

TECHNICAL REPORT

INFLUENCE OF VOLCANIC ASH ON FATIGUE LIFE OF STEEL WIRE ROPES

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Framework

In recent times, many users of steel wire ropes for cableway installations have consulted about how certain atmospheric factors affect the performance of steel wire ropes.

On June 4th 2011, the Puyehue volcano, located in Cautín, between the regions of Los Lagos and Los Ríos, Chile, erupted throwing to the atmosphere a cloud of ashes. This cloud crossed the Andes entering Argentina, and affecting the daily life of thousands of people in cities such as Villa La Angostura, Bariloche, Villa Traful, San Martín de los Andes. Even Buenos Aires and Montevideo were affected.

The winter resorts of said cities were not strangers to the consequences of this eruption. Great amounts of volcanic ashes deposited over steel wire ropes of cableway systems, creating uncertainty within the users about how the ashes could affect the performance of their equipment.

Introduction:

In order to quantify the influence of the presence of volcanic ash on the steel wire ropes in their useful life, the field working conditions of these wire ropes were replicated under laboratory conditions.

A wire rope test piece was obtained as a reference standard, whose characteristics are detailed later, and fatigue tested in a test bench owned by IPH in its plant, located in San Miguel, Buenos Aires. Then the fall of volcanic ash was artificially simulated on two stretches of the same wire rope to also fatigue test them and to quantify the loss of performance in comparison with the reference standard.

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How does a steel wire rope fail due to fatigue?

In a typical cableway installation, the steel wire rope is subjected to multiple thousand cycles of fatigue during its life. These cycles are present due to the combination of traction and flexion stresses.

Fatigue is a change in the wire rope's linear stress state.

During fatigue under simple flexion, each cycle generates on the wire rope a compression stress (in the area of support with the pulley) and one of traction in the opposite zone.

The fatigue cycles do not occur only due to flexing induced by the pulleys or the load of the equipment. They may also happen due to dynamic loads generated by external factors (eg, climatic factors).

These fatigue cycles cause diverse failure modes on the wire rope. In this report, wire breaks were taken into account by flex fatigue cycles. Failure modes are described below:

1. Broken wires on ridges due to variation of traction-compression stress generated per flex cycle.
2. Broken wires on ridges due to friction and abrasion against elements of the installation.
3. Broken wires on valleys due to friction between strands
4. Broken wires on valleys due to friction against the steel core.
5. Localized diameter reduction as a consequence of all the above.

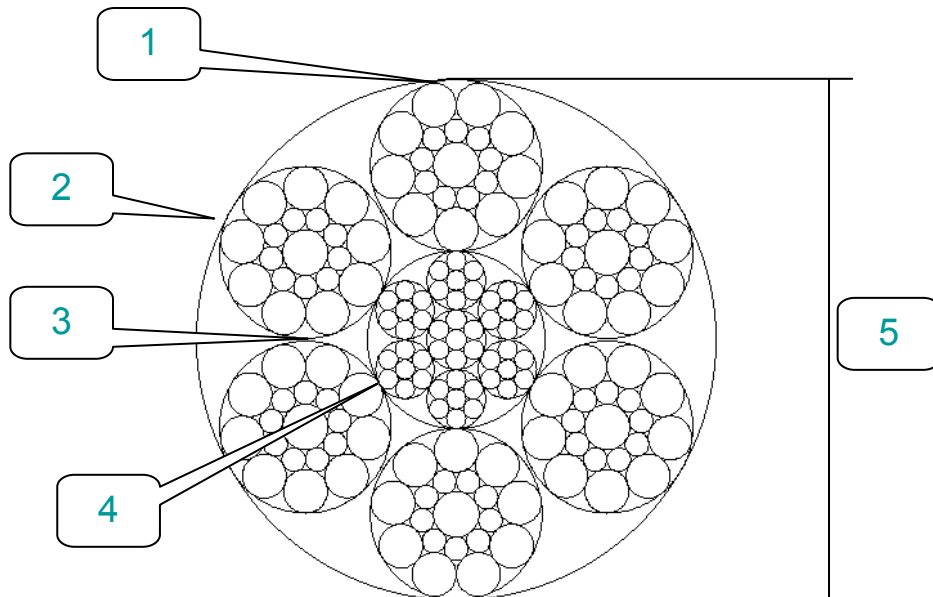
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Shown below is the cross-sectional view of the tested wire rope, where the failure modes are indicated.



Methods:

From December 2011 to July 2012 the three wire ropes previously mentioned were fatigue tested. During the preparation of the samples, installation, testing, and analysis, personnel from IPH's Engineering Department worked together with the Ropeways Department from the National Institute of Industrial Technology (INTI).

1- Test Bench:

The test bench used in this experience gives the possibility to perform flexural fatigue tests where each wire rope section or zone receives different numbers of flexion applied per cycle of the machine. The following picture shows an example of the test bench.

