80->30 km/h
4.1 Pressure sensitivity 100°C; 40->0 km/h
Pressure [bar]
4.2 Pressure sensitivity 100°C; 80->40 km/h
Pressur [bar]
4.3 Pressure sensitivity 100°C; 120->80 km/h
4.4 Pressure sensitivity 100°C; 160->130 km/h
4.5 Pressure sensitivity 100°C; 200->170 km/h
5 Characteristics 30 bar; 80->30 km/h
6 Cold Appl. VA = 40->5 km/h
30 bar
7 Motorway vA =100 km/h; vA = 160 km/h
vE = 5 km/h vE=90 km/h a=60%
8 Characteristic 30 bar; 80->30 km/h

Lapinus			Schedule	J2522	Material FB
	Brake	VW Golf	Test No.	Fernao1611	Test Description
Date of Test 15-03-16	Inertia	65	Test Ref.	Fernao1611	Cu Free FB

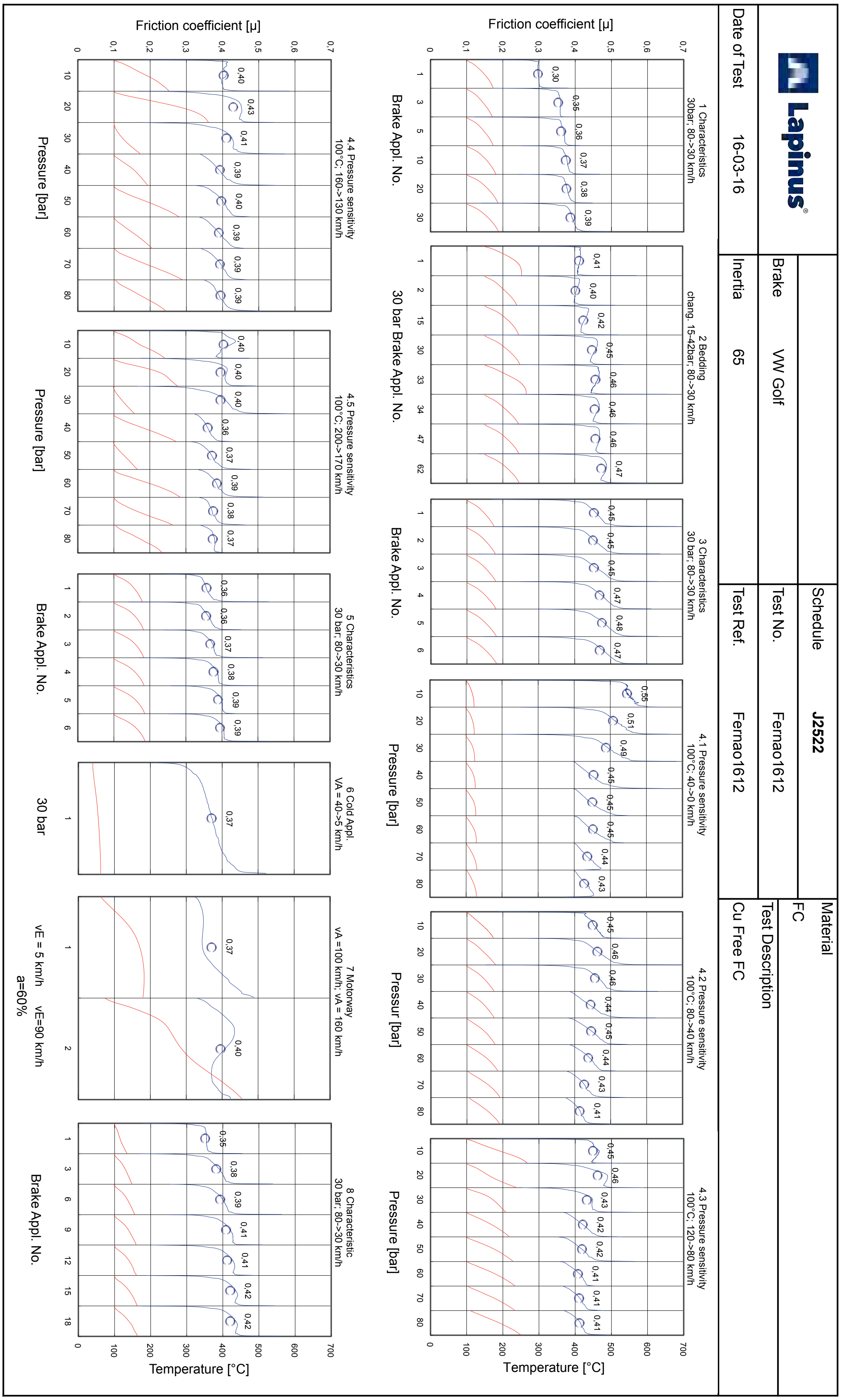




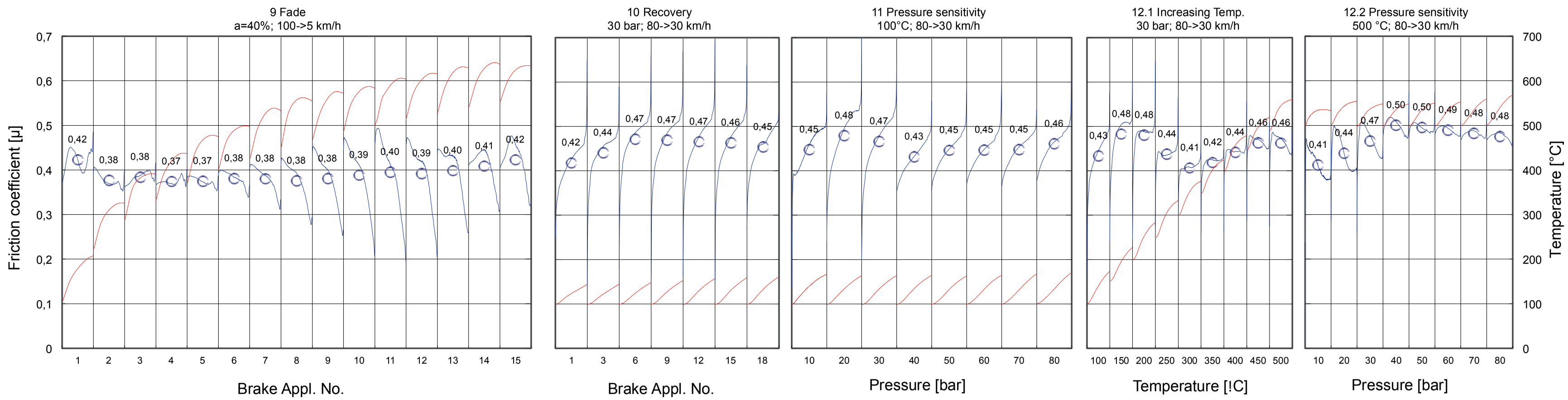
µ Values			Avg.	Min
operating	(3)	µ op =	0,50	
speed	(4.3)	µ 120 =	0,47	
speed	(4.5)	max =	0,39	
operating	(5)	µ op =	0,39	
40 C braking	(6)	µ 40 =	0,40	
motorway	(7)	µ mw =	0,41	
operating	(8)	µ op =	0,42	
1. Fade	(9)	µ f 1 =		0,37
operating	(10)	µ op =	0,48	
temperature	(12)	µ 500 =		0,39
operating	(13)	µ op =	0,52	
2. Fade	(14)	µ f 2 =		0,44
operating	(15)	µ op =	0,52	
		µ ave =	0,45	

