HIGH-QUALITY WEAR-RESISTANT PAVING BLOCKS IN ICELAND

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SUMMARY

Studded tyres have been used in Iceland since 1964, and during the winter months 60-70% of all cars use studded tyres. The impact of the studs on roads is a function of their weight, vehicle speed and wetness of the road. Rutting is a typical problem here on Icelandic roads, especially in the centre of Reykjavik, the capital, where streets are narrow. Two years ago, BM Valla Ltd, in collaboration with the Director of Roads in Reykjavik city, designed and tested high-quality wear-resistant paving blocks. The aim of this project was to learn more about the behaviour of wear from studded tyres, try imported aggregates versus Icelandic, and look for good equipment here in Iceland and abroad to measure wear resistance. In addition to this, the service life of the high-quality paving blocks was estimated using a model based on the SPS value. Twelve different types of concrete mixes were designed for this project. Maximum grain size varied between 8 mm and 12 mm, and three types of sand were used. All the samples were measured in the laboratory for wear resistance, using Dorry, Tröger and Wide Wheel, in addition to standard flexural and modified compressive strength, density, frost resistance and absorption. Six different concrete types were tested in the field and ten were sent to a rolling facility abroad. The results suggest that flexural strength reflects wear resistance more accurately than compressive strength, that there is close correlation between Wide Wheel and real wear. The SPS value was calculated to be approximately 15, which is a 50% better result than for asphalt.

1. INTRODUCTION

Iceland is one of few countries in the world where studded tyres are used as a protection against icy roads. The use of studded tyres in Iceland started in 1964, and soon after that 90-98% of all cars were equipped with studded tyres in winter. In 1981 this percentage had dropped down to approximately 60-70% and has stayed in that range ever since. On the other hand, due to high maintenance cost, only 3% of heavy trucks use studded tyres. The use of studded tyres is only allowed from November 1st to April 15th (photograph 1).



Photograph 1. This paving block used to be 8 cm thick, but is now only approx. 3 cm. During its four-year service time, it took the abuse of 6.1 million studded tyres.

The impact of studs on the road is a function of their weight, vehicle speed, and the wetness of the road. Studies show that roads tend to wear twice as fast in wet conditions then dry (Sigfusson 2001, Tveter 1994). Today the weight of each stud for a normal car is a little less then 2 g, but in the future it will be closer to 1 g (Sigfusson 2001).

By designing high-quality wear-resistant paving blocks, this not only saves expenses in the long run, but the formation of road dust is also reduced, thus keeping the air cleaner.

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Thordarson (2001) published data on quantities and sources of particulate matter in Reykjavik for the period 1986 to 2000. It was found that 36-46% of the particulate matter in Reykjavik could be linked to the wear of the roads.

In the last few years, Icelanders have experienced unusually calm and warm winters, resulting in extreme wear of our roads due to the absence of ice and snow over extended periods during the "studded tyre time frame". It is in the hands of the politicians to decide whether to place restrictions on the use of studded tyres, but, in the meantime, it is necessary to study how producers can improve the production of paving blocks to increase their resistance to wear.

In the year 2000, BM Valla Ltd, in collaboration with the Director of Roads in Reykjavik city, designed and tested high-quality wear-resistant paving blocks. The main aim was to learn more about the behaviour of wear from studded tyres and different types of aggregates, and to try to find good equipment here in Iceland and abroad to measure wear resistance. Model calculations were also done to estimate the service life of the paving blocks.

Table 1. Aggregates and cement used.

	Code	Quality	Size	Source
Sand	a	Low	<4 mm	Sub-glacial volcanism – local
	b	High	<4 mm	Natural beach sand – imported
	c	Middle	<2 mm	Crystalline volcanic basalt - local
Gravel	a	High	4-8 mm	Extrusive volcanism – local
	b	High	8-12	Extrusive volcanism – local
	c	High	2-12	Metamorphic rock – imported
	d	High	8-12	Metamorphic rock – imported
	e	High	8-12	Metamorphic rock – imported
Cem.	a			Av. strength – 55 MPa
	b			Av. strength – 62 MPa