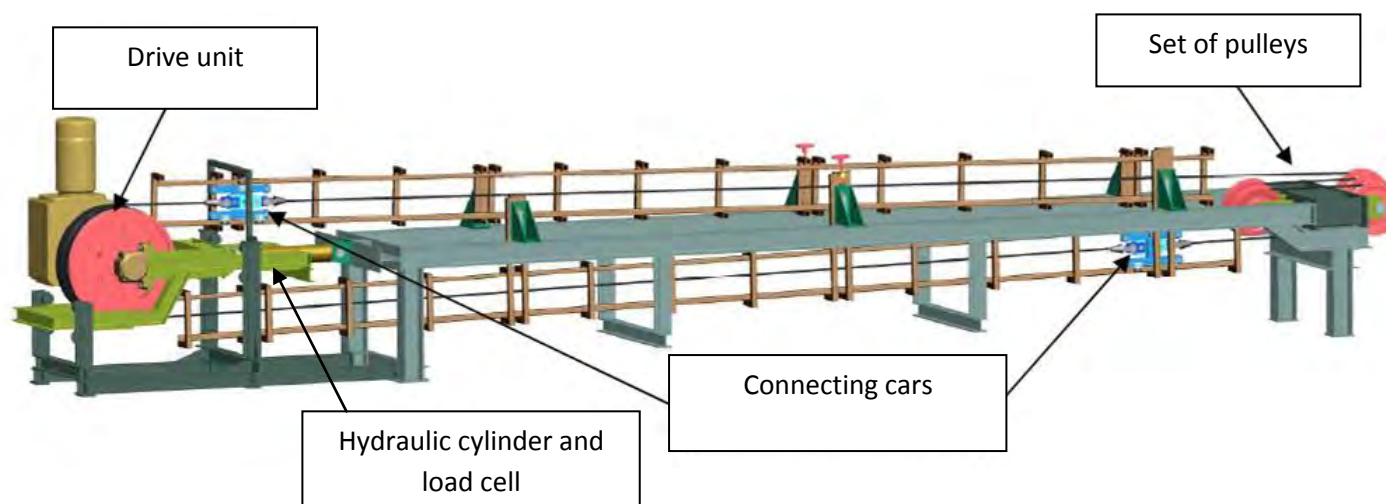
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Test bench:



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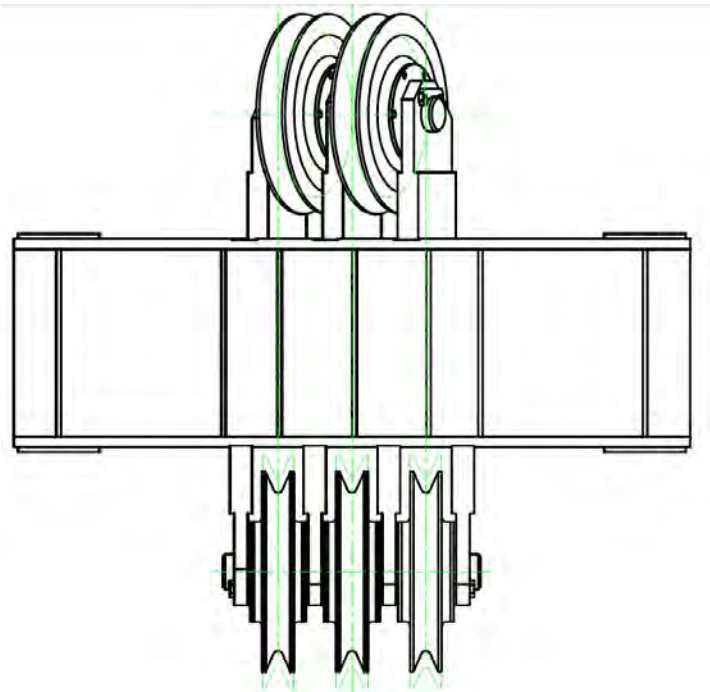
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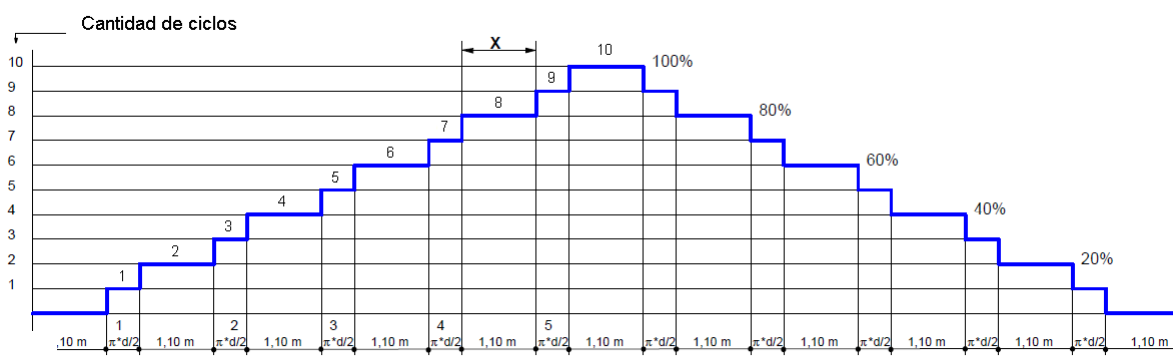
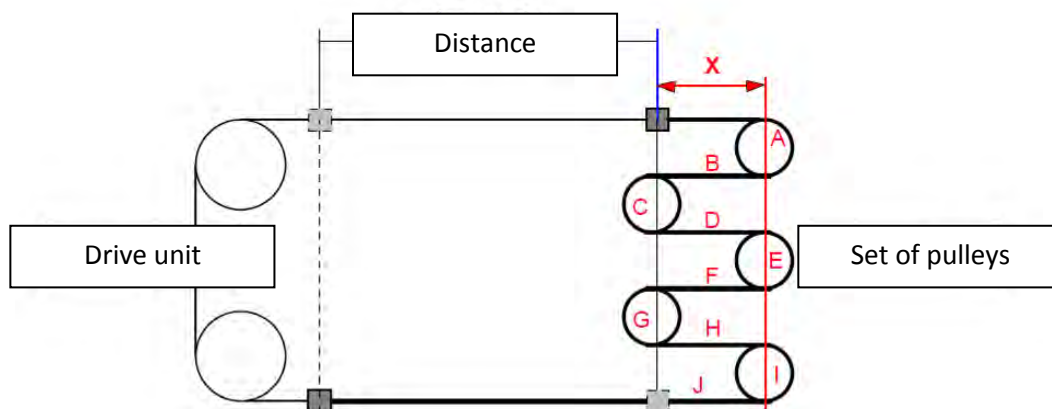
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- 1 Drive unit: it provides the oscillating movement of the test piece..
- 2 Hydraulic cylinder: provides the work load on the test piece
- 3 Load cell: the sensor by which the load applied to the specimen is checked.
- 4 Connecting cars: they link the bench with the test piece.

