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Frost fracturing of riprap armour stones in Sporðalda Dam, Iceland.

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ABSTRACT

The Sporðdu Dam was constructed in 2011-2013. It is a part of the Búðarháls Hydroelectric Project (95 MW) in Southern Iceland. It is a conventional earth and rockfill dam with a central moraine core. Following the first subzero temperatures in the autumn of 2012 extensive fracturing of recently placed riprap armour stones and coarse grain fill material was noted. Riprap placed during the summer was largely unaffected. Site and laboratory investigation were conducted showing that it is hard to test armour stones for this type of fracturing.

Key words: Earth and rockfill dam, frost fracturing, riprap armour stone.

1 INTRODUCTION

The Sporðalda Dam is located in South Iceland and is a part of the Búðarháls Hydroelectric Project (95 MW) in the Þjórsá-Tungnaá Basin. Figure 1 shows the location of the Búðarháls Project and the Sporðalda Dam. The Dam is 1500 m long conventional earth- and rockfill dam with a maximum height of 26 m and a total volume of 630.000 m³. Construction took place in 2011-2013. All construction materials were found in the vicinity of the dam. The core is a morainic material borrowed downstream of the Dam. Other construction materials were quarried or borrowed within the reservoir area and are inundated by the reservoir. The Dam is divided up into three sections; the Northwest Dam, the Southeast Dam and a concrete spillway weir. The reservoir formed by the Dam is the intake lake for the Búðarháls Power Station. The lake is 7 km² at normal lake levels. The lake is not intended for water storage and variations in the lake level are due to daily fluctuations in the operations of the up- and downstream power plants. The lake level is therefore almost constant. .

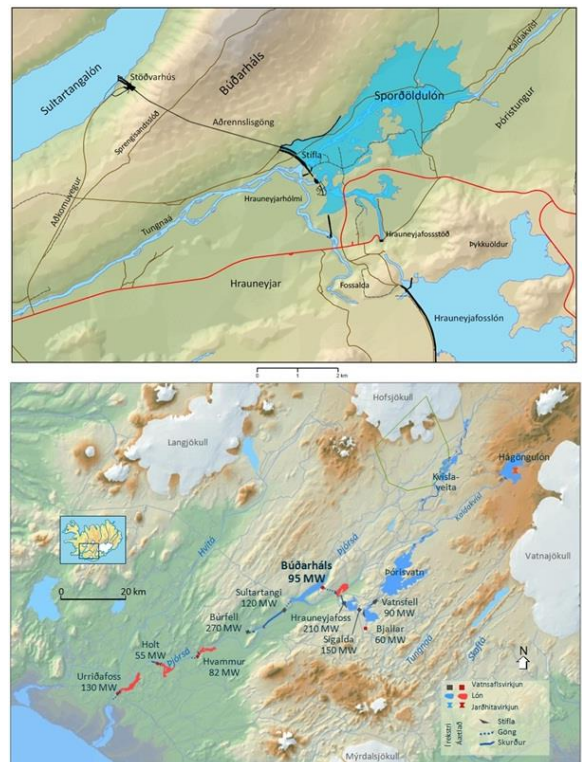


Figure 1. Location and layout of the Búðarháls Hydroelectric Project and the Sporðalda Dam