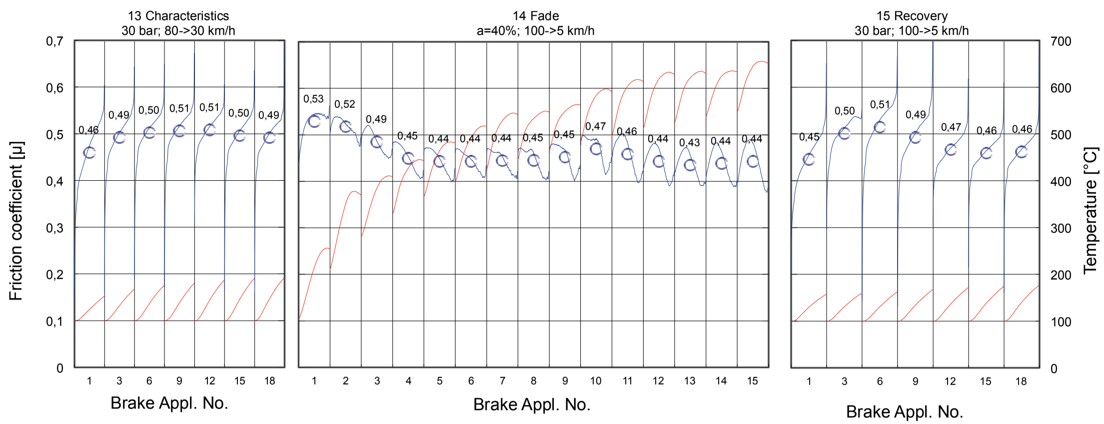
µ - 90 %
µ - Average
t - Progress

Data sampled by UniTEST, a Software from FRÖHLICH & SCHADE GmbH, Germany, on a Krauss GmbH, Gemany, dynamometer


Lapinus
Schedule
J2522
Material
FC
Brake
VW Golf
Test No.
Fernao1612
Test Description
Date of Test
16-03-16
Inertia
65
Test Ref.
Fernao1612
Cu Free FC
1 Characteristics
30bar; 80->30 km/h
2 Bedding
chang. 15-42bar; 80->30 km/h
3 Characteristics
30 bar; 80->30 km/h
4.1 Pressure sensitivity
100°C; 40->0 km/h
4.2 Pressure sensitivity
100°C; 80->40 km/h
4.3 Pressure sensitivity
100°C; 120->80 km/h
4.4 Pressure sensitivity
100°C; 160->130 km/h
4.5 Pressure sensitivity
100°C; 200->170 km/h
5 Characteristics
30 bar; 80->30 km/h
6 Cold Appl.
VA = 40->5 km/h
7 Motorway
vA =100 km/h; vA = 160 km/h
8 Characteristic
30 bar; 80->30 km/h
Friction coefficient [μ]
Temperature [°C]
Brake Appl. No.
30 bar Brake Appl. No.
Pressure [bar]
Pressur [bar]
30 bar
vE = 5 km/h
vE=90 km/h
a=60%

Lapinus		Schedule J2522	Material FC
	Brake VW Golf	Test No. Fernao1612	Test Description
Date of Test 16-03-16	Inertia 65	Test Ref. Fernao1612	Cu Free FC