5 Set of pulleys: it represents the main difference between this test bench and traditional ones. Both sets have 5 pulleys each and its configuration avoids torsioning the wire rope due to deflection angles (as in real operating conditions). The configuration of the set of pulleys used is shown:



The tractor wire rope drives the test piece through the pulley system. Throughout a complete cycle of the machine the most fatigued area (in the middle of the test piece) travels forward and backward, flexing a total of 10 times (5 times forwards and 5 times backwards). Identified in the following figure as Zone J or Zone 10, it is in this section where the wire rope will show greater signs of fatigue wear. To each side of this zone we find zones that have undergone 8, 6, 4 and 2 flexion cycles, each of which receives 80%, 60%, 40% and 20% of the total cycles performed by the test bench.



After the test, a sample of zone 10 and two samples from each 8, 6, 4 and 2 zones are obtained. A sample of each zone is analyzed in the laboratory to determine the number of broken wires. The other is put through a tensile test to determine how the residual breaking load of the wire rope varies depending on the number of fatigue cycles..

2- Characteristic of the test piece:

- **Designation:** CAB.AC.NAT. 6x19 S.+1 AAC R.D. 19.00 mm 1770 N/mm²
- **Wire specification:** Natural
- **Construction:** 6 X 19 S
- **Core material:** Steel
- **Torsion:** Right Regular lay
- **Diameter:** 19.00 mm
- **Break Load:** 1770 N/mm²
- **Lubricant:** IPH
- **Minimum Breaking Load (MBL):** 22800 daN / 23256 Kg.

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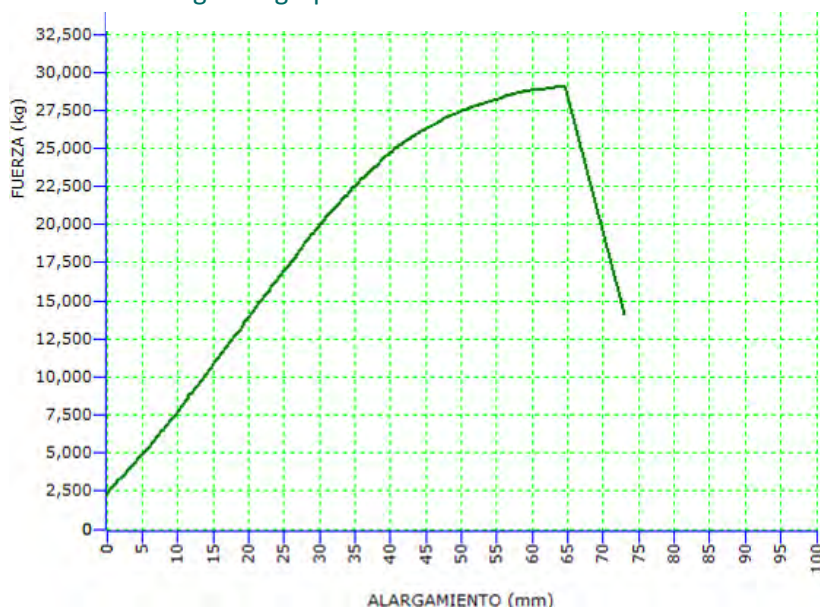
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The mechanical properties of the wire rope were determined. In order to obtain them a traction testing machine with a maximum capacity of 80 tons, located at IPH's San Miguel plant, was used. The results of these determinations are:

- **Real breaking load:** 28509 daN / 29080 kg (25% over **MBL**)
- **Diameter without tension:** 19,65 mm
- **Diameter 10%:** 19,55 mm
- **Lay length:** 126 mm
- **Elongation at break:** 4.28%

The load - elongation graph obtained is shown below



In order to determine how the ash affects the useful life of the wire rope, three comparative tests have been carried out with the following characteristics:

1. Reference standard wire rope in its original state
2. Wire rope with volcanic ashes from Bariloche.
3. Wire rope with volcanic ashes from Cerro Bayo.

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The following is an image of the wire rope after the simulated ash fall:



Test parameters:

- **Pulley diameter:** 480mm
- **D/d ratio:** 25
- **MBL:** 23256 Kg.
- **Service factor:** 5
- **Load applied to each rope ending:** 4651 Kg.
- **Piston load:** 9302 Kg.
- **Translation speed:** 0.575 m/s

3- Analysis Procedure:

The procedure for the analysis of the samples is as follows:

- The resulting test sections given by the test bench (2, 4, 6 and 8) are cut. We get two of each section (11000 mm length).
- A sample of each section is subjected to tensile test.
- On the other sample, lay length is marked, and then the rope is untwisted in order to count broken wires and their location.

Results:

Condition	Cycles at break	%
Reference Standard	54830	100
Bariloche's volcanic ashes	48120	87.7
Cerro Bayo's volcanic ashes	50380	91.9

Samples are analyzed under the discard criteria established by ISO4309 (Wire ropes -- Care and maintenance, inspection and discard):

1. Wire rope diameter reduction.
2. Number of wire breaks in 6 x Ø (Max. 3)
3. Number of wire breaks in 30 x Ø (Max. 6)

1- Wire rope diameter reduction:

For this criteria, discard diameter is calculated according this expression:

$$\frac{D_{\text{ref}} - D_m}{D} = D_{\text{dec}}$$

Where: Dref is the measured diameter on a section with no flexion cycles, Dm is the measured diameter in the zone we are analyzing, Ddec is the maximum diameter reduction allowed by standard and D y the nominal diameter. For a 20% severity rating, Ddec equals to 3.5%. For a 100% severity rating (discard) Ddec equals to 7.5%. Measuring the values for each sample and calculating Dm, we get the discard diameter for each one.

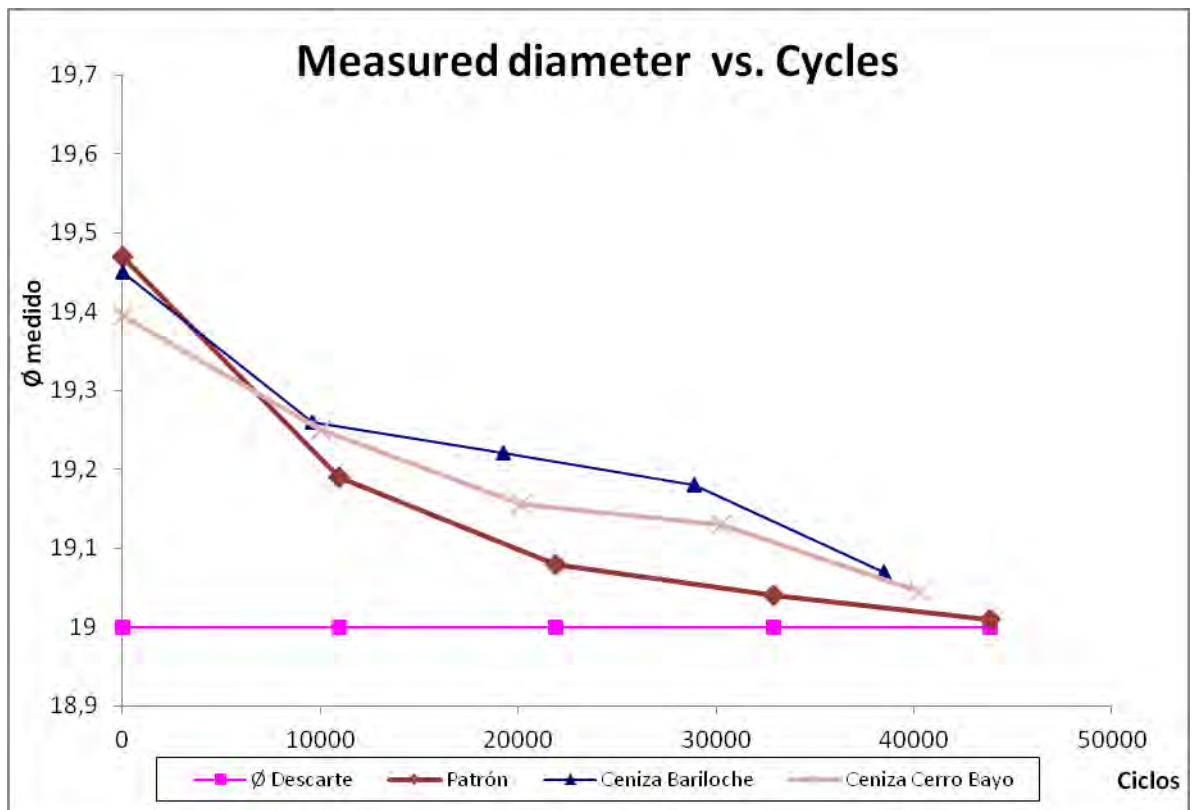
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Ref. Standard	ZONE	Cycles	Measured Ø	20% Severity Rating	100% Severity Rating
	0	0	19.47	18.99	18.23
	20	10966	19.19	18.99	18.23
	40	21932	19.08	18.99	18.23
	60	32898	19.18	18.99	18.23
	80	43864	19.01	18.99	18.23
	100	54830	-	-	-

