Uncertainties in Grout Penetrability Measurements; Evaluation and Comparison of Filter pump, Penetrability Meter and Short Slot

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Abstract To measure grout penetrability in fractured hard rock, various measuring instruments have been developed over the years. Penetrability meter and Filter pump have been designed to use in both the lab and the field. Short slot has been applicable mainly in the lab due to its complexity. The fact, that these instruments have been built based on different assumptions, limitations, and test conditions, makes their results occasionally in contradict. Deficiency in design of the instruments as well as the methods of evaluating grout penetrability is additionally a basis for uncertainty in results. This study is an experimental effort to determine and thoroughly perceive the nature of the most governing uncertainties in grout penetrability measurements. The test apparatus, procedure, and method used to evaluate the grout penetrability in both Penetrability meter and Filter pump were thus modified. The aim was to control the corresponding uncertainties and make their limitations and test conditions as similar as possible with the ones in Short slot. The results suggested that to obtain a more realistic evaluation of the grout penetrability, measurement should be accomplished at both the high and the low pressures with sufficient grout volume

using Short slot. Moreover, application of both Filter pump and Penetrability meter is no longer recommended due to the revealed uncertainties.

Keywords Penetrability · Filtration · Filter pump · Penetrability meter · Short slot · Cement-based grout

1 Introduction

Cement-grouting is a common solution for rock sealing, whereas a key factor to success is to achieve sufficient penetration length in fractures (Houlsby 1990; Lombardi 2003; Warner 2004; Gustafson and Stille 2005; Fransson 2008; Gustafson et al. 2013; Stille 2015). Filtration, generally defined as separation of the suspended solid and the liquid phases of a fluid, limits the grout spread in rock, due to arching/bridging of the cement particles before a constriction through the fractures (Rushton et al. 2000; Eriksson et al. 2004; Hernqvist et al. 2009; Rafi and Stille 2015). Several instruments have been developed over the years to measure the filtration and the penetrability of the cement-based grout, with a summary of the test conditions and the evaluation methods presented in Table 1. The filter-pump and the penetrability-meter, developed by Hansson (1995) and Eriksson and Stille (2003) respectively, are two of the most commonly used instruments in Scandinavia applicable in both the lab and the field due to the simplicity of their

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Table 1 A summary of the grout penetrability measuring instruments

	Instrument	Evaluation method	Test conditions				Developed/investigated
			Filtration media	Stop mechanism	Pressure (bars)	Grout volume (L)	
1	Sand column	Ra–T–V	Sand	C–F3–Re	2.6	10	Axelsson et al. (2009)
2	Pressure chamber	Ra	Fleece fine sand soft rock	F4	1.6	N.A.	Gandais and Delmas (1987)
3	Filter pump	T	Wire mesh	F2	0.5	0.3	Hansson (1995)
4	Penetrability meter	T	Wire mesh	F2	1.0/2.0	1.0	Eriksson and Stille (2003)
5	NES method	W	Slot	F1	0–20	N.A.	Sandberg (1997)
6	Nobuto method	W	Slot	F1	10–50	Unlimited	Nobuto et al. (2008)
7	PenetraCone	Vt	Slot	F2	1.5/3.0/5.0	Unlimited	Axelsson and Gustafson (2010)
8	Short slot	W	Slot	F2	0–15	1.7	Draganovic and Stille (2011)
9	Long Slot	W–P	Slot	F2–Re	0–15	1.7	Draganovic and Stille (2014)

F1 filtration at connection between a borehole and a fracture, *F2* filtration at constriction through a fracture, *F3* filtration, where the grains enter the aperture but gradually separate from the flow and plug the pores, *F4* filtration through the walls of the fracture due to the porosity of the rock matrix and existing micro-cracks, *C* clogging, where the grains are stuck before entering the aperture, *Re* resistance, where the grouting pressure reaches the frictional resistance, *Ra* raise of the water column, *T* total volume of passed grout, *V* visual inspection of the sand column, *Vt* visual inspection of the flow transition from undisturbed flow to dripping and from dripping to the flow stop, *P* pressure–time measurement, *W* weight–time measurement, *N.A.* not available

performances. Short slot has been designed based on geometry and pressure conditions much closer to the rock grouting conditions in field; however, it is a bit more complicated in performance and rather applicable in the lab (Draganovic and Stille 2011).