Figure 2 shows plan view and a longitudinal section of the Dam

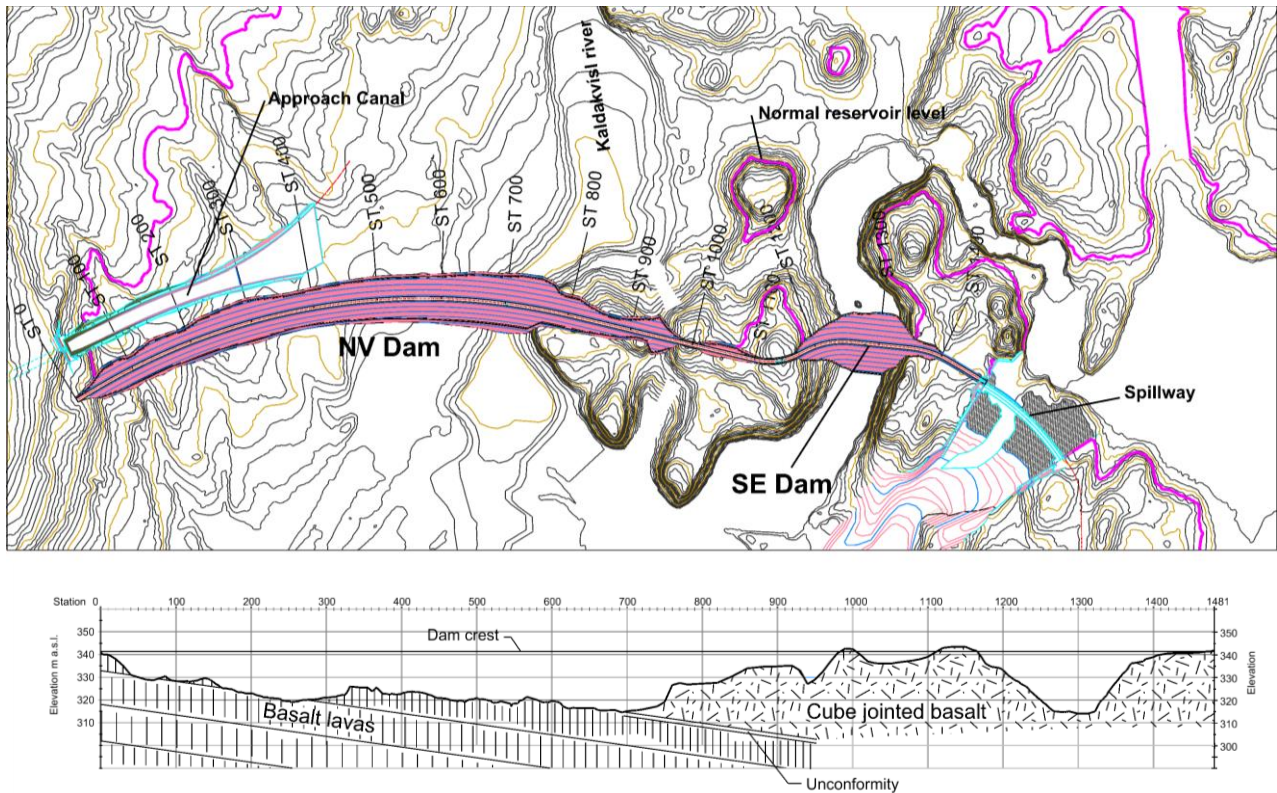


Figure 2. Plan and longitudinal section of the Sporðalda dam

2 GEOLOGY OF THE DAMSITE

The geology of the damsite is simple. Figure 2 shows geology. The northern part the dam foundation is made of gently dipping basaltic lavafloes of quaternary age. The jointing in the basalts lava flows is characterized by unusually large columns. The rock type is unaltered and fresh olivine tholeiite. Figure 3 shows excavation in the Approach Canal. The excavator is loading stones for riprap from the excavation. The columnar jointing is visible in canal wall.

In the southern part of the dam the foundation is made up of basaltic cube jointed formation which lies horizontally on the older basaltic lavafloes. Between these two formations there is an unconformity which is clearly visible at station approximately 750. The structure of the cube jointed basalt is different to that of the lavafloes. The jointing forms irregular cubes that are typically 10 to 30 cm in diameter. The rock is relatively fresh and has a rather porous texture.



Figure 3. Excavation of basaltic lava in the Approach Canal

Figure 4 shows a quarry in the cube jointed basalt and the type of fill material produced from the cube jointed basalt.



Figure 4. Cube jointed basalt quarry

Because of this the Contractor demanded extra payment for quarrying shell material for the NW dam from the cube jointed basalt formation or processing shell material from tunnel spoil. This would have increased the cost of the dam considerably. It was however decided to use the relatively fine grained river gravel for shell material in the NW Dam.