2. PROJECT OUTLINE

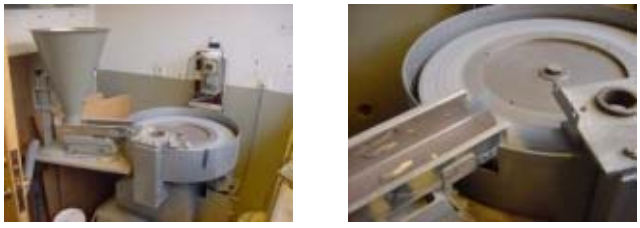
2.1 Mixes, production and curing

In total, twelve different types of concrete mixes were designed for this project (table 2), using the aggregates listed in table 1. A hydraulic paving machine was used to produce the test blocks from a semi-dry concrete mix. All the blocks were 20 cm (L) x 10 cm (W) x 8 cm (H). The blocks were kept in a curing chamber overnight (20°-25°C, 70-90% humidity). All the blocks tested in the lab were kept for 28 days in a 20°C water bath prior to testing. Those used in the field study were kept outside for a few weeks prior to testing.

2.2 Abrasion and durability tests

2.2.1 Dorry test

This method has been used here in Iceland since 1976, on pure aggregates. The test is used to estimate wear from studded tyres and does not have an impact factor, as for example an LA-test. This is the first time that this test has been used to measure abrasion from a paving block.



Photograph 2. Dorry set-up.

Normally, only pure aggregates are tested, of grain size 11.2 - 12.5 mm. The aggregates are divided according to petrographical analysis and 25 pieces are picked out and glued in a mould. The standard mould used is 85 x 85 mm, and four moulds are used for each specimen. We did not use the mould; instead, the paving block was sawn down to the accurate size, and 25 small cubes sawn on the abrasive side, imitating the aggregate grains.

The test rig has a rotating steel plate on which the sample is positioned upside down under weight (13.7 kg), and abrasive sand (ALODUR ESK 80) is distributed at a rate of 80 g/min. The sample is first abraded to get an even surface. Then four test runs are made on each sample, and the volume loss measured after each run. The sample is turned 90° after each run. The final abrasive value for the sample is the average volume loss of four specimens (mm^3).

The Dorry abrasive test can be used for both wet and dry samples. In this project, dry samples were used.

2.2.2 Tröger test

The Tröger test was designed to simulate impact on roads, for example from studs. The aperture has a pressure-driven needle hammer and a rotating steel plate, rotating at 30 rounds/min. The needles go up and down, crushing and scraping the samples, during the test run. Each test run takes 2 x 5 min, with a 40 sec adjustment period prior to the test. Four specimens are used, with the thickness of each sample around 30 mm. The test results are given in cubic centimetres.



Photograph 3. Tröger. The needle hammer is located above the rotating steel plate.

Tröger has not shown good repeatability, except within the same test load. To be able to compare individual specimens together, they need to be tested in the same test batch.

2.2.3 Wide wheel test

The Wide wheel test is relatively new (Dowson 1996) and has been used in Iceland for two years for general production control. This test is described in detail in EN 1338 (Concrete paving block – requirements and test methods).

2.2.4 Nordic Ball Mill Test

This test is sometimes called the Studded Tyre Test (Bjarnason et al. 1999), Swedish Ball Mill Test (Petursson 1992), or even the Nordic Abrasion Value (Torfason 1996). In this paper, the Nordic Ball Mill Test (NBMT) was used. This test is used quite extensively by the Public Roads Administration in Iceland, to find out the quality of aggregates used in asphalt roads. The NBMT data used in this study was gathered from various sources.

The NBMT value is important to this study since earlier studies have established a relationship between the NBMT value, Dorry, and wear in the field caused by studded tyres.

The test involves 1 kg of aggregates (11.2-16 mm) and steel spheres with water in a hollow drum, which rotates around a horizontal axis. The inside diameter of the drum is 206.5 mm, the length is 335 mm and the diameter of the steel spheres is 15 mm. The drum rotates 90 rounds/min for 5400 revolutions. Inside the drum there are 3 ribs. After the test, material below 2 mm is weighed. The results are given in weight percents.

2.3 Absorption value

This test is described in ASTM C642 (Specific gravity, absorption and voids in hardened concrete). The following modifications were done on the test procedure: each sample was approximately 400 g and saturation was done by vacuum, not boiling.

2.4 Strength tests

2.4.1 Compressive strength

The compressive strength of the specimens was measured using 6 x 6 x 6 cm cubes. Before testing, the top and bottom of the samples were ground, leaving an even, smooth surface. No packing was used. The load was applied at a rate of 10 kN/sec.

2.4.2 Flexural strength

The flexural strength of the specimens was measured according to the Danish standard DS 400. The distance between the support rollers was set to 170 mm and the load was applied at the rate of 1 kN/sec.