Comparison of the results obtained from different test apparatus has been previously done by several researchers with various objectives. There were, however, many disagreements between the outcomes of those studies. This was principally due to the fact that the instruments have been designed based on different assumptions, limitations, and test conditions. For instance, the results obtained from Penetrability meter and Filter pump were mostly in contradiction with the ones obtained from Short slot (Draganovic and Stille 2014). Hjertström (2001) using the NES method, a smooth slot approximately similar to Short slot, and Eriksson and Stille (2003) using Penetrability meter illustrated that the penetrability is independent of water to cement (*w/c*) ratio. However, Hansson (1995) by comparing the results of Filter pump with the ones on the sand column and the smooth slot, Eklund and Stille (2008) using Penetrability meter, Axelsson

et al. (2009) using the sand column, and Draganovic and Stille (2011) using Short slot disclosed that increasing the (*w/c*) ratio improves the penetrability. According to Hansson (1995), adding super plasticizer improves the grout penetrability using the smooth slot and Filter pump. However, Eriksson and Stille (2003) showed that use of super plasticizer has no significant influence on penetrability using Penetrability meter. A deep survey in all those studies revealed that the corresponding uncertainties and contradictions are mainly originated in association with:

- (a) The applied pressures
- (b) The designated grout volumes
- (c) The type and the geometry of the filtration areas, e.g., the geometry of the constrictions
- (d) The methods used to evaluate the grout penetrability in terms of b_{min} and b_{crit}
- (a) *The Applied Pressure*

One of the weak points of Filter pump is primarily the operator-dependency of the applied pressure, which is definitely not identical in experiments performed neither by different operators nor by an exhausted operator after

plenty of performances. According to Hansson (1995), the ordinary applied pressure in Filter pump is tolerably around 0.5 bar. In Penetrability meter, the grout tank pressure is regularly set to 1 bar during the experiments (Eriksson and Stille 2003). The ordinary applied pressure of 15 bar in Short slot, however, is considerably higher than the other two instruments (Draganovic and Stille 2011). It is well known that the grout penetrability is improved by increasing the pressure (Eriksson et al. 1999; Hjertström 2001; Nobuto et al. 2008; Draganovic and Stille 2011; Stille et al. 2012). Therefore, the penetrability measurement is undeniably dependent on the grouting pressure and the experiments on identical grout samples under different pressures should definitely reveal diverse or even contradictory results.

Furthermore, in grouting operations in the field, the grout pressure at the beginning of a fracture is equal to the pressure applied at the grouting borehole (relatively high). This pressure gets close to zero or the ground water pressure at the grout front depending on the saturation condition. The grout pressure along the fracture is, however, somewhat in between and also varies at each point during the grout spread. It should be highlighted that we are mainly concerned on the grout pressure at the constrictions within a fracture, where the filtration of the cement particles mostly occurs (Draganovic and Stille 2011, 2014). This suggests the significance of the magnitude of the applied pressure in order to measure the grout penetrability more realistic.

(b) *The Designated Grout Volume*

According to Eriksson and Stille (2003, 2008), grout filtration tendency will reasonably be increased by increasing the volume of the grout passed through the mesh filter. The more the grout volume, the greater is the probability of accumulation and clogging of the cement particles and clusters before the constrictions. It should be noticed that the capacity of Filter pump is about 0.3 L compared with the designated grout volume of 1 L in Penetrability meter and 2.6 L capacity of the grout container in Short slot. This difference in the grout

volume will possibly generate different results in examining identical grout samples, disregarding the influences of uneven pressures and geometries.

(c) *The Constriction Geometry*

Even though, the key question and consequently the geometry in design of different instrument have been different, they have been all designed to evaluate grout penetrability. For instance, the mesh geometry used in Filter pump and Penetrability meter has been mainly designed to replicate a fracture opening, whereas the slot geometry used in Short slot is to study the grout penetrability at the constrictions within a fracture. Filter pump, due to the simplicity of its performance, is currently used for assessment and quality control of cement and mixing process in field. However, as illustrated by Hansson (1995), Eriksson and Stille (2003), and Eklund and Stille (2008), they have been all used to study the influence of varying parameters on grout penetrability.

The corresponding diversity in the type and the geometry of the filtration areas, e.g., the geometry of the constrictions in different instruments is also an origin of dissimilar results. In Penetrability meter and Filter pump, the thickness of the woven metal mesh filter is somewhat less than 100 μm , depending on the size of the employed steel wires. In Short slot, the length of the constriction, however, is about 100 times longer equal to 10 mm (Draganovic and Stille 2011). Consequently, the resisting friction against the grout flow along the thickness of the mesh filters/constrictions in both Penetrability meter and Filter pump will reasonably be negligible, compared with that in Short slot. Furthermore, the effective area in the instruments is different, which leads to different results in examining identical grout samples.