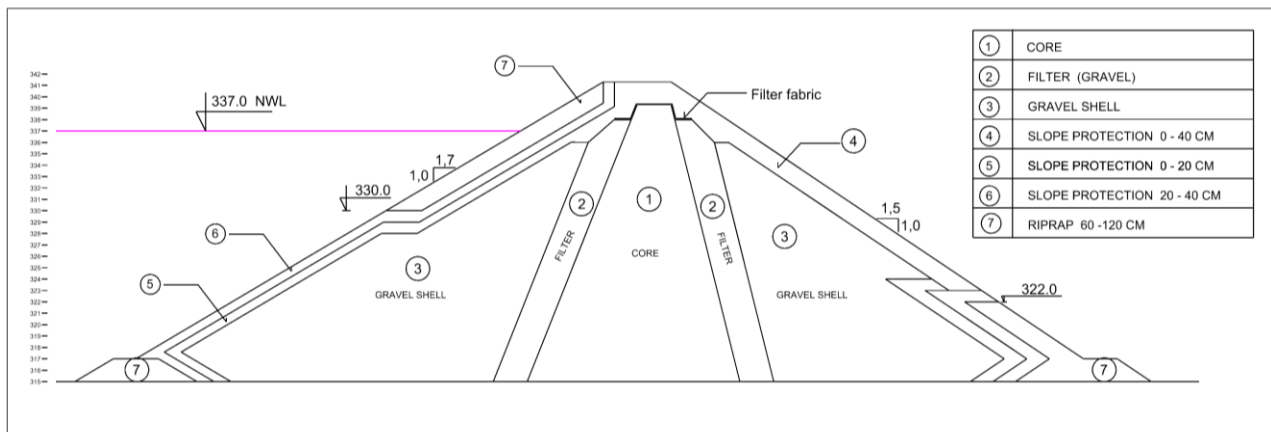


Figure 5. Dam cross section.

3 DAM CROSS SECTION AND CONSTRUCTION MATERIALS

Figure 5 is a cross section of the NW Dam. For core material glacial moraine was used. Filters for the core are sandy gravels or sand taken from an upstream borrow area.

According to the Contract Documents shell materials were to be found as alluvial sandy gravels along the Kaldakvísl river upstream of the Dam and excavated material from the Spillway, the Approach Canal and Headrace Tunnel excavations.

The Contractor chose to use the alluvial sandy gravel for shell material in the NW Dam. The sandy gravel found in the designated borrow area at the Kaldakvísl river was however finer grained than the specified shell material.

Shell materials in the NW Dam are therefore essentially of the same material as the filters adjacent to the core. This placed extra demands on the slope protection material which also acts as a filter between the rip rap and the shell material. Testing a single layer filter that fulfilled the filter criteria, it was found that such filter could not be placed without the risk of segregation.

A solution was found by dividing the filter the other 20-40 cm. This led to the extra benefit of providing coarser material for the upstream slope protection below and behind the riprap. The 0-20 and 20-40 cm filters were produced from quarries in the cube jointed basalt formation with some extra cost. The SE dam shell material was however produced from the cube jointed basalt.

Most of the riprap material was obtained from the basalt lava flows in the Approach Canal excavation. The rest was obtained from tunnel spoil and a separate quarry in basalt lava formation.

4 FROST FRACTURING OF RIP RAP MATERIAL

Once the filter and shell material problems had been sorted out during the summer of 2012, the dam construction proceeded as foreseen until fall 2012. Considerations of possible floods required that the dam had to be filled up to an elevation of 333 m a.s.l. in 2012. On October 22nd 2012 following a weekend break, during which the temperature in the area reached -5 °C for the first time that autumn, it was noted that considerable portion the riprap stones placed during the previous two weeks was fractured. Figure 6 shows an example of this. During that particular weekend the stones in the riprap may have experienced one or two frost/thaw cycles.



Figure 6. Fractured riprap stone.

Examination of the rip rap already placed in the Dam in late October 2012 showed that the riprap that had been placed in the preceding one or two weeks was extensively fractured. This was the case for station 100-350 along the dam axes in the NW dam. Riprap placed during the summer and early autumn at station 400–700 was largely intact. The percentage of fractured stones was determined at six locations. Figure 7 shows the result of this investigation. At each

location 60-80 stones were examined. The riprap material in all cases came from the basaltic lava flow formation and appeared to be similar in every respect. The only difference was that the ambient temperature had fallen below 0°C shortly after the rip rap at station 100-350 was placed.

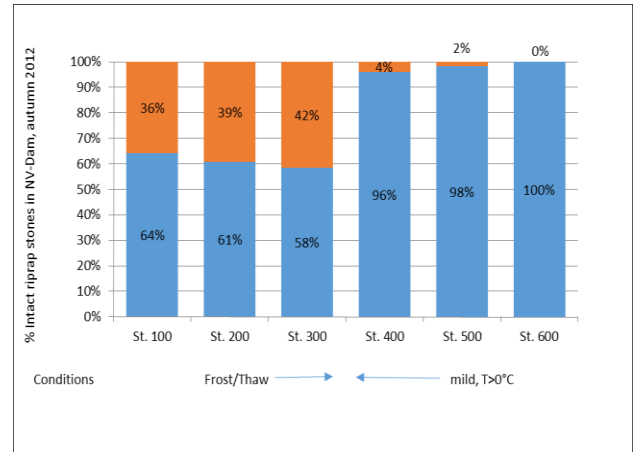


Figure 7. Percentage of intact riprap stones in the NW Dam in autumn 2012

5 SITE TESTING OF RIP RAP STONES

A site test of riprap stones was conducted in November and December 2012. The aim was to observe the progress of fracturing and find if the degree of fracturing was similar in riprap stones from different sources in the basaltic lava formation.