Bariloche's Ashes	ZONE	Cycles	Measured Ø	20% Severity Rating	100% Severity Rating
	0	0	19.45	18.99	18.24
	20	9624	19.26	18.99	18.24
	40	19248	19.22	18.99	18.24
	60	28872	19.18	18.99	18.24
	80	38496	19.07	18.99	18.24
	100	48120	-	-	-

Cerro Bayo's Ashes	ZONE	Cycles	Measured Ø	20% Severity Rating	100% Severity Rating
	0	0	19.40	18.99	18.12
	20	10076	19.25	18.99	18.12
	40	20152	19.16	18.99	18.12
	60	30228	19.13	18.99	18.12
	80	40304	19.05	18.99	18.12
	100	50380	-	-	-

Obtained results are shown in the following graph.



The analysis of this graph shows:

- Diameter decreases with the number of flexion cycles
- Diameter for a 20% severity rating was never reached.

2- Number of wire breaks in 6 x Ø:

The second applicable criteria is the number of wire breaks in 6 x d (120 mm aprox). The lay length with the highest number of broken wires was considered:

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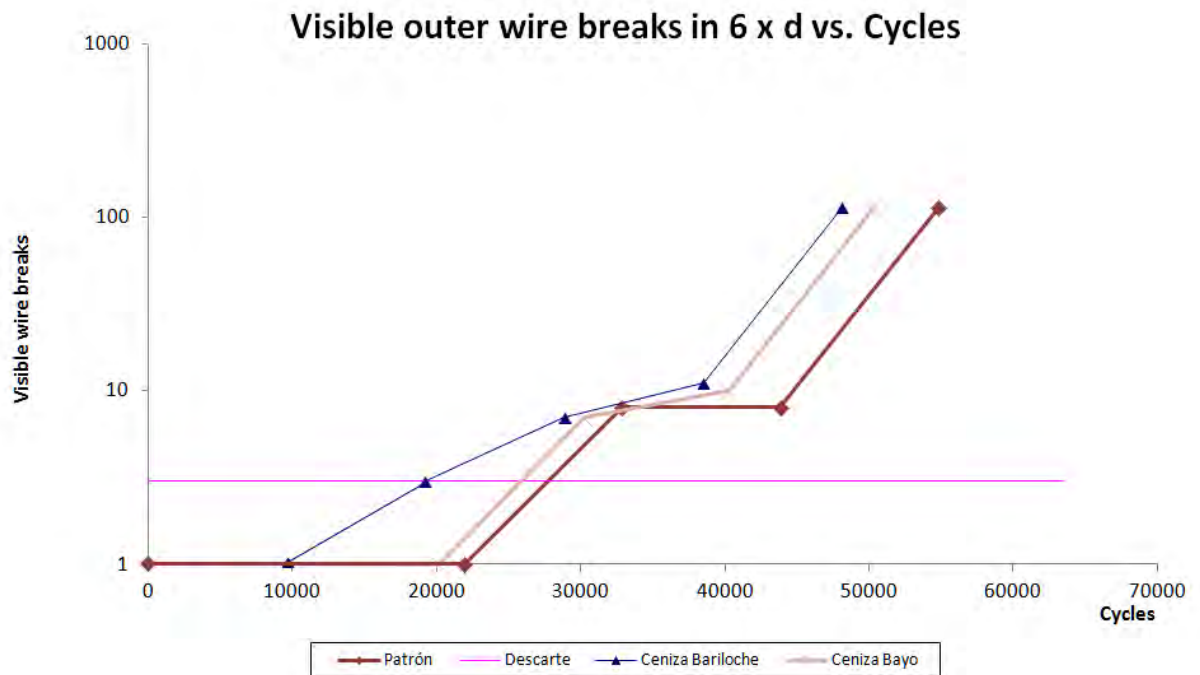
Ref. Standard	ZONE	Cycles	Visible WB in 6xØ	ISO4309 Discard Criteria
	0	0	0	3
	20	10966	0	3
	40	21932	1	3
	60	32898	8	3
	80	43864	8	3
	100	54830	114	3