(d) *The Evaluation Method*

The quantities of b_{min} and b_{crit} , developed by Eriksson and Stille (2003), have been the most common used criteria representing the filtration tendency and the penetrability of the grout (Draganovic and Stille 2014). By definition, the b_{min} is the minimum fracture aperture a grout

Fig. 1 Application of weight–time measurement to visualize the uncertainty in evaluation of b_{crit} using the total weight of passed grout

can penetrate at all, whereas the b_{crit} represents the minimum fracture aperture a grout can penetrate without filtration. In Penetrability meter and Filter pump, the total volume of grout passed through each filter is regularly used as the method to estimate the values of b_{min} and b_{crit} . Each experiment is started using the minimum mesh size, enlarged stepwise in successive tests. The narrowest mesh filter, through which the total designated grout volume can entirely pass, represents the value of b_{crit} . The uncertainty of this evaluation method becomes discernible at the mesh sizes sufficiently close to the b_{crit} , using a stepwise bottom-up approach towards the b_{crit} . To visualize this, the measure of weight in time as depicted in Fig. 1 is employed. In this evaluation, a linear relation between the weight and time is an indication of no-filtration versus a non-linear relation which indicates the filtration (Draganovic and Stille 2011). As seen in the figure, in the vicinity of the b_{crit} , i.e., in the tests 5 and 6, despite of slight filtration at the mesh surface, the remained opening is still adequate to let the entire designated grout capacity pass through. Using the total volume of passed grout as the evaluation method, the value of the b_{crit} is therefore estimated smaller, i.e., equal to the mesh size in test 5, while the weight–time measurement reveals a greater value equal to the mesh size in test 7 with no filtration at all. In this study, the uncertainties (a)–(d) above are addressed by a series of experiments. Various aspects are examined and discussed that

influence the penetrability and evaluation of the parameters b_{min} and b_{crit} . We aim to perform the tests using different instruments at conditions as similar as possible, in order to have a fair comparison between the results. Our intention is to study the reasons that cause the corresponding differences between the results. Since Short slot is considered to best replicate the filtration process at a constriction in a rock fracture, the test apparatus and procedure in both Penetrability meter and Filter pump were modified to approach the similar test conditions as in Short slot. Comparison of the results in such conditions provided the opportunity to better evaluate the reliability and functionality of the instruments. Furthermore, the weight–time and the pressure–time evaluation methods are proposed as more accurate alternatives for evaluating the grout penetrability with Filter pump and Penetrability meter. The work presented here intends to support the development of instruments to measure the filtration and the penetrability of the cement-based grout.

2 Materials and Methods

2.1 Adjustment of Filter Pump

Adjustment of Filter pump was to increase the applied pressure from 0.5 to 1 bar as in Penetrability meter, to exclude its operator-dependency and to improve repeatability. It was also to employ the weight–time measurement in order to observe the filtration evolution during the experiments. A 20 kg mass was therefore suspended from the handle of Filter pump using a steel cable passed through two designated rollers (Fig. 2). A grout pot was then suspended from the lab ceiling through an S-shaped load cell, *RSCC C3/50* kg from *HBM*. Each experiment was regularly started using the minimum mesh size of 26 μm attached to the instrument inlet. To run the test, the operator had to release the mass, whereas the instrument inlet was submerged in the grout pot. The grout is consequently sucked inside the instrument, whereas the cement particles build an arch/bridge at the openings in mesh surface (Fig. 2). After the full stroke, the handle had to be kept in maximum position,

Fig. 2 Schematic depiction of modified filter pump and details of arching/bridging at mesh filter, (1) DAQ-data acquisition system, (2) filter pump, (3) load cell

Fig. 3 Evaluation of b_{min} and b_{crit} using the weight–time measurement

while the weight record continued until the flow stop. The process had to be successively repeated by enlarging the mesh sizes as far as no filtration observed during the experiment. The weight–time measurement, as explained earlier, was the method used to distinguish the filtration. The maximum mesh size with negligible passed grout was therefore a representation of the b_{min} , while the minimum mesh size with no filtration at all was an indication of the b_{crit} (Fig. 3).