Table 1 shows the quarries, number of stones from each source, date of blasting, date of first exposure to frost, date of transport to test site and first examination of stones. The test site was selected on top of the dam fill so that snow would not cover the stones. Figures 8 to 11 show the test site and stones in the test.

The riprap stones in the test were examined three or four times in the period from November to December 2012 and again in summer 2013. Figure 12 shows the results. It appeared that the stones started cracking following first exposure to mild frost (-5°C). Most of the fracturing took place within the first 10 days. The number of freeze/thaw cycles does not appear to have a significant effect on the progress of fracturing. The degree of fracturing seemed to be independent of stone size.

Table 1. Site test of riprap stones.

Quarry/source	Date of blast	No. of stones	First frost exposure	Transport to test site	First examination
Headrace Tunnel	6.11	28	6.11	6.11	7.11
Approach Canal	31.10	44	31.10	7.11	7.11
New Quarry G1	7.11	25	7.11	7.11	8.11
Approach Canal	8.11	25	8.11	8.11	8.11
Approach Canal	21.11	21.11	21.11	22.11	



Figure 8. Site test of riprap stones



Figure 9. Fractured riprap stone in the site test

The fracture surfaces are in many cases completely fresh and don't appear to follow pre-existing weaknesses in the rock.



Figure 10. Another fractured riprap stone in the site test



Figure 11. Fractured riprap stone in site test

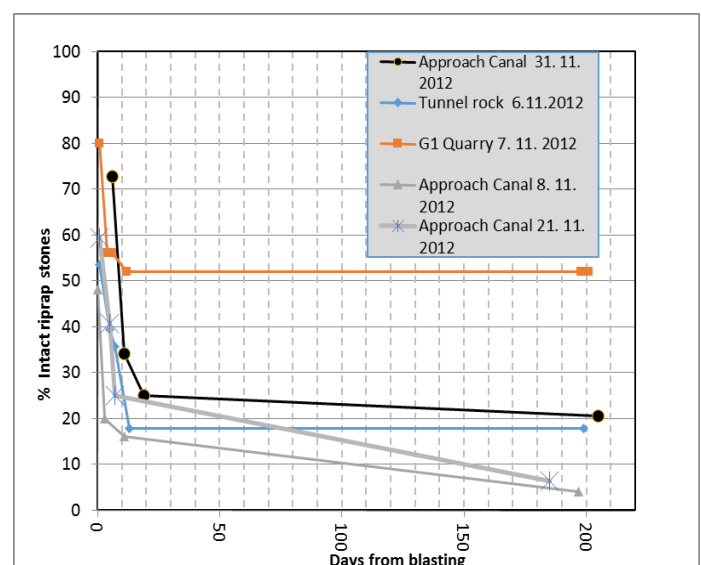


Figure 12. Results of site investigation of riprap stones.

Further surveying of the test stones could have revealed if the fracturing all takes all place within the first month or not. However, the test stones became covered with ice and snow and could not be examined further until next spring. The rock from quarry G-1 appears to have a higher resistance to cracking than rock from other sources in the area. The rock in quarry G1 may not have been saturated at the time of blasting while rock blasted from the Approach Canal and from the Headrace tunnel were probably saturated.

6 RE-EXAMINATION OF DAM RIPRAP.

In June of 2013 when snow had disappeared from the riprap already placed in the Dam the counting of fractured riprap stones was repeated in the same locations as in November 2012, counting essentially the same stones as before. The results are shown in Figure 13.

Comparing the results from 2012 and 2013 reveals that the proportion of fractured rip rap stones that were placed during the summer of 2012 increased to 10 % at station 600 and 500.