Bariloche's Ashes	ZONE	Cycles	Visible WB in 6xØ	ISO4309 Discard Criteria
	0	0	0	3
	20	9624	0	3
	40	19248	3	3
	60	28872	7	3
	80	38496	11	3
	100	48120	114	3

Cerro Bayo's Ashes	ZONE	Cycles	Visible WB in 6xØ	ISO4309 Discard Criteria
	0	0	0	3
	20	10076	0	3
	40	20152	0	3
	60	30228	3	3
	80	40304	10	3
	100	50380	114	3

For the zone 100, where the rope breaks, all wires are considered broken (6 x 19 =114).

The obtained results are shown in the following graph:



Analyzing the graph, we take to the following conclusions:

- The discard criteria is reached at 32898 cycles for the reference standard, 30228 cycles for the rope with volcanic ashes from Cerro Bayo, and 19248 cycles for the rope with ashes from Bariloche.
- Up to 37% of the reference standard service life (20000 cycles), there is no evidence of ash influence on the number of broken wires
- After reaching 70% of the reference standard service life (38.000 cycles), the influence of the ash is evidenced in the number of broken wires in each sample (Test piece: 8 WB, Cerro Bayo:10 WB, Bariloche: 11 WB)
- After 80% of the service life of the ropes with ashes, there is a considerable increase of wire breaks due to ash influence.
- Considering the total number of cycles until failure, the rope with ashes from Cerro Bayo suffers a loss of 8.1% of its service life, and the rope with ashes from Bariloche loses 12.3% of its service life, both compared to the reference standard wire rope.

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3- Number of wire breaks in 30 x Ø:

The third applicable criteria is the number of wire breaks in 6 x d (570 mm aprox). The lay length with the highest number of broken wires was considered.

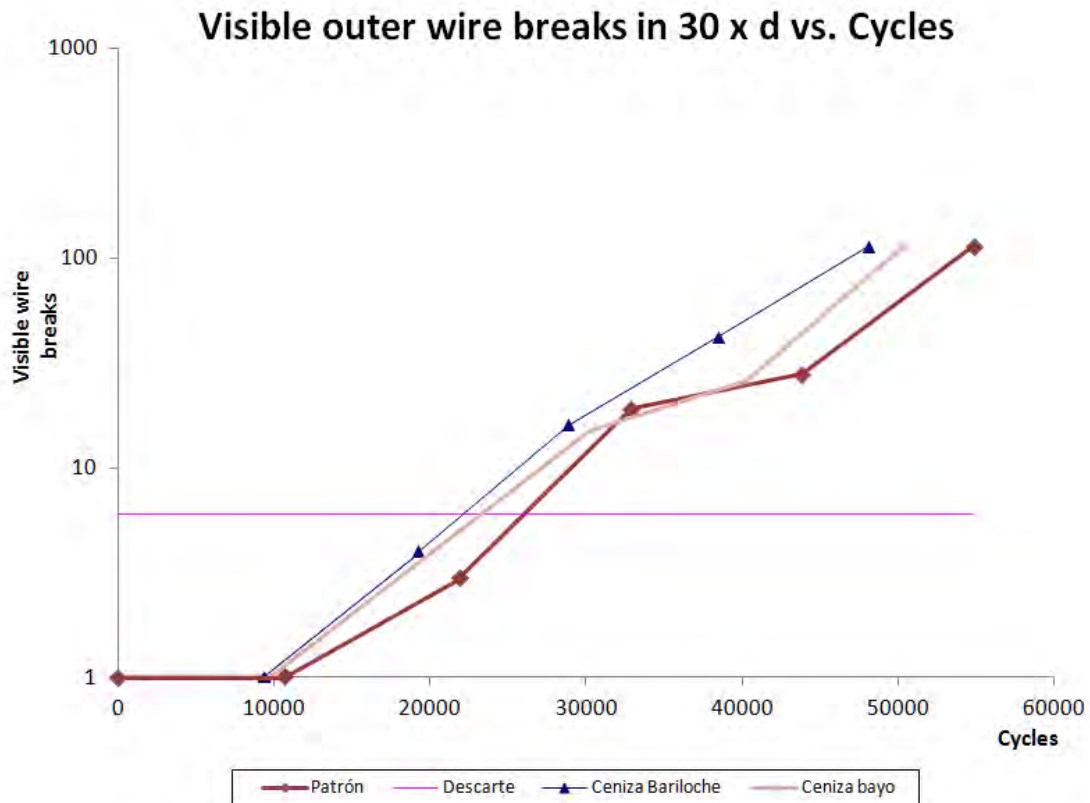
Ref. Standard	ZONE	Cycles	Visible WB in 30Ø	Discard Criteria
	0	0	0	6
	20	10966	0	6
	40	21932	3	6
	60	32898	19	6
	80	43864	28	6
	100	54830	114	6