2.2 Adjustment of Penetrability Meter

Adjustment of Penetrability meter was primarily to follow the filtration evolution in time using the two

evaluation methods; the measures of weight and pressure in time and compare it with the filtration process in Short slot. In this way, the similarity of the filtration process in the filter mesh and the slot's constriction or a real fracture could be better studied. It was also to increase the designated grout volume from 1 to 2.6 L to make it similar to Short slot. The constriction geometry, i.e. the mesh and the pressure condition were approximately similar to those in modified Filter pump. To register the grout weight in time, the grout tank was therefore suspended from the lab ceiling through an *S-shaped* load cell, *RSCC C3/50 kg* from *HBM* (Fig. 4). To provide a constant pressure of 1 bar, a high-pressure gas tank was then connected to the grout tank via a regulator. To register the pressure variation in time, a pressure transmitter, *P15RVA1/20BAR* from *HBM*, was appended to the tank. Finally, to replicate a fracture constriction, a cap holder, keeping the mesh filter in position, was attached to the system.

Each experiment was started using the minimum mesh size of 26 μm . The grout in grout tank was first pressurized up to the designated 1 bar pressure. By opening the outlet valve and start of the grout flow, the cement particles began to build an arch/bridge at the openings in mesh surface, similar to what occurs in filter pump (Fig. 4), whereas the weight and pressure were recorded in time. The process was then successively repeated by enlarging the mesh sizes as far as no

Fig. 4 Schematic depiction of modified penetrability meter and details of arching/bridging at mesh filter, (1) gas tank, (2) pressure regulator, (3) pressure sensor, (4) grout tank, (5) load cell, (6) DAQ-data acquisition system, (7) outlet valve, (8) filter holder and mesh filter

Fig. 5 Monitoring filtration and evaluating the b_{min} and b_{crit} using the pressure–time measurement

filtration was observed. To identify the filtration and to evaluate the values of b_{min} and b_{crit} , weight and pressure in time were alternately measured. The weight–time measurement was similar to that in modified Filter pump but the designated grout volume was 2.6 L in modified Penetrability meter versus 0.3 L in modified Filter pump. Therefore, the evaluated value of b_{crit} using modified Penetrability meter was expected to be greater than the values obtained from modified Filter pump, due to the higher probability of filtration associated with the higher volume of passed grout.

In the pressure–time measurement, when the flow began, a sharp drop in pressure regularly occurred until the balance point, in which the outflow of grout was compensated by the inflow of gas (Fig. 5). Subsequently, the pressure was maintained constant

Fig. 6 Results of the experiments conducted with water, evaluated by the pressure–time method, using modified penetrability meter with 26, 43 and 144 μm mesh filters under 1.3 and 16 bar pressures

provided that the grout was stable without filtration tendency. Such behavior is ideally observed in water. To validate this, the pressure state after the balance point was examined in a couple of water tests under the applied pressures of 1.3 and 16 bar, using the mesh sizes of 26, 43, and 144 μm (Fig. 6). There was no sign of pressure increase subsequent to the balance point in any of the test results, indicating no filtration. On the contrary, in examining a grout with filtration tendency, the pressure state after the balance point showed a continuous increase. The mesh opening and consequently the grout flow progressively decreased due to the filtration of the cement particles. In this approach, a mesh filter maintaining the pressure constant after the balance point is considered to be representative as the b_{crit} , while a mesh filter resulting in a negligible

Fig. 7 Theoretical depictions of the weight-time and the pressure drop-time methods

pressure drop, followed by an immediate flow stop represents the b_{min} (Fig. 5). Note that in this study, variation of pressure in time is presented in the form of pressure drop versus time, to display the results, all starting from the zero level. The results of both the weight-time and the pressure drop-time measurements should reveal the same values of b_{min} and b_{crit} as shown in Fig. 7.

2.3 Short Slot

The test apparatus in the experiments with Short slot was similar to that in modified Penetrability meter except for the cap holder which was replaced by a

disk-shaped slot with different constrictions appended to the grout tank (Fig. 8). In this method, the cement particles build an arch/bridge at the constriction. The method used to evaluate the grout penetrability was the weight-time measurement similar to those in modified Filter pump and penetrability meter. More details of the test setup and procedure can be found in Draganovic and Stille (2011).