For rip rap stones placed at stations 100-300 the fracturing increased considerably. Only 40 % were unfractured in June 2013. The 20 % increase of fractured rip rap stones at stations 100 -300 shows that the initial fracturing was not over by the end of October 2012. At stations 500 to 600 the number of intact stones was about 90 % which is similar to observations from other dams in Iceland. The results at station 400 do not fit into either of the above classes and is unexplained.

7 LABORATORY TESTING OF ARMOUR STONES

To gain a further insight into the behaviour of the riprap stones a laboratory testing program was conducted in a frost-thaw chamber in Reykjavík. Riprap stones cannot be used directly because of size restrictions and the difficulties in handling such large stones. So

stones 5-25 kg were used in the experiment, originating from the Headrace Tunnel and the Approach Canal.

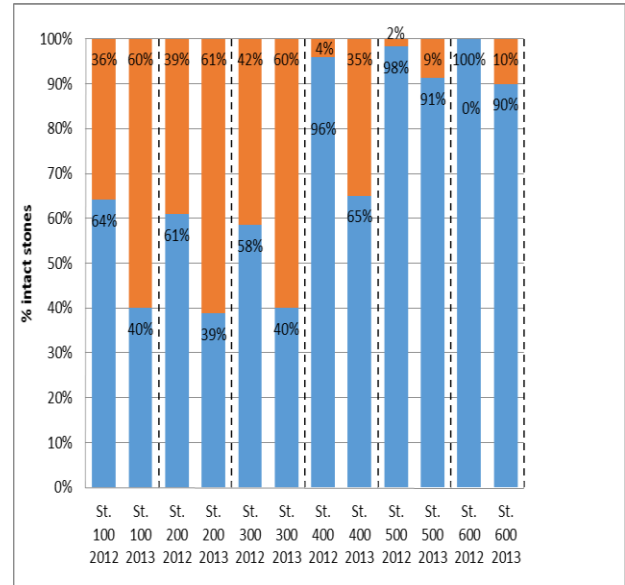


Figure 13. Proportion of fractured rip rap stones along the dam axes in 2012 and 2013.

Most of the stones were submerged in water during the test but a few were tested dry. Air temperature varied from +40°C to -40°C and water temperature varied between +10°C to -10°C. No stones were fractured after 8 cycles. After 25 cycles one stone was found fractured or 4 %. No flaking or weight loss was observed.

8 G_s AND ABSORPTION OF THE RIP RAP STONES.

In table 2 testing of the specific gravity and absorption of the rip rap stones is shown.

Table 2 Specific gravity and absorption of riprap stones from the Búðarháls Project.

Sample	G _s (Mg/m ³)		Absorption
	Apparent	SSD	
1	2,898	2,810	1,7
2	2,818	2,745	1,5
Notes:	Apparent: Oven dry/(Oven dry in water)		
	SSD: Saturated surface dry/(Saturated, surface dry in water)		
	Absorption: (Saturated surface dry- oven dry)/Oven dry		

9 GUIDELINES FOR SELECTING ARMOUR STONES FOR RIP RAP.

No testing of material for riprap was conducted during the design phase of the dam. This is in accordance with the fact that testing of rip rap materials for dam construction is not usually done in Iceland. By contrast it is rule in the selection of armour stones quarries for breakwaters in the country. An Icelandic classification scheme developed for selecting armour stones for breakwaters (Smarason O.B. et al. 2000) indicates that the riprap rock type in the case of the Sporðalda Dam (olivine tholeiite) is qualified as “good”, the specific gravity is also considered “good”. The water absorption would be classified as “fair”.

Standards and guidelines such as ASTM D4992, Practice for Evaluation of Rock to be used for Erosion Control and Designation USBR 6025-09 Procedure for Sampling and Quality Evaluation Testing of Rock for Riprap Slope Protection give some general guidance as to selection of materials. These documents recommend a petrological examination, frost/thaw, specific gravity and absorption testing, but do not indicate specific requirements.

In CIRIA Rock Manual (CIRIA, CUR, CETMEF 2007) it is assumed that frost resistance is generally sufficient if the water absorption of the rock is $< 0,5 \%$. The quality of armour stones is still considered good if water absorption is 0,5-2,0. Quality is considered excellent if $G_s > 2,7$.

Bulletin 91 from ICOLD (ICOLD 1993) lists similar tests as the above but appears to place more importance on petrological examination of rock. It is also implied that stones for riprap should fulfil the same requirements as aggregates for concrete.

