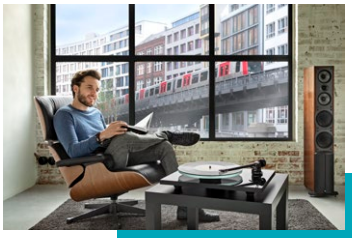
Lapinus®

Part of the ROCKWOOL Group

Resilient railway systems with stone wool



How stone wool effectively controls vibration and extends structural life for rail tracks

Introduction

The world is moving towards a future in which 80% of the population will be living in urban environments and energy resources will continue to shrink. This will result in more rail traffic, which could potentially create more vibrations and noise. Ground-borne vibrations may cause stress for people and damage to buildings and other structures. That is why as communities consider new rail projects, they are looking for more effective solutions to control ground-borne vibrations, reduce maintenance and prolong the life of track components.

Proven solution for challenging projects
In that future you can make a difference with Rockdelta stone wool mats. The use of stone wool for vibration control in railways may seem relatively new or even counterintuitive. However, they have been successfully used to control ground-borne vibrations on railways in some of the harshest conditions in Scandinavia since the early 1970s. Rockdelta® stone wool mats are backed by over 80 years of experience in stone wool production and over 43 years of expertise in vibration control solutions. Today stone wool is the preferred solution for rail track vibration control and structure protection in Scandinavia and many other countries across the globe.

This white paper provides insight into how Rockdelta stone wool mats work to control vibration and protect structures for rail tracks. It explains what properties make Rockdelta stone wool mats work more effectively compared to conventional organic materials currently used.

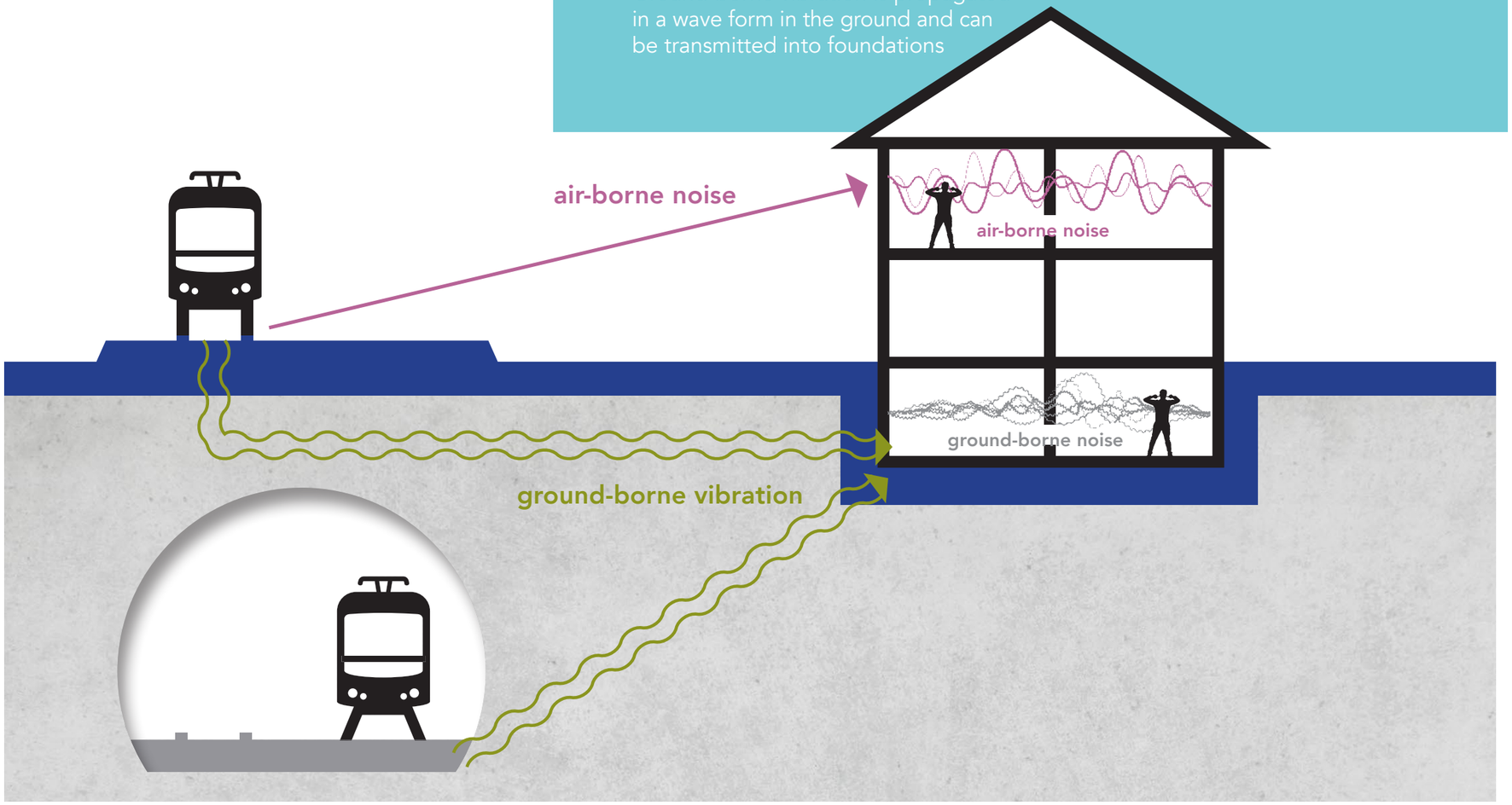
Rockdelta stone wool mats provide effective vibration control and structure protection for rail tracks.