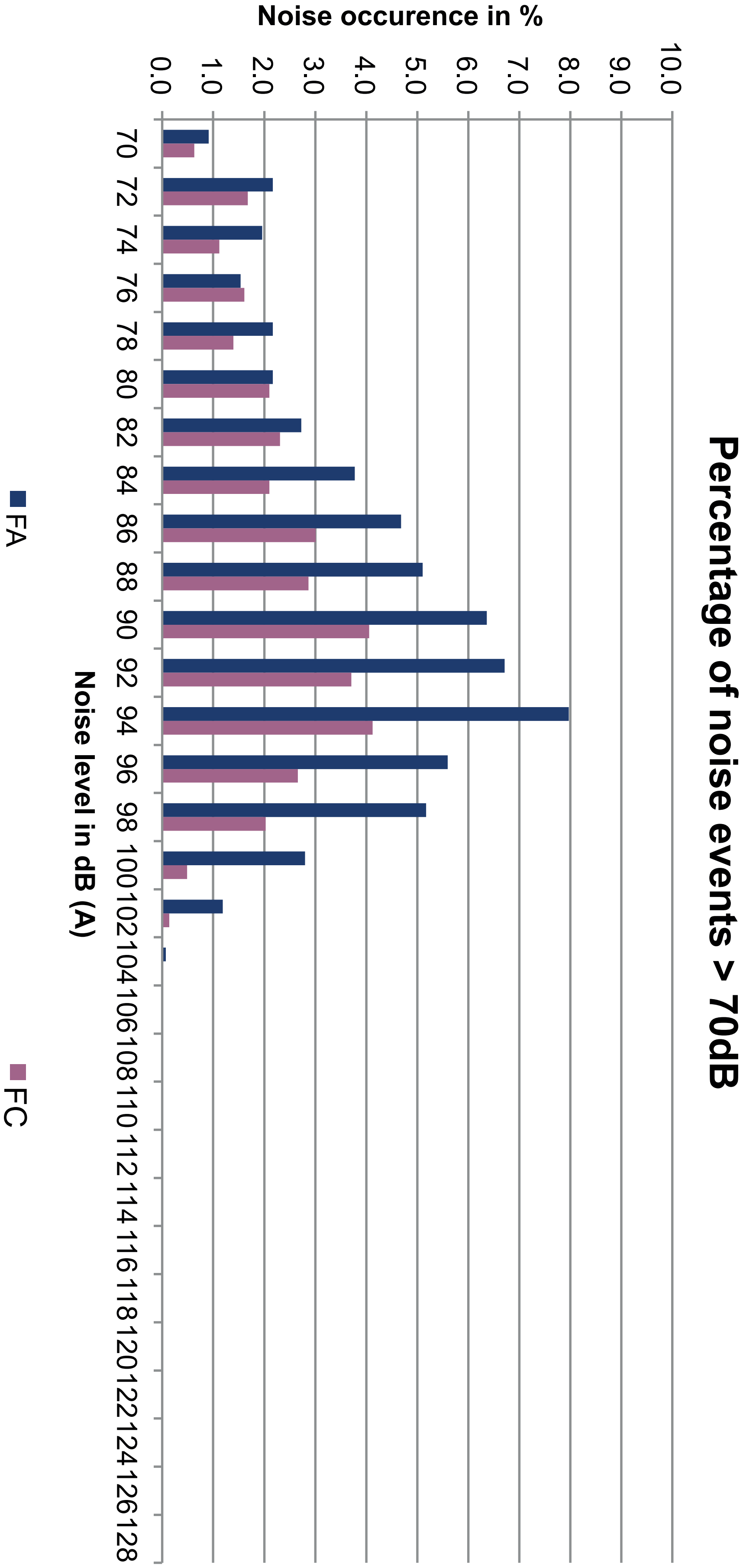
μ Values			Avg.	Min
operating	(3)	μ op =	0,46	
speed	(4.3)	μ 120 =	0,44	
speed	(4.5)	max =	0,39	
operating	(5)	μ op =	0,37	
40 C braking	(6)	μ 40 =	0,37	
motorway	(7)	μ mw =	0,40	
operating	(8)	μ op =	0,40	
1. Fade	(9)	μ f 1 =		0,37
operating	(10)	μ op =	0,46	
temperature	(12)	μ 500 =		0,41
operating	(13)	μ op =	0,50	
2. Fade	(14)	μ f 2 =		0,44
operating	(15)	μ op =	0,48	
		μ ave =	0,43	