2.5 Rolling load

A pilot trial was conducted in the rolling load facility. Eleven types of pavers, with different concrete, were tested with specially made studded tyres. The test comprises a truck that shuttles back and forth over a 9 m x 2 m test area. The axle load used was 14 t. The test is computer controlled, so as to simulate different situations in acceleration and deceleration.

Usually the test is conducted with regular street tyres, but in this case it was decided to increase the wear by using specially made studded tyres. Double set of tyres was used, with 420 pieces of 5.1 g studs in each one. The test area is kept wet all the time, to create a more realistic scenario. During the test the truck was driven over a bump to ensure that the studs would not hit the same spot all the time. The bump was moved frequently around the test area.

After 125,000 cumulative standard axles, the wear was measured for each type of paver. Two samples from each type of paver were measured. Each result is the average of three typical locations in the sample.

2.6 Tests in the field

To be able to compare the wear measured in the laboratory to the real wear, paving blocks were put on a heavily trafficked strip of road in central Reykjavik, where a high level of traffic is channelled through very narrow stretches to reduce speed, resulting in extreme wear effects in the narrow wheel tracks. The old road was four years old and deep ruts had formed (photograph 1). The strip used is 44 m long and 3.5 m wide where narrowest. The positive inclination of the road is a few degrees, resulting in increased abrasion when cars with studded tyres cross the study area. A herringbone pattern was used and only minor movements in the road have been seen. Five different types of concrete mix were tested. The wear was measured two years after the paving blocks were installed.

2.7 Freeze/thaw resistance

Most of the samples were tested for freeze/thaw resistance, according to EN 1338.

Table 2. Test results and types of aggregates used.

Number	Sand	Gravel	Cement	Density	Wide wheel	Tröger	Dorry	Flexural strength	Compress. strength	Freeze/thaw	Rolling load facility	Real wear	Absorption
	Code (see below)			(g/cm³)	(mm)	(cm³)	(mm³)	(MPa)	(MPa)	(kg/m²)	(mm)	(mm)	(%)
1	a	a	a	2.57	20	9.4(1)	687(1)	9.8	81	0.24	---	20	15
1a	a	a	a	2.6	19	8.4(1)	692(1)	10	103	0.38	1.15	17.5	15.7
2	b	a	a	2.56	17	7.2(1) 10.9(2)	531(1) 537(2)	11.2	110	0.02	2	10	15.6
4	a	a	a	2.57	19	7.4(1)	722(1)	9.3	90	---	---	---	---
5	a	b	a	2.59	19	7(1)	695(1)	10	113	0.01	1.95	17.5	13.8
6	a	a	b	2.6	18	8.3(1)	784(1)	11	99	0.1	---	14.2	15
7	a	c	a	2.5	20	9.7(2)	698(2)	10.1	94	0.01	2.15	---	14.1
8	c	c	a	2.52	19	8.7(2)	641(2)	10.2	100	0.01	2.2	---	14.8
9	a	d	a	2.5	21.5	9.5(2)	432(2)	9.4	104	0.01	3.05	---	10.7
10	c	d	a	2.49	20.5	9.5(2)	470(2)	10.7	90	0.02	1.7	---	13.4
11	a	e	a	2.45	18.5	7.7(2)	524(2)	9.9	103	0.01	3.95	---	10
12	c	e	a	2.5	18.5	6.1(2)	473(2)	9.9	115	0.01	3.7	---	11.8

Sand
a – sub-glacial volcanism (local)
b – Natural beach sand (imported)
c – Crystalline volcanic basalt (local)

Gravel
a and b – extrusive volcanism (local)
c, d and e – metamorphic rock (imported)

Cement
a – av. strength 55MPa
b – av. strength 62MPa

(1) = Batch one, (2) = Batch two

3. TEST RESULTS

3.1 Real wear compared to different tests

3.1.1 Wide wheel

Previous comparison tests using Wide wheel (WW), have shown little difference in WW values for regular products for pedestrian use and wear-resistant paving blocks (table 3). Therefore, the test has not been thought of as an indicator of real wear but more as a tool to distinguish between wear-resistant and non-wear-resistant products. The results from the field suggest there is a good connection between real wear and results from the WW test (figure 1).

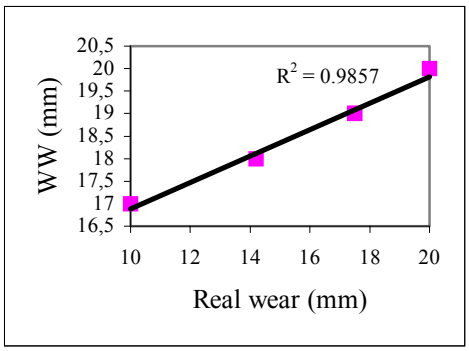


Figure 1. Connection between real wear and Wide Wheel value.