Materials for Embankment Dams (United States Society on Dams 2011) states similar requirements and includes a table over properties such as soundness % loss in magnesium sulphate. The same table shows

maximum absorption should be $< 2-6$ according to the Department of Transportation but < 1 according to the Corps of Engineers.

Norwegian guidelines (NVE 2012) state that certain rocktypes are suitable for slope protection while others are not.

The authors conclusion is that it is unlikely that the frost fracturing of the riprap rock at the Sporðalda Dam would have been strongly indicated by usual laboratory testing.

10 EXPERIENCE FROM OTHER QUARRIES IN ICELAND

Fracturing of newly blasted basaltic rock exposed to freezing temperatures have been observed before in four armour stones quarries in Iceland (Sigurðarson 2015). In all cases the fracturing disappeared when the rock was blasted in temperatures above 0°C . The armour stones from these quarries have performed well after years in a harsh environment, exposed to saltwater and a large number of freeze/thaw fluctuations each year. In one of these quarries, located in Hafnarfjörður Iceland, extensive fracturing took place during quarry operation in sub-zero temperature during construction of a new breakwater in 1999-2001. In this quarry the rock was fresh basaltic rock with large columnar jointing like the rock at the Sporðalda Dam. The armour stones from the same quarry were used for a large breakwater constructed in 1969-1970. Inspection of the rock in that breakwater showed that the armour stones were in excellent condition and fracturing of the stones was minimal.

11 CUBE JOINTED BASALT FILL

As explained earlier the slope protection materials (20-40 cm) and the coarser filter (0-20 cm) were obtained from the cube jointed Sporðalda basalt formation. On that dreadful autumn day in 2012 when the fractured riprap was discovered it was also found that the slope protection material was extensively fractured.

Figures 14 and 15 show this. This was serious not only for the upstream slope protection but also because slope protection material is underlying the riprap wave protection and filter criteria had to be fulfilled. Cube jointed basalt has not commonly been used for damfill materials in Iceland. Parts of many quarries in basaltic material contain some cube jointed basalt. Fracturing due to frost has not been noticed as far as the authors know. Cube jointed basalt with smaller cubes than found at the Spordalda dam has been used in bearing courses for roads with good results. Therefore, extensive frost fracturing of this material was unexpected.



Figure 14. Frost fractured slope protection materials in autumn 2012.



Figure 15. Frost fractured slope protection materials in autumn 2012.

Figure 16 shows a comparison between fractured and unfractured slope protection material (20-40 cm) from cube jointed basalt. The d_{50} (average grainsize) of the unfractured samples taken during the summer is reduced from approximately 250 mm to 150 mm in a sample taken from the dam in late November. The fractured material still fits the originally specified gradation for slope protection.

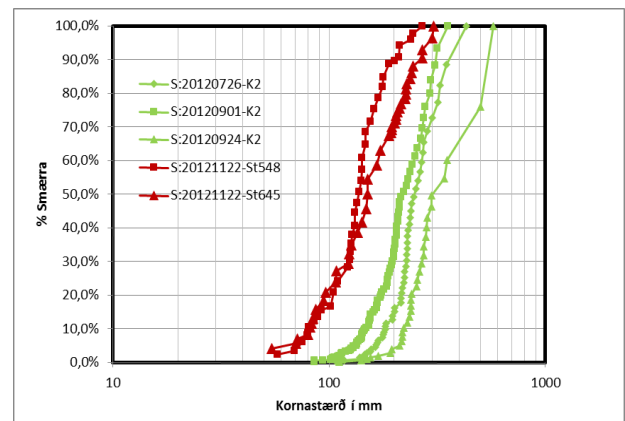


Figure 16. Grain size of frost fractured and unfractured fill from cube jointed basalt. K2: Unfractured fill from K2 quarry, St548 and St645, frost fractured material from dam.

Figure 17 shows a comparison between the grain size of the fractured slope protection material and measurement of riprap stone sizes from 2012. As can be deduced from Figure 16 classical filter criteria for the riprap stones is just about fulfilled between the riprap and the slope protection

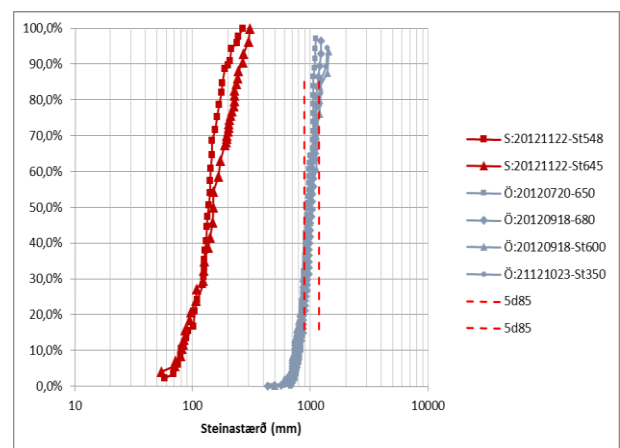


Figure 17. Comparison between the grain size of frost fractured slope protection material and measurement of riprap stone sizes in 2012.