Why add elasticity to rail tracks?
Rail traffic generates physical vibration, from the passage of wheels over rail surfaces, joints and sleepers. This vibration is transmitted as ground-borne vibration or air-borne noise.

In residential areas, the passage of cars on railways or tramways, and the resulting noise and vibration created, can cause everything from discomfort to a reduced quality of life for people living nearby. It often increases levels of stress during daytime and sleep problems at night.

Ground-borne vibration is propagated in a wave form in the ground and can be transmitted into foundations of nearby buildings. This causes vibration in the building that may damage masonry and plaster. Historical buildings and delicate machinery in buildings near rail tracks are adversely affected by this kind of vibration.

Adding elasticity to rail tracks protects people and buildings from ground-borne vibrations caused by rail transport systems. It also protects track superstructures against dynamic forces and extends the life of ballast stones by reducing wear on the track superstructure and vehicle components.

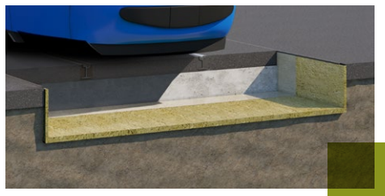


How elastic mats improve track performance

In modern railways, elastic elements are commonly used in track structures because of their proven ability to reduce maintenance costs, prolong the life of track components and improve rail-side living conditions by reducing excessive noise and vibration generated by passing trains.

Elastic elements can be added at different levels of the superstructure. Some of the most commonly used elastic elements are rail pads, sleeper pads, rail fasteners, embedded rail systems, Under Ballast Mats (UBMs), and continuous or discrete Under Slab Mats (USMs). The choice of elastic system depends on the track type (ballast or slab track), rolling stock, project and legislative specifications, required performance and other factors.

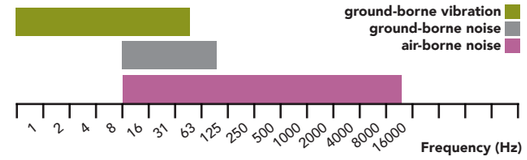
Example of Rockdelta®
RB Under Ballast Mat
for ballasted tracks



Example of Rockdelta®
RX Under Slab Mat
for ballastless tracks

Elastic mats – the effective way to control vibration and protect structures
Since the early 70s, Under Ballast Mats for ballasted tracks and Under Slab Mats for ballastless tracks have been successfully used to introduce additional elasticity in tracks. They have proven to be very effective solutions because they decouple the rail superstructure from the substructure, reach high levels of vibration isolation with low resonance frequencies and help evenly distribute track loads over the surface area, compared to other systems available. Under Ballast Mats can be used to protect the ballast from being crushed against the subgrade to extend its lifetime. UBMs and USMs are also some of the simplest ways to build transition zones in railways due to their wide range of stiffness.

Vibration isolation
Vibrations are inherent to all traditional railway systems due to the interaction between the wheel and the rail.

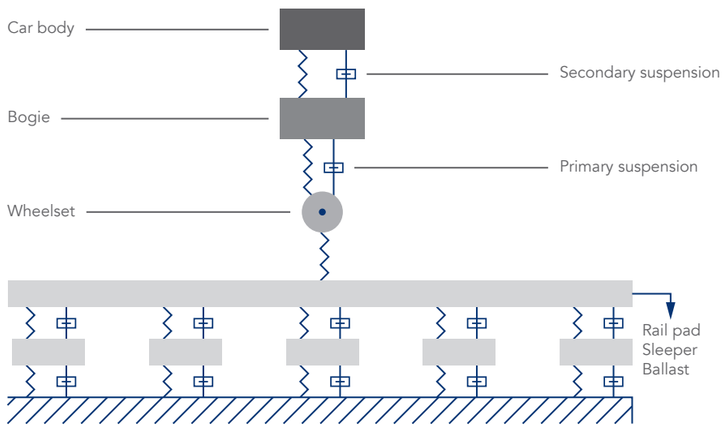


Rockdelta enables an optimal reduction of vibration in a range from 16 up to 120 Hz, depending on the project specific conditions and frequency.

When vibrations are generated in the track (the source), they are transmitted as mechanical waves through the ground (the path) to adjacent structures (the receiver). Once vibrations reach the receiver, they can be perceived by people as a noticeable vibration (ground-borne vibration) or disturbing noise (ground-borne noise from a resonating structure). Although vibrations can be tackled at the source, path or receiver, it has been proven that the most effective way of isolating or attenuating vibrations is by acting at the source: the track. It is exactly here where Rockdelta elastic mats are placed.

To reduce rail vibrations, it is necessary to introduce elasticity to the track components that dissipate the energy generated by the passing train and thereby attenuate the vibrations. In contrast to audible sound, vibrations have the biggest impact at low frequencies (between 1 and 200 Hz).