Bariloche's Ashes	ZONE	Cycles	Visible WB in 30Ø	Discard Criteria
	0	0	0	6
	20	9624	0	6
	40	19248	4	6
	60	28872	16	6
	80	38496	42	6
	100	48120	114	6

Cerro Bayo's Ashes	ZONE	Cycles	Visible WB in 30Ø	Discard Criteria
	0	0	0	6
	20	10076	0	6
	40	20152	0	6
	60	30228	8	6
	80	40304	22	6
	100	50380	114	6

For the zone 100, where the rope breaks, all wires are considered broken (6 x 19 =114).

The obtained results are shown in the following graph



From the analysis of this graph:

- The discard criteria is reached at 32898 cycles for the reference standard, 30228 cycles for the rope with volcanic ashes from Cerro Bayo, and 19248 cycles for the rope with ashes from Bariloche.
- After reaching 80% of the reference standard service life (43.000 cycles), there is a considerable increase of wire breaks due to ash influence.

4- *Residual breaking load test*

In addition to the analysis of the discard criteria, with the remaining 4 samples from the test bench, residual breaking load testing is performed.

The following charts show the evolution of the residual breaking load.

Ref. Standard	ZONE	Cycles	MBL [Kg.]	BL [Kg.]
	0	0	23256	29080
	20	10966	23256	29200
	40	21932	23256	29020
	60	32898	23256	26420
	80	43864	23256	24660

Bariloche's Ashes	ZONE	Cycles	MBL [Kg.]	BL [Kg.]
	0	0	23256	29080
	20	9624	23256	29500
	40	19248	23256	28700
	60	28872	23256	26560
	80	38496	23256	23940

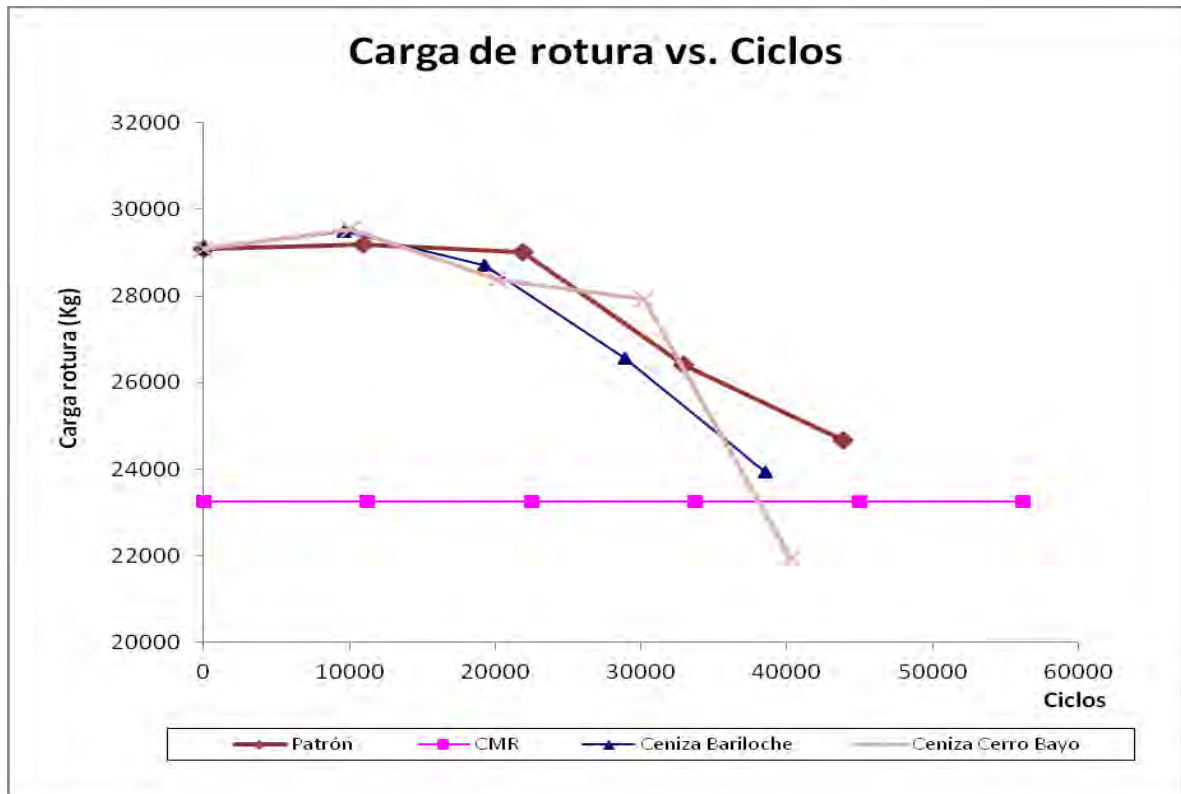
Cerro Bayo's Ashes	ZONE	Cycles	MBL [Kg.]	BL [Kg.]
	0	0	23256	29080
	20	11248	23256	29100
	40	22496	23256	28640
	60	33744	23256	26600
	80	44992	23256	25100