12 TESTING OF THE CUBE JOINTED BASALT FILL

A similar test program as for the riprap was conducted for the cube jointed basalt fill. A site test was made in the source quarry. This revealed that all grains larger than 50 mm fractured due to frost. In one of those field tests the material was kept inside to dry for 3 weeks and then exposed to frost. This had little if any effects on the frost resistance.

A laboratory program using a frost-thaw chamber was conducted both on material directly from the quarry and also on material that had been dried for three weeks in temperatures $> 0^{\circ}\text{C}$. Table 3 shows the results.

Table 3 Freeze/thaw chamber testing of cube jointed basalt stones.

Preparation of samples	Test condition	Number of stones in test	Fractured after 25 freeze/thaw cycles	
			No.	%
Sample dried for one month before testing	Tested dry	5	4	80
	Tested submerged	12	6	50
Sample tested two days after blasting	Tested dry	4	4	100
	Tested submerged	26	15	58

No flaking or loss of weight was observed. The absorption and specific gravity of samples of the cube jointed basalt were also tested. Table 4 shows the results.

Table 4. Specific gravity and absorption of cube jointed lava.

Sample	Gs (Mg/m^3)		Absorption
	Apparent	SSD	%
1	2,775	2,726	1,0
2	2,637	2,567	1,7
3	2,590	2,546	1,1
Notes:	Apparent: Oven dry/(Oven dry in water)		
	SSD: Saturated surface dry/(Saturated surface dry in water)		
	Absorption: (Saturated surface dry-oven dry)/Oven dry		

13 REMEDIAL MEASURES.

Riprap was to be placed on the dam from elevation 330 m a.s.l. to the top of the Dam. For flood protection it was necessary to construct the Dam up to elevation 333 m a.s.l. before winter break in 2012. The Dam was finished up to elevation 333 m a.s.l. in the beginning of December 2012 using mainly rock from the G-1 quarry knowing that some of the riprap stones were bound to fracture after placement in the Dam. Next spring the fractured riprap stones were removed but only from the top the rip rap. Replacing of individual stones further down on the upstream slope was not considered feasible, since this would have involved the complete removal of the rip rap from station 0 to station approximately 400. A factor affecting this decision were that the slope protection was well built with tight interlocking between armour stones, filter criteria between the riprap and the underlying slope protection was most likely fulfilled and it was foreseen that the reservoir water level would extremely seldom be lowered below elevation 333 m a.s.l.

Also in 2013 the Contractor was requested to finish blasting of armour stones before the end of September before temperatures dropped to below freezing and stockpile riprap stones for three weeks before placing in the Dam. This however did not quite work out and blasting of riprap stones continued into the winter period. The riprap stones were generally stockpiled for one or two weeks. As a result, some broken riprap stones are to be found in the wave protection.

The use of cube jointed basalt as a slope protection material (20-40 cm) on the upstream slope was discontinued. Instead material processed from tunnel spoil was used. This material had been exposed to several freeze/thaw cycles.

14 SUMMARY AND CONCLUSIONS

Extensive fracturing occurred when armour stones for riprap were exposed to freezing temperatures shortly after blasting. These stones were quarried from a fresh and unaltered columnar jointed basalt. Armour stones from the same quarries that were subjected to the same temperature fluctuations but had been blasted during summer showed only very limited fracturing. Testing for this type of frost fracturing in armour stones is difficult and does not show up clearly in conventional testing program for armour stone quality. To avoid this type of frost fracturing the rock has to be stockpiled for at least 20-30 day or ensure that the wave protection will not be exposed to freezing temperatures for the same length of time. Frost fracturing of cube jointed basalt has not been observed before. Fracturing of this type of rock shows up in freeze/thaw chamber testing. Where this type of rock is to be used as fill material subject to freeze/thaw conditions freeze/thaw testing is mandatory.

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