Reducing vibration through the mass-spring effect
As a railway is built up of several layers and components, each having its own stiffness, a track can be modelled as a multi-degree-of-freedom system. However, to explain the basic principle, a simplified single-degree-of-freedom model can be created, where the acting mass is the sum of all fixed railway elements (the unsprung mass of the train, rails, fastenings, sleepers, ballast bed or concrete slab, etc.), and the spring is the sum of all elastic components in the track. In the actual design phase of a track, we use the more accurate multi-degree-of-freedom calculations.



Now imagine a railway system situation. The running train generates a force which is transmitted from the top of the rail to the elements below the track superstructure. To limit the effect of those forces, a spring (elastic material or isolator) should be inserted to absorb mechanical energy.

When an elastic element is placed under a track, the element will change the vibrational response by first amplifying the vibration effect until it reaches its peak, called the resonating frequency. As from that point, the system will start losing energy and start isolating. The frequency at which the system is resonating depends on the mass as specified by the track design and the spring constant given by the type of isolating system. To determine the effectiveness of a vibration isolation system, the best compromise between the k_{dyn} spring constant and the mass must be calculated.

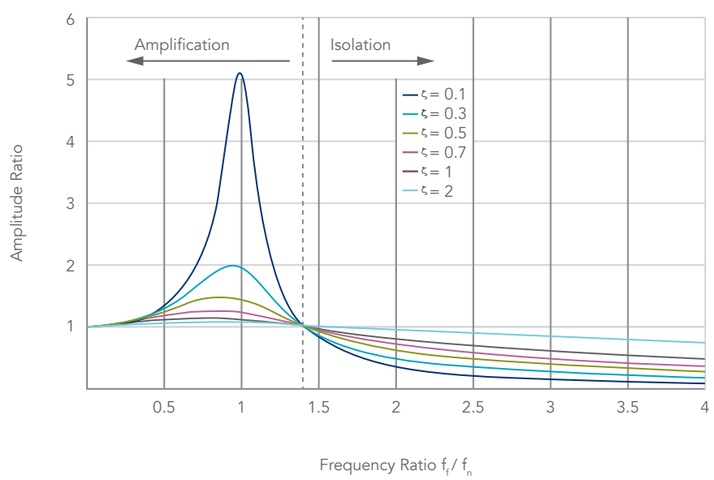
The effectiveness of an isolator depends on three main parameters:
- The acting mass (m) = The track
- The isolator stiffness or bedding modulus (k_{dyn})
- The damping (ζ) of the isolator

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k_{dyn}}{m}}$$

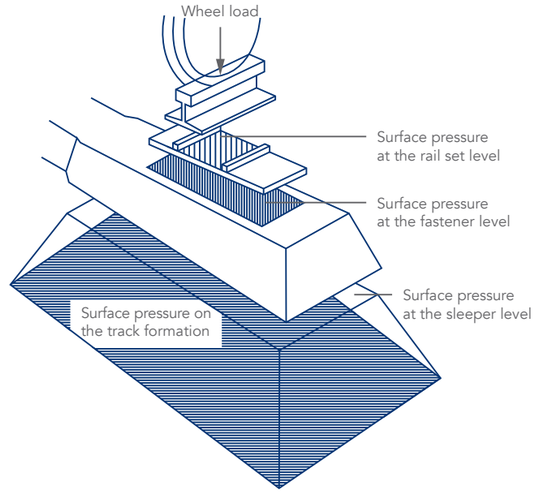
For a single-degree-of-freedom system, a lower spring constant (called stiffness) or a higher mass will result in lower resonance frequency and thus a higher vibration isolation performance. Note that, contrary to common belief, the higher the level of damping, the less effectively the system works as a vibration isolator.

Transmissibility

This figure illustrates how a system loses energy after reaching its natural frequency



Ballast and substructure protection



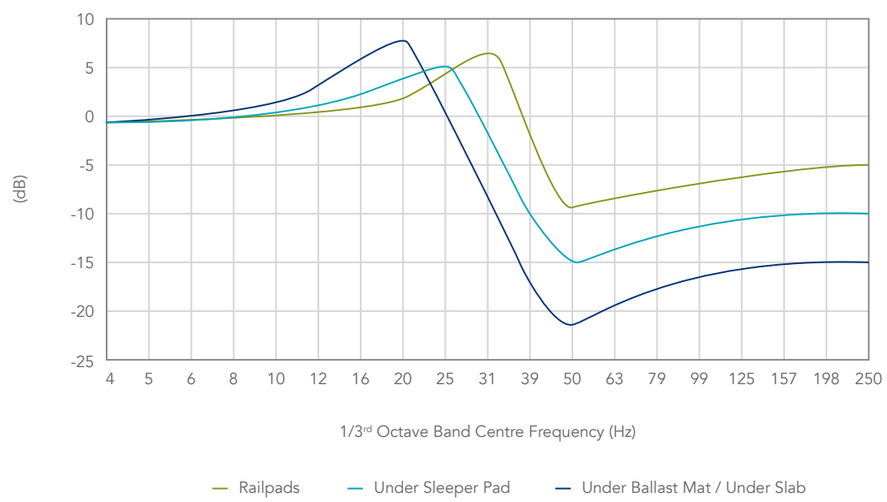
Stress distribution
Tracks are designed to transfer loads through the different components of the superstructure to the foundation. In general, the deeper the loads travel through the track, the lower the stress level becomes as a result of the increasing area of the active bearing surface. Since stresses are more important at higher levels of the track, elasticity (stiffness) of the components must be carefully defined. Mats are exposed to lower levels of stresses as a result of a higher bearing load surface, so they can be designed to have low stiffness values.