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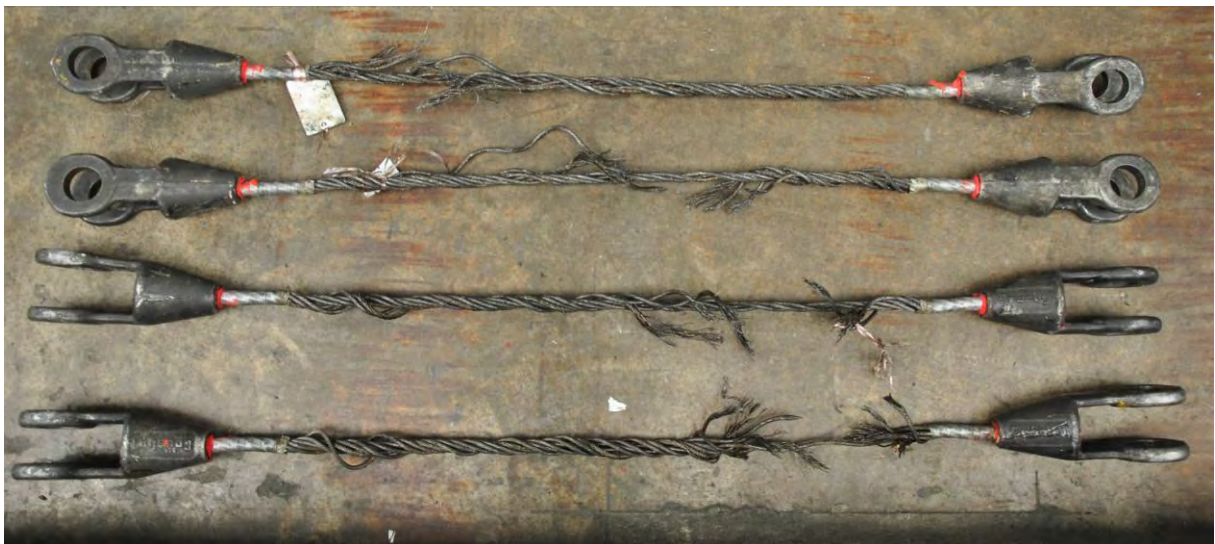
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The following graph shows MBL vs. Cycles:



Test pieces after breaking load test:



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The decreasing breaking load is due to the accumulation of fatigue wire breaks occurring on both the ridges and valleys. The following images show the increasing number of broken wires against fatigue cycles.



20% bending cycles zone



40% bending cycles zone



60% bending cycles zone

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80% bending cycles zone



100% bending cycles zone (close to failure)

Conclusions:

According to the discard criteria presented on ISO 4309, we can conclude:

- i. **Wire rope diameter reduction:** Ashes had no influence on the measured diameter
- ii. **Number of wire breaks in $6 \times \varnothing$:**
 - a. After reaching 70% of the reference standard service life, the influence of the volcanic ash is evidenced in the number of broken wires.
 - b. From the 80% of the service life of the ropes with ashes, there is a considerable increase in the number of wire breaks.
- iii. **Number of wire breaks in $30 \times \varnothing$:**
 - a. From 80% of the reference standards service life there is a considerable increase on the amount of wire breaks in the ropes with ashes.

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- iv. **Residual breaking load test:** Relating discard criteria and breaking load test graphs, it can be ensured that when the rope reaches discard criteria the safety factor of the installation is unchanged.

Finally, it is determined the rate at which each wire rope reached any of the discard criteria through linear interpolation, and the results are shown in the following chart.

	ISO 4309 discard criteria		
	\emptyset	WB 6 x \emptyset	WB 30 x \emptyset
Ref. Standard	-	46%	44%
Bariloche Ashes	-	40%	45%
Cerro Bayo Ashes	-	40%	43%

With these percentages, is established the number of cycles in which the wire ropes reached the first discard criteria:

	Cycles	%	Criteria
Ref. Standard	24125	100	30x \emptyset
Bariloche Ashes	19248	79%	6x \emptyset
Cerro Bayo Ashes	20152	83%	6x \emptyset

Under the conditions of this test, the volcanic ashes affect the steel wire rope performance, decreasing its service life by 20% over the reference standard wire rope. It is important to clarify that the wire rope is fatigued with ashes from its initial condition, which is unlikely to happen on these types of installations.