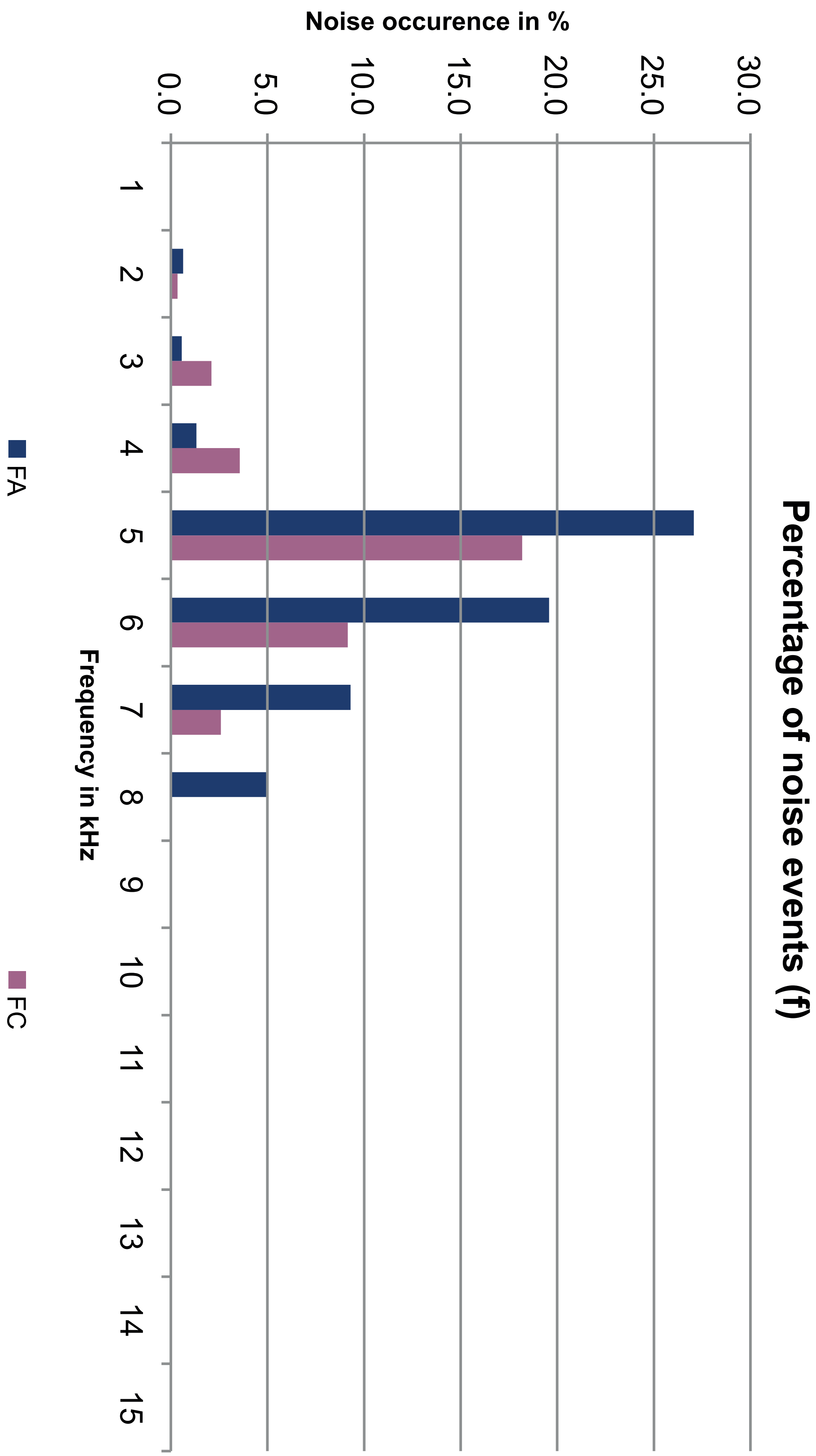
μ - 90 %	blue line
μ - Average	○
t - Progress	red line