When the loads generated by a running train are not properly distributed on to the rail and the other track components, this can accelerate the deterioration of the superstructure. It has been proven that by adding elasticity to the track, the active load bearing surface is increased and, therefore, the stresses on the track components are lowered. This extends the life time of track components and reduces wear-related expenses and maintenance efforts. This is the reason Rockdelta elastic mats are placed between the ballast bed or concrete slab and the foundation.

Since Under Ballast Mats and Under Slab Mats are elements that continuously support the entire track, they add extra elasticity to the track and thereby spread the train load over a higher number of elements (rail pads, fasteners and sleepers). In the life cycle of track components, less stress leads to less maintenance and a longer life span. Because of their higher bearing surface (mass [m]) and low stiffness values (k_{dyn}), Rockdelta Under Ballast Mats and Under Slab Mats outperform other track isolation solutions, providing a low resonance frequency (f_{res}), while limiting track deflection.

Insertion Loss

Comparison different isolation systems



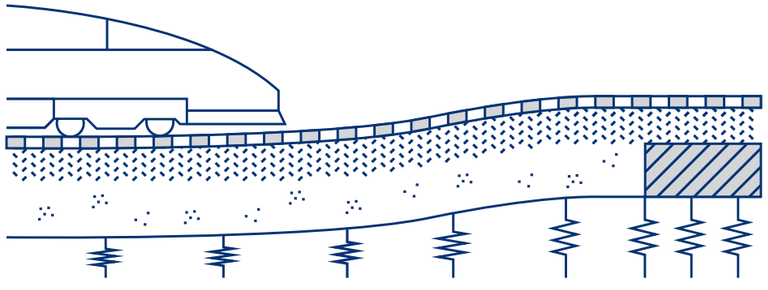
Ballast and rigid structure protection
Another point of concern in ballasted tracks is ballast crushing. The ballast stones deteriorate due to the constant dynamic forces that crush them against the hard subgrade. Ballast crushing can:

- Compress the bed of the track making it stiffer, which can affect its vibration isolation performance
- Increase maintenance costs for tamping and replacing faulty track components

The use of an elastic element such as an Under Ballast Mat decouples the ballast bed from the subgrade to prevent ballast crushing and extend the life of the ballast stones.

Under Ballast Mats and Under Slab Mats also provide protection for the rigid structure of ballasted bridges.

Transition zones
Elastic systems offer advantages for building smooth transition zones. These are a major challenge when engineering railway lines, which usually have a mix of different superstructures: standard ballasted tracks, slab tracks, bridges, tunnels, etc. Each behaves differently and has different stiffness properties. A transition zone is a length of the track which has to smooth out the effects of a train as it passes from a rigid zone to a softer zone or vice versa.



The easiest way to build transition zones is by placing elastic elements just below the ballast bed or slab track. Creating transition zones with other methods, such as by varying the sleeper spacing or the fastener stiffness is complicated and requires a high degree of precision. By simply changing the stiffness of the elastic mat, the overall stiffness of a section of track can be easily adapted.

Unique advantages of stone wool for elastic mats in tracks

Release the natural power of stone to improve track design
Track engineers and consultants often face conflicting demands when designing a track: they need to assure track stability to guarantee user safety and comfort, and they need to assure sufficient track elasticity to meet legal requirements for ground-borne vibrations. As said before about track elasticity, Under Ballast Mats and Under Slab Mats have proven very effective solutions, providing a high level of vibration isolation with low resonance frequencies and the best distribution of track loads when compared to other systems on the market.

Stone wool is well known for its exceptional performance as an energy-saving, fire-resistant and environmentally friendly, thermal insulation material. It benefits many other industrial applications as well: acoustic control in ceiling systems, façade panel boards, reinforcement fibres in brake linings, gaskets and plastics.

Thanks to its non-directional fibre orientation, stone wool also has some unique characteristics that make it ideal for adding elasticity to tracks. Using a Rockdelta stone wool-based solution for an Under Ballast Mat or Under Slab Mat delivers resilient and effective track support. This material provides unsurpassed fatigue resistance, ultra-low sensitivity to environmental factors and advanced fire and smoke safety features.

Lapinus, part of the Rockwool Group, brings the Rockdelta product line to the market. Rockdelta products are an acknowledged solution in the industry. They meet the most demanding international standards for specifying UBMs and USMs, including the BN 918-071-1, DIN 45673-5 and DIN 45673-7 railway norms drafted by the German Deutsche Bahn. Lapinus also helps shape new standards as an active member of the European Committee for Standardization working groups for drafting the future European norms for the evaluation of Under Ballast Mats and Under Slab Mats.

Rockdelta® RB
Under Ballast Mats

A dual-density sub-ballast mat made up of a low-damping, soft and resilient bottom layer and a high-density, force-distributing top layer.