Table 3. Wide Wheel results from yearly production control.

Specimen	WW value (mm)
1 (pedestrian use)	22
2 (pedestrian use)	20
3 (areas with high point loads)	23.5
4 (wear-resistant paving blocks)	18
5 (wear-resistant paving blocks)	17.5

3.1.2 Strength tests

Scholars studying abrasive behaviour of concrete usually plot their results against compressive strength and a good relationship has been established: the higher the compressive strength, the better the wear resistance (Tveter 1994, Neville 1995, Torfason 1996 and Horiguchi et al. 1994). This trend was also seen in this study (figure 2), but when real wear was plotted against flexural strength, a better relationship was seen (figure 3). The results suggest that the flexural properties of a paving block can tell us more about the wear resistance of a paving block than the compressive strength.

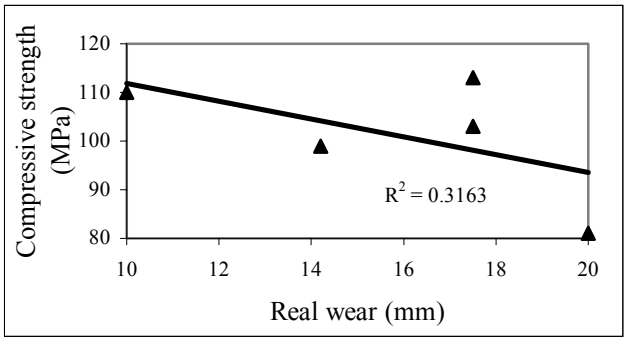


Figure 2. Relationship between real wear and compressive strength. The samples all have 8 mm max. gravel, except (a), which has 12 mm max. If (a) is left out the R^2 = 0.69.

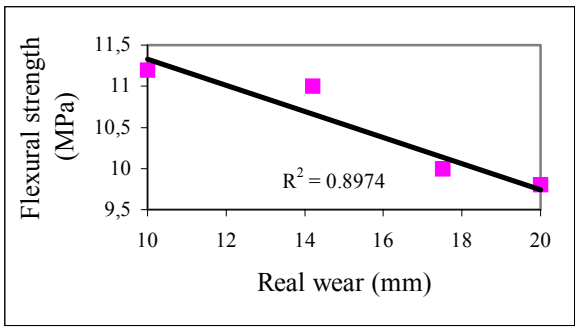


Figure 3. Relationship between real wear and flexural strength.

3.1.3 Dorry test

Wallevik and Johannesson (1996) reported a good correlation between results from the Dorry test and wear from studded tyres (using a wear index, SPS-value). In this study, a weak correlation between the Dorry results and real wear was found (R^2=0.3). The Dorry value was measured using the product itself (sand, gravel and cement), while Wallevik and Johannesson measured the Dorry value only from the aggregates. It seems that these two methods, using pavers against aggregates, do not give the same relationship to real wear. Further research is needed, though, to conclude if this is the case.

3.1.4 Tröger test

The Tröger test shows a similar relationship to the real wear as Dorry (R^2=0.36). Since this is one of the first times Tröger has been used to measure wear in paving blocks, it is not possible to compare

results with other studies. However, from this project it can be concluded that Tröger tests are able to show the difference between different quality pavers.

3.1.5 Rolling facility

The results from the rolling facility were not as good as had been hoped. Three concrete mixes were tested, both in the rolling facility and in the field. No clear connection could be established between the test results and real wear. Similar studies performed in Scandinavia (Tveter 1994) used test rigs that can easily reach up to 60 km/h, while the truck at the rolling facility reaches maximum speed of less than 5 km/h. This was known from the beginning, but it was anticipated that the dragging effect of the studs and the heavy load applied by the truck on the road would produce enough wear to create an anomaly. This pilot test might indicate the importance of speed when studying wear in rolling facilities.

3.2 Aggregates

3.2.1 Gravel

In an attempt to make as strong and wear-resistant paving blocks as possible, the decision was made to use high-quality and dense imported gravel (table 1) and evaluate its quality compared to local gravel, using abrasive tests. A well-known test, the Nordic Ball Mill Test (NBMT), was used as an indicator of the hardness of the gravel.