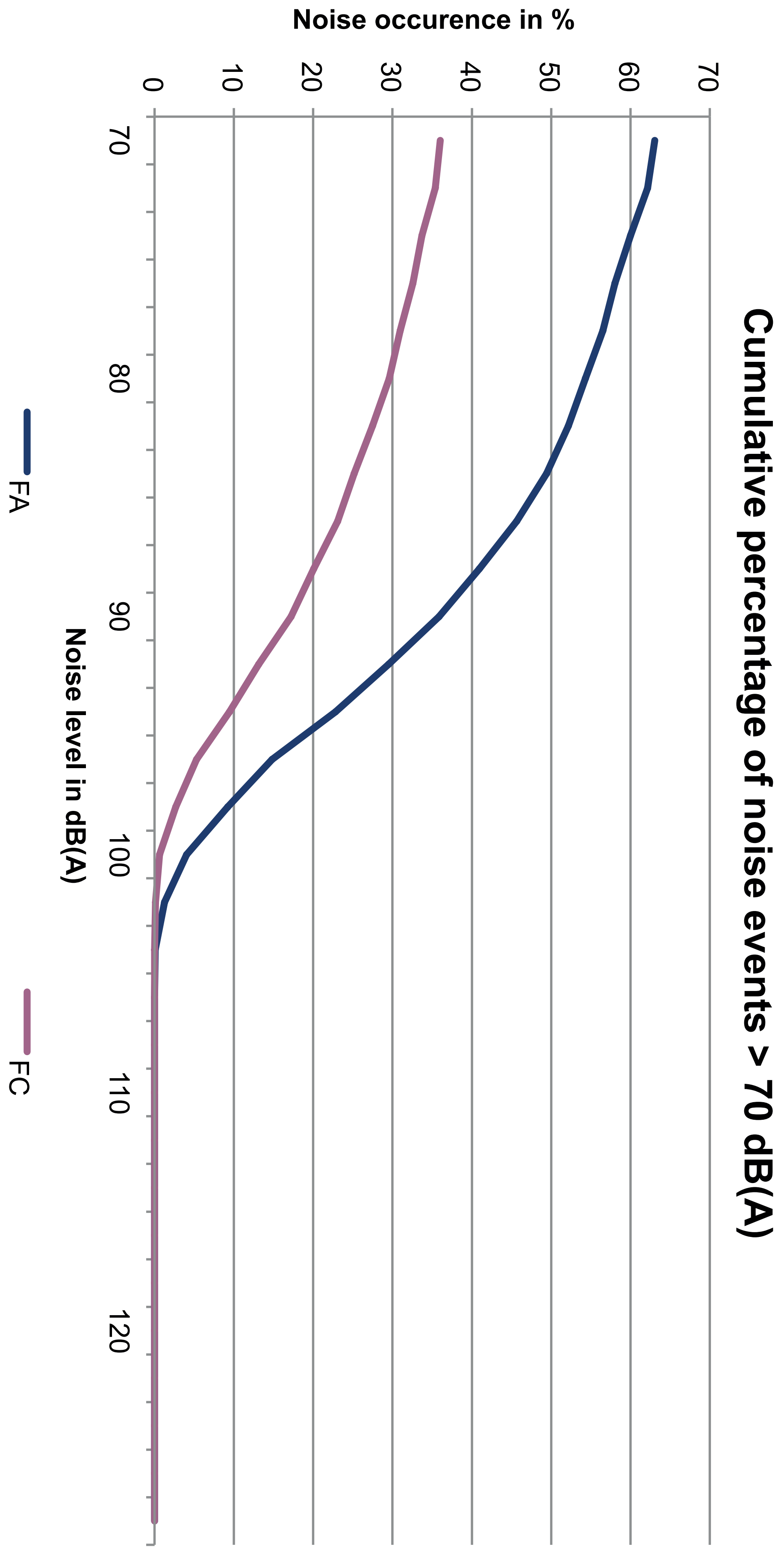
Data sampled by UniTEST, a Software from FRÖHLICH & SCHADE GmbH, Germany, on a Krauss GmbH, Gemany, dynamometer