Rockdelta® RX
Under Slab Mats

Full-contact, continuous single-density mat that introduces a very efficient spring-damper element into the track structure. It effectively decouples the dynamic behaviour of the concrete slab and the track system from the ground.

Rockdelta® RG
Ballast Protection Mats

Full-contact, continuous single-density mat which decouples the ballast bed from the substructure, preventing ballast crushing and protecting the substructure from the dynamic forces of the ballast.

Vibration reduction up to 30 dB with resonance frequencies between 15 Hz and 30 Hz can be achieved, depending on the train and track design, conditions and stiffness of the chosen Rockdelta solution.

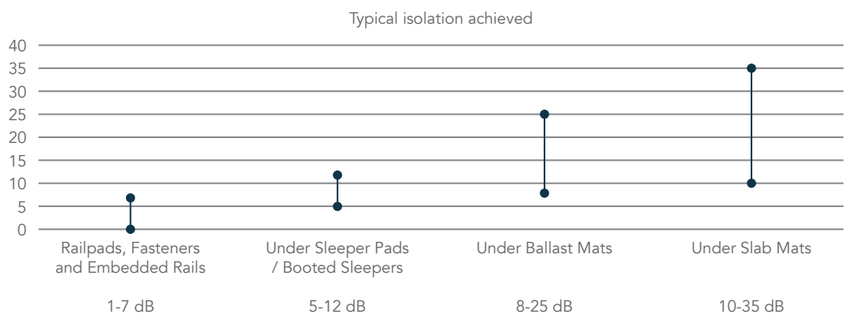
Vibro-acoustic capabilities

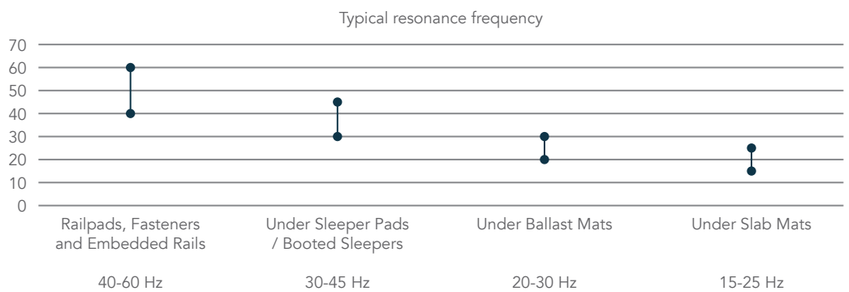
Effectively reduces vibration and noise

There are many factors that determine how well an elastic material will perform when used to control track vibration and noise. While the static stiffness or static bedding modulus C_{stat} determines how the mat behaves under certain loads, the dynamic stiffness or dynamic bedding modulus C_{dyn}, as described by the mass-spring system, determines how well the mat will isolate vibrations.

Rockdelta stone wool mats provide premium vibro-acoustic performance as confirmed by on-site measurements from numerous installations. A vibration reduction of up to 30 dB in the critical range of active frequencies with resonance frequency between the 10 Hz and 20 Hz can be achieved, depending on the train and track design, conditions and stiffness of the chosen Rockdelta solution.

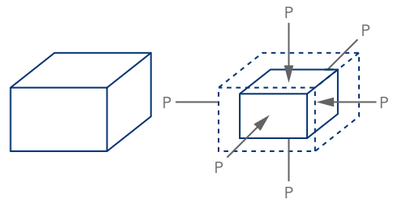
Typicial vibration reduction and resonance frequencies values for different track systems





Track dimensioning support
The dimensioning of an elastic solution can be challenging. The experts at Lapinus work together with your team to assess the expected rail deflection and insertion loss levels (reduction mitigation achieved by using Rockdelta RB, RX or RG systems). We then perform multi-degree-of-freedom calculations to help you choose the right solution for your track. These calculations are used for the final design as they have proven to be more accurate than single-degree-of-freedom calculations used in a preliminary design.

The following material properties of Rockdelta mats influence their ability to effectively reduce vibration and noise.



Rockdelta elastic mats possess a uniquely high degree of volume compressibility with a Poisson's Ratio of almost zero.

Excellent dynamic properties with first-rate volume compressibility
In confined space applications, such as concrete slab tracks, viaducts, tunnels or bridge decks, the material's ability to absorb loads with no significant change in its elastic properties is important. The stone wool elements in Rockdelta mats consist of interconnected fibres, so they compress when force is applied and then resume their original shape. This ability is described via the bulk elastic (volume compressibility) properties of the material, which determine how much the material compresses under an external load. Rockdelta elastic mats possess a uniquely high degree of volume compressibility with a Poisson's Ratio of almost zero. For Under Slab Track application, this is a key advantage since the stiffness of Rockdelta RX mats remains consistent across the track bed width.

Low dynamic-to-static stiffness ratio
The static bedding modulus C_{stat} is a parameter used to determine the compression of the ballast mat while under service loading with a train running at a quasi-static speed.