The main difference between the samples tested is the type of gravel used and its grain size distribution. The physical difference between the imported and the local gravel, apart from their geological origin, is their specific gravity and absorbed moisture. The Icelandic rock has a specific gravity of approximately 2.95 g/cm^3, while the imported rocks have one of 2.7 g/cm^3. The absorbed moisture content in the Icelandic rocks is 1.3%, while the values for the imported rocks are ten times lower.

Results from the abrasive tests are summed up in figure 4. This figure shows how different gravel responds to different tests and how the local gravel is only showing better results in the Wide wheel test. The results for NBMT are gathered from various sources, while Dorry and Wide wheel were measured on the test blocks (see 2.2). Good correlation has been established between the NBMT and measured wear of aggregates in asphalt surfacing (R^2=0,9031), as well as between NBMT and Dorry, tested on pure aggregates (R^2=0,733) (Torfason, 1996). Good correlation is also observed in this project, between NBMT and Dorry, tested on paving blocks (R^2=0,842), while the NBMT and Wide wheel do not show any logical correlation. This is troubling, owing to the fact that Wide wheel is showing very good correlation with real wear in this project (figure 1). From these test results, it is difficult to ascertain whether the local gravel is of better or worse quality than the imported gravel.

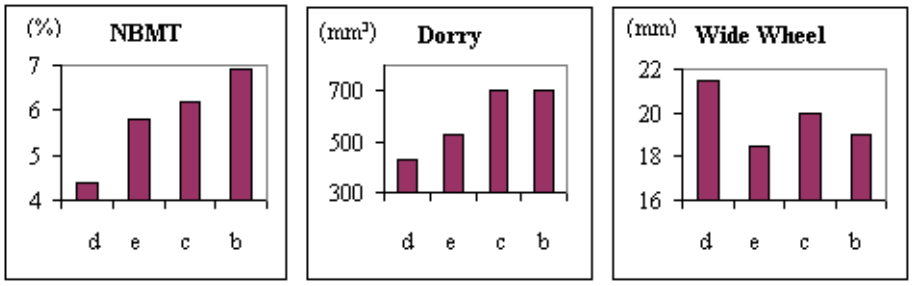


Figure 4. Comparison between NMBT and the wear test; d, e, and c are imported gravels, but b is local gravel.

3.2.2 Sand

Three different types of sand were used in the project. However, the effectiveness of only two types was tested in the field study. In figure 5 the difference is shown after two years. The paving blocks used in this comparison are identical except they have different types of sand.

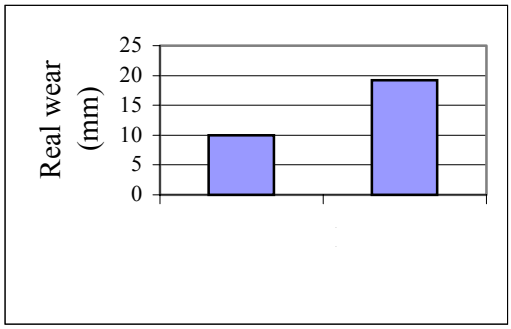


Figure 5. Quality of the sand, data from the field. The same type and size of gravel are used in this comparison.

In 3.1.2, a connection between flexural strength and real wear was mentioned. The results here indicate that by increasing the strength of the sand, the flexural strength will automatically increase, resulting in better wear resistance.

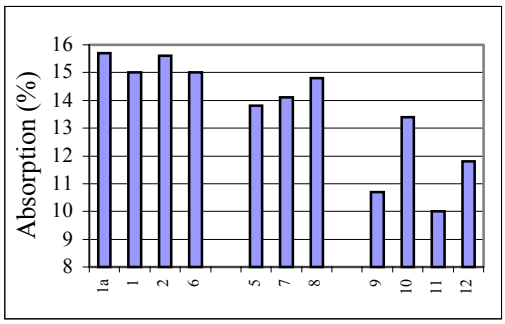


Figure 6. Absorption values. Specimens 1a, 1, 2 and 6 have 8 mm max. grain size. Specimens 5, 7, 8, 9, 10, 11 and 12 have 12 mm max. grain size.

3.2.3 Maximum grain size and compaction

By increasing the maximum grain size in the concrete mix, it was possible to better compact the paving blocks (figure 6). Specimens 1a, 1, 2 and 6 all have 8 mm maximum grain size and absorption around 15-16%. Samples 5 and 7 to 12 have 12 mm maximum grain size. Those specimens have much lower absorption values. It should be pointed out that the same type of cement was used for all the specimens, except no. 6. From the data it is not possible to tell if absorption is affecting the wear resistance, but it would be logical to conclude that more compacted paving blocks would result in better wear resistance.