APPENDIX 2

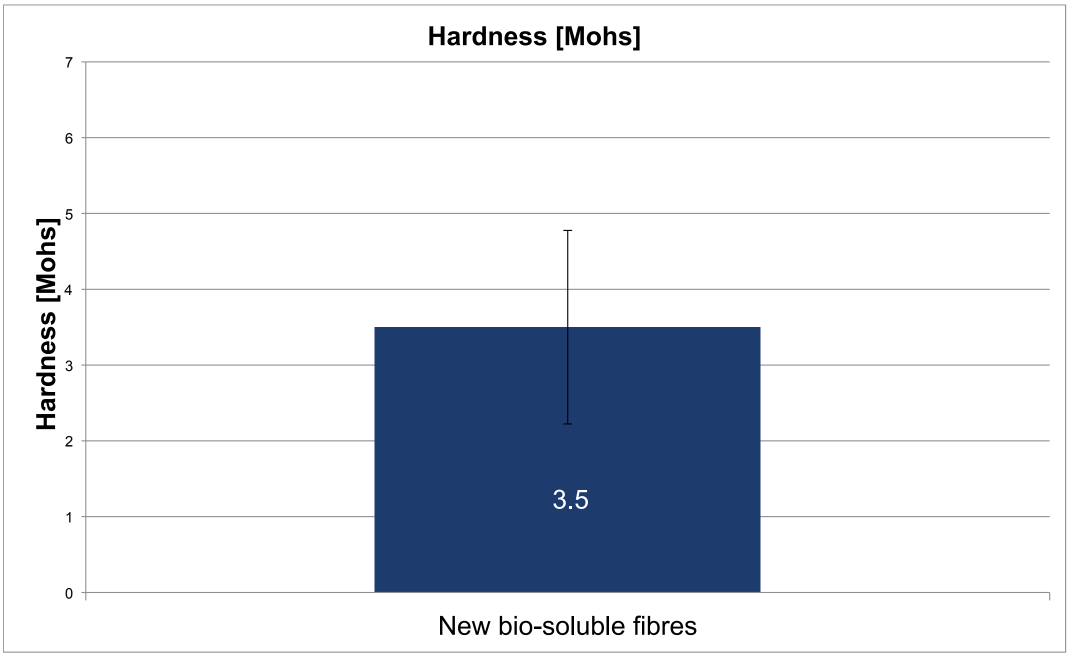
NVH RESULTS



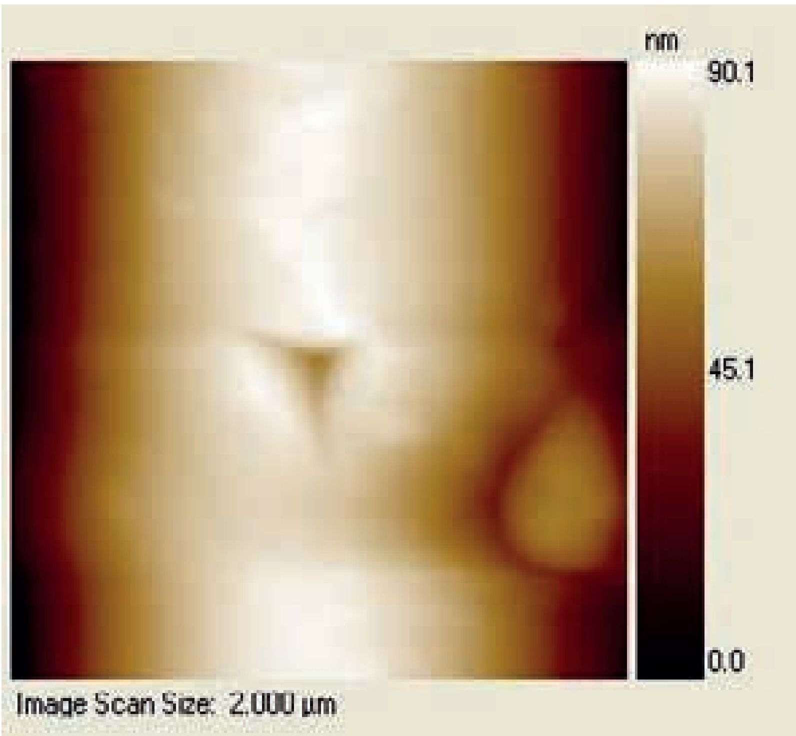

Percentage of noise events (f)
Noise occurence in %
0.0
5.0
10.0
15.0
20.0
25.0
30.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Frequency in kHz
FA
FC


Cumulative percentage of noise events > 70 dB(A)
Noise occurence in %
0
10
20
30
40
50
60
70
Noise level in dB(A)
70
80
90
100
110
120
FA
FC

APPENDIX 3
SCANNING PROBE MICROSCOPY



Measured values of hardness for new developed stone fibres



SPB Image of typical indent made by new fibre chemistry

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