The dynamic bedding modulus C_{dyn} at low frequencies relates to the elastic rail deflection of a moving train at higher speeds, whereas the dynamic bedding modulus at medium and high frequencies generally relates to the mat's vibration isolation capacities. This suggests that a resilient mat that combines a high static stiffness with a low dynamic stiffness (at medium and high frequencies) is beneficial, since such a mat will help to minimise the potential conflict between maximum allowable elastic rail deflection and the necessary (minimum) level of vibration isolation.

All Rockdelta resilient mats exhibit a low dynamic-to-static stiffness ratio with a typical value of 1.3 and they have proven to deliver this performance in numerous installations.

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A broad range of stiffness
Railway lines have different superstructures with different stiffness properties. To provide the optimal performance for each application and project specifications, Lapinus can offer a wide range of stiffness. Rockdelta solutions can be split into three main application areas:

- Rockdelta RB: Under Ballast Mats designed to control ground-borne noise and vibrations in ballasted tracks. The static bedding modulus C_{stat} is available from 6 to 53 MN/m³
- Rockdelta RX: Under Slab Mats designed to control ground-borne noise and vibrations in ballasted tracks. The static bedding modulus C_{stat} is available from 8 to 22 MN/m³
- Rockdelta RG: Under Ballast Mats designed to protect the ballast layer and substructure, as well as provide effective ground-borne noise and vibration mitigation. The static bedding is available up to 75 MN/m³

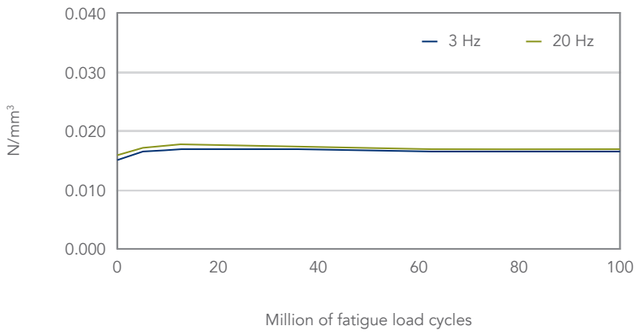
The stiffness of Rockdelta mats comply with the most relevant and well-known industry standards, including BN 918 071-1, DIN 45673-5, DIN 45673-7 and ISO 10846-2.

Robustness
Performs consistently under any conditions

Fatigue strength
In railway and transit track design, predictability and longevity are key requirements. For elastic track solutions two parameters are of special importance: uniform rail deflections and the level of vibration isolation. The rail deflections should preferably be constant and known for the entire lifetime of the track, since excessive deflections can lead to fatigue problems in the rails and thus higher maintenance costs. High deflections can also lead to operational safety issues.

There is virtually zero long-term variation of the low frequency dynamic bedding modulus at 3 Hz and 20 Hz on a Rockdelta® RX mat after 100 million cycles.

Dynamic stiffness at 20 to 100 kN/m³ periodic load



The graph on the left virtually shows zero long-term variation of the low frequency dynamic bedding modulus at 3 Hz and 20 Hz on a Rockdelta® RX mat after 100 million cycles.

Rockdelta RB, RX and RG products lines show less than 10% variation in their bedding modulus properties and an outstanding fatigue strength after undergoing demanding mechanical strength tests at globally recognized laboratories, according to the BN 918 071-1, DIN 45673-5 and DIN 45673-7 norms.

Resistance to extreme temperatures and UV rays
Many key characteristics of elastic mat materials are prone to changes when stored improperly. For example, storage and transportation hardening occurs with some types of rubber, as a result of spontaneous cross-linking or due to problems with stacking. Low temperature crystallisation and, most importantly, exposure to sunlight can adversely affect stored materials. Although some of these effects may be reversible to a certain degree, the problems associated with storage and transportation will often be revealed only after a material has been installed in the track substructure, which can result in time-consuming and expensive repairs.

Thanks to their inorganic and chemically inert nature, Rockdelta mats can be transported and stored worry-free. Rockdelta elastic mats exhibit no transportation hardening, no low temperature crystallisation and no sensitivity to sunlight exposure. Following the international standard ISO 4892-3, the changes in the compressive strength of Rockdelta stone wool have been measured to be less than 10%, when exposed to 0.2 GJ/m^2 UV radiation (3 years of exposure of the material to UV).

Resistance to ozone, oil and grease
Because of their location in the track superstructure, Under Ballast Mats and Under Slab Mats will have limited exposure to high ozone concentrations, oil and grease; however, for safety reasons, ozone exposure remains a concern for railway operators. The ozone properties of Rockdelta stone wool mats have been tested according to the DIN 53509-1:2001-01 standard and showed that the change in the static bedding modulus of the material was lower than 5%, and no cracks or abnormalities were present after ozone exposure.

Additionally, Rockdelta stone wool mats have been tested for resistance to oil and grease according to the ISO 1817:2008-08 international standards. The results showed that the change in the static bedding modulus of the material was lower than 1% after exposure to oil and grease.

Ageing
Carrying out accelerated aging tests in a laboratory is a way of evaluating the service life and long-term safety of the properties of a product. When measuring the change in mass and in the static bedding modulus of the Rockdelta mats according to the DIN 53508 standard, practically no difference was found in either. The dynamic and static stiffness of Rockdelta mats remain virtually unaltered, even after decades of use.