3.3 Freeze/thaw resistance

All the samples tested exhibited very good frost/thaw resistance (table 2). Environmental factors such as freeze/thaw action can significantly reduce the wear resistance of paving blocks if they are not resistant to freeze/thaw action.

4. MODELLING SERVICE LIFETIME OF PAVING BLOCKS

Model calculations were used to find out the service lifetime of the specimens used in the field study. This model is based on measurements done on concrete roads here in Iceland and estimates wear from studded tyres based on the amount of material ground away per one kilometre per vehicle; this measuring unit is expressed as the SPS-value: 1 SPS = 1 g/km/vehicle = the specific maximum wear of the road. The specific wear from studded tyres can be investigated in the field by measuring areas of wear, in cross-section, related to traffic flow. Traffic flow can be expressed as the average numbers of equivalent vehicles/day during the year, or ADT. The maximum rut depth for a specific period is calculated from the assumption that the traffic is normally distributed in a cross-section with a standard variation of 0.3 m for 3.75 m wide lanes (figure 7). Traffic flow

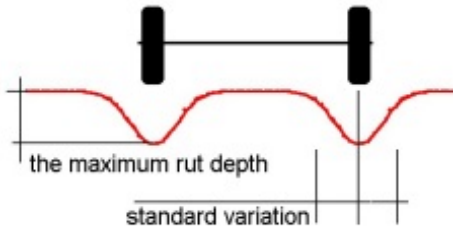


Figure 7. Model for estimating the maximum rut depth. Standard variation of traffic in cross-section depends on, among other things, the lane width.

across the study area has been estimated to ADT 10,000 equivalent vehicles/day and the width of the lane is 3.5 m.

From the measurements performed on the test specimens, SPS values have been estimated (table 4). Typical SPS-values of different types of roads obtained from measurements in Iceland are: asphalt pavements (30 – 40 SPS), normal strength concrete pavements (20 – 30 SPS) and high strength concrete pavements (15 – 20 SPS) (Johannesson 1997, Wallevik and Johannesson 1996).

Quality of paving blocks	SPS-value [kg/km/ vehicles]	Maximum rut depth after two years [mm]	Service lifetime [years] Max. rut depth = 30 mm	
			Lane width = 3.5 m SV= 0.18 m	Lane width = 3.75 m SV = 0.30 m
Class I	10	8	7.1	11.7
Class II	15	13	4.7	7.8
Class III	20	17	3.6	5.9
Class IV	25	21	2.8	4.7
Class V	30	25	2.4	3.9

Table 4. Prediction of service lifetime of block pavements on lanes of different width (3.5 m and 3.75 m). The SPS values used in the table are estimated from measurements in the field.

Table 4 shows model calculations based on measurements of rut depth after two years and an estimated service lifetime for paving blocks reaching a rut depth of 30 mm.

As seen in table 4, service lifetime decreases with decreased lane width. On narrow lanes in city centres, service lifetime of paving blocks is about 40% shorter than the lifetime of paving block on lanes of "normal" width.

From the ongoing tests of paving block in Reykjavik city, only SPS-values greater than 15 (class II) have been identified. This means that expected service lifetime on narrow city lanes, with an average traffic flow of 8.500 cars/day, is 4.7 years for paving blocks of extra high quality (class II), but only 2.4 – 3.6 years for blocks of moderate to good quality (classes III, IV and V).

5. CONCLUSIONS

- Flexural strength of the paving blocks showed better correlation with real wear than compressive strength, which suggests that flexural strength could be more useful in estimating wear resistance.
- Although based on limited results, a good correlation was observed between the Wide Wheel test and real wear in the field.
- By using high-quality sand in the concrete mix, the wear resistance can be increased by 50%.
- By changing different parameters, paving blocks with SPS around 15, which is 50% better than asphalt, were produced in this project.
- By increasing the width of a street from 3.5 m to 3.75 m, the service lifetime of the road can be increased by 40%.
- Concrete mixes with 12 mm maximum grain size had lower absorption values than those with 8 mm maximum grain size. It was not possible to establish if absorption is affecting the wear resistance.
- The Dorry abrasive test did not show a good correlation with real wear. More studies need to be performed to ascertain if there is a large difference in Dorry values when using pure aggregate or paving blocks.
- Specimens measured with the Tröger abrasive test cannot be compared unless they are from the same test load. Tröger did not show good correlation with real wear.

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