Resistance to chemical, biological and environmental factors
Acid rain is probably one of the most common environmental conditions experienced by a track. This environmental condition relates to above-ground, open-air tracks but can also potentially affect underground tracks due to flooding and other moisture issues. Some materials such as polyurethane are attacked by moisture and organic elements which can reduce their elastic properties. Elastic mats made of stone wool, which is an inorganic material, exhibits outstanding resistance to all naturally occurring soil alkalis and acids. Since Rockdelta elastic mats are inorganic and chemically inert, microorganisms, bacteria and fungi do not adversely affect stone wool.

Fire resistance

Protects construction environment from fire

Rockdelta's Under Ballast Mats and Under Slab Mats can withstand temperatures above 1000°C.

Made of volcanic rock, Rockdelta's Under Ballast Mats and Under Slab Mats have outstanding fire resistance. They can withstand temperatures above 1000°C. Rockdelta mats are A2 classified (s1,d0) under the EN 13501-1:2007 + A1:2009 standards, meaning they do not contribute to fires, are non-combustible and produce minimal smoke emissions and no flaming droplets or particles during combustion.

Fire resistance is an important aspect that can increase safety and reduce risk of financial losses during and after railway installation. Rockdelta products:

- By nature will not burn nor contribute to the spread of fire or generation of toxic smoke.
- Are not affected by potential fires in storage areas or depots for construction materials to reduce the risk of financial losses
- Are immune to damage caused by sparks or droplets from the welding of rails, eliminating the need to replace damaged sections of mats after steel reinforcements are in place

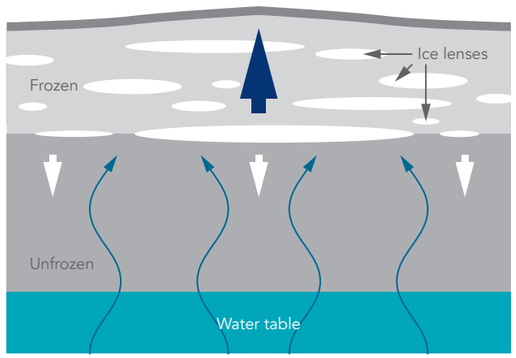
Thermal properties

Insulates against frost heaves and heat loads

In environments with extreme weather conditions, Rockdelta mats provide robust performance regardless of sub-zero or high temperatures. When tested according to the DIN 45673 standards, the dynamic bedding modulus of the Rockdelta mats is relatively stable. There is less than 8% variation in the properties of the bedding modulus when compared at -25°C and at 25°C. That means the ambient temperature does not affect the mats' ability to mitigate vibration.

There is less than 8% variation in the properties of the Rockdelta bedding modulus when compared at -25°C and at 25°C.

Moreover, thanks to their excellent thermal isolation properties, Rockdelta stone wool mats significantly suppress the potential effects of frost heaves (upward swelling of soil at freezing temperatures), a common occurrence with ballasted tracks in cold climates. Frost heaves can cause track deformations and damage track components that are costly to repair. By limiting the effects of frost heaves, Rockdelta mats preserve the track geometry for the entire lifetime of the mats, significantly reducing the cost of maintenance.



Frost heave

When water from the water table freezes, it expands, creating ice lenses. When it thaws back into the soil, the ice lens leaves a gap in the soil which weakens the ground. This gap is known as a frost heave.

A good way to avoid the frost heave phenomenon is to build a proper drainage system that prevents water coming from the surface, and thermally isolate the foundation using Rockdelta mats.

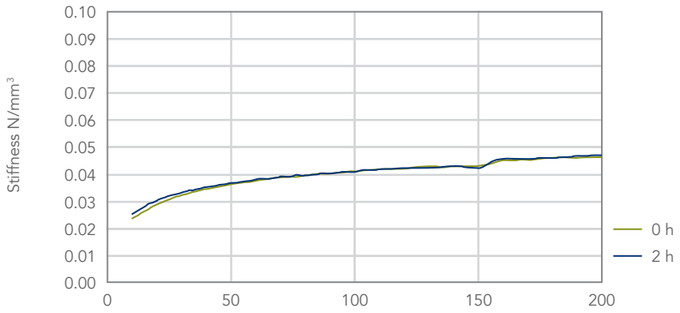
Water properties

Resistant to water

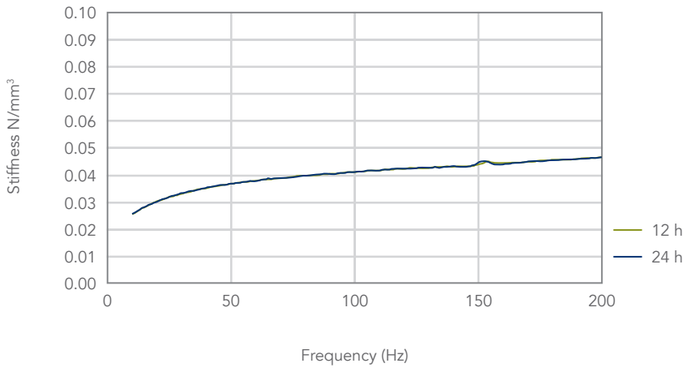
Even after 24 hours, the difference between the stiffness curves of the dry and wet samples of the Rockdelta stone wool mat was hardly noticeable.

Many polyurethane and rubber elastic materials are sensitive to water, which can degrade their stiffness and thereby lower the vibration isolation performance and change the track dynamics. The stiffness and damping of Rockdelta elastic mats remain virtually unchanged after water immersion.

The resistance of stone wool to water has been proven by testing the dynamic stiffness of the mats according to the ISO 10846-2 international standard by immersing a sample in water for 2, 12 and 24 hours. Even after 24 hours, the difference between the stiffness curves of the dry and wet samples of the Rockdelta stone wool mat was hardly noticeable. In the same tests, a 30% change in the dynamic behaviour of the mat's polyurethane counterparts was observed.



Rockdelta - dry/wet
Dynamic stiffness
C_{dyn} tested according to ISO 10846-2:1997
Constant sine velocity
5 mm/s rms



Rockdelta - wet
Dynamic stiffness
C_{dyn} tested according to ISO 10846-2:1997
Constant sine velocity
5 mm/s rms

The water resistance properties of stone wool have also been evaluated according to the DIN 45673-5 and DIN 45673-7 standards and showed a variation of less than 6% in the static bedding modulus of the material after being immersed in water for 168 hours at 50°C.

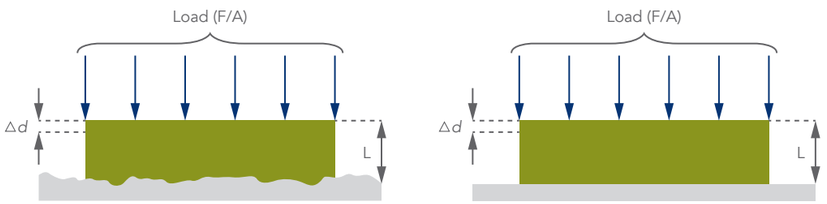
Installation and storage

Efficient and simple

Rockdelta elastic mats can be quickly, easily and safely positioned in the track bed. They are lightweight for easy handling by one person, easy to cut and easy to fit into curves and special track works without applying glues, thermos sealers or adhesive strips. Based on our project experience, up to 30-40 m^2 of Rockdelta elastic mats can be installed per man hour, making them one of the fastest to install systems on the market.

Rockdelta mats can be installed directly on compacted ground (no smooth concrete layer needed) with an Ev2 as low as 40-50 MPa.

No special preparation of the substructure is required to achieve a specified level of Insertion Loss with Rockdelta mats. They have a unique feature that allows them to withstand surfaces that are not completely even. The mats can be installed directly on compacted ground (no smooth concrete layer needed) with an Ev2 as low as 40-50 MPa and small sharp objects or stones can be left underneath the mats without influencing their functional performance. This simplifies formation levelling and reduces project construction works.



The diagram above on the right shows a perfectly leveled sub-grade while the left diagram shows an uneven sub-grade. Rockdelta elastic mats can be installed in both situations with no change in Insertion Loss.

Finally, thanks to their excellent durability, non-flammability and resistance to extreme temperatures and UV rays, Rockdelta stone wool mats can be stored near the installation site indoors or outdoors, in a non-covered storage area, inside of a tunnel, etc.
This significantly reduces the storage costs for the materials.

Aesthetics

Can be used with all track top finishes

When building tramways and other transportation systems in urban environments, aesthetics is an important concern for governments, administrations, owners, project designers and architects. Rockdelta mats can be used with all track top finishes, such as natural grass, artificial grass, asphalt, cobblestones and concrete to create beautiful public environments.

Circularity

Natural product for a circular economy

Stone wool is 100% recyclable so it can be re-used again and again.

Stone wool is a natural product made primarily from the volcanic rock basalt. Basalt is a sustainable raw material, sourced directly from our earth and is almost inexhaustible: every year the earth produces many times more basalt than is used for the production of stone wool.

Stone wool is produced in a sustainable and environmentally friendly way and is 100% recyclable. It can be re-used again and again, engineered into new stone wool, contributing to a circular economy.

Rockdelta elastic mats are manufactured at Rockwool factories in compliance with the following standards: Quality System Certificate, EN ISO 9001:2015 Environmental Management System Certificate 14001:2015.

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1. International Union of Railways (UIC). "Recommendations for the use of Under Ballast Mats. UBM". June 2011. Paris, France.
2. International Union of Railways (UIC). "Railway Induced Vibration. State of the art report". November 2017. Paris, France.
3. Lakušić S. Ahac M. "Rail Traffic Noise And Vibration Mitigation Measures In Urban Areas". June 2012. Technical gazette, Vol. 19 No. 2. Slavonski Brod, Croatia.
4. Prakoso, P. "The Basic Concepts of ModellingRailway Track Systems usingConventional and Finite Element Methods". July 2012. Info Teknik, Volume 13 No. 1. Banjarmasin Utara, Indonesia.
5. Esveld, C. "Modern Railway Track. Digital Edition Version 3.8". 2001. MRT-Productions. Zaltbommel - The Netherlands.
6. Nawrat, W. Gatzwiller, K.B. "Substructure versus Superstructure Resilience: An Investigative Look into the Key Differences from a Ground-Borne Vibration Perspective". June 2013. Railway Technology. London, UK.

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