2.4 Material Selection and Mixing

The grout comprised of Sika® *Injektering 30* from Sika Sverige AB, a low-alkali injection cement based on Portland cement with d_{95} of 30 μm (95% of the cement particles pass through a 30 μm sieve), using a water to cement ratio (w/c) of 0.8 as a common used grout recipe in Sweden. A dispersing agent, Sika® *iFlow-1*, was also employed with 0.5% of concentration of the cement weight to improve the grout penetrability by generating electrostatic and/or steric repulsion between the cement particles. A rotor–stator lab mixer from VMA was employed to mix the grout with 10,000 rpm. The mixing period was 4 min. After 1 min of mixing, the superplasticizer was added to the mixture. The prepared grout (approximately 2.8 L in each batch) was subsequently used to fill the grout tank and run the test immediately.

2.5 Test Plan

The experiments were conducted based on the test plan presented in Table 2. Due to the limited pressure

Fig. 8 Schematic depiction of short slot and details of arching/bridging at the constriction, (1) gas tank, (2) pressure regulator, (3) pressure sensor, (4) grout tank, (5) load cell, (6) DAQ-data acquisition system, (7) short slot

Table 2 Test plan

Test group	Pressure (bar)	Test device	Evaluation method	No. of repetitions with every mesh size										No. of repetitions with every slot size						
				26 μm	35 μm	43 μm	54 μm	61 μm	77 μm	90 μm	104 μm	122 μm	144 μm	200 μm	43 μm	50 μm	70 μm	84 μm	169 μm	177 μm
1	1	OFP	WT	1	4	4	4	3	3	3	2	–	–	–	–	–	–	–		
2	1	MFP	WT	–	4	3	3	3	3	3	2	1	2	1	–	–	–	–		
3	1	MPM	WT	–	2	2	2	–	3	3	1	2	1	3	–	–	–	–		
4	1	MPM	PT	–	2	3	3	–	1	1	–	3	–	3	1	–	–	–		
5	1	SS	WT	–	–	–	–	–	–	–	–	–	–	–	–	1	1	3		
6	15	SS	WT	–	–	–	–	–	–	–	–	–	–	–	1	3	1	–		
Sum =				1	12	12	12	6	10	5	6	3	7	1	1	3	2	–	1	3
Total																				
				No. = 85																

OFP ordinary filter pump, MPM modified penetrability meter, MFP modified filter pump, SS short slot, WT weight–time, PT pressure–time

capacity of both Filter pump and Penetrability meter, the applied pressure of 1 bar was determined for all experiments except for the test group 6, conducted with 15 bar pressure using Short slot. Test groups 1 and 2, using ordinary and modified Filter pump, were designed to visualize the uncertainties and examine the effectiveness of the modifications. Test groups 3 and 4 were thereafter performed using modified Penetrability meter to compare the efficiency of the weight–time and the pressure–time evaluation methods and the evaluated b_{min} and b_{crit} with these methods. To investigate the influence of the applied pressure, as a governing origin of the contradiction, test groups 5 and 6 were thus organized under application of 1 and 15 bar pressure using Short slot. The tests were continuously re-performed to check the repeatability of the adjusted instruments and methods.

3 Results

A summary of the values of b_{min} and b_{crit} evaluated for the same materials and recipe using the aforementioned instruments with different pressure conditions, designated grout volume, geometries, and evaluation methods are presented in Table 3.

3.1 Penetrability Measurement Using Filter Pump

The results of the experiments examined by ordinary Filter pump using the weight–time measurement evaluation are presented in Fig. 9. The experiments with 26 and 35 μm mesh filters illustrated negligible passed grouts and immediate flow stop due to the instant filtration, while the efforts with 43 μm mesh filter disclosed some minor grout flows. The value of b_{min} was therefore evaluated as 35 μm . The measurements with 54–90 μm mesh filters resulted noisy graphs with varied mass flow rates, showing a very poor repeatability. Considering the total volume of passed grout to evaluate the values of b_{crit} , the result would be 77 μm , since the grout tank was completely filled in all three repetitions. However, using the weight–time measurement evaluation, a fair estimation of the b_{crit} will approximately be 90 μm , since some filtration is detectable in the results of the 77 μm mesh filter.

The results of the experiments examined by modified Filter pump using the weight–time

Table 3 Summary of the results

Test device	Evaluation method	Pressure (bar)	b_{min} (μm)	b_{crit} (μm)
OFP	T	1	35	77
OFP	W	1	35	90
MFP	T	1	43	61
MFP	W	1	43	77
MPM	W	1	43	200
MPM	P	1	35	200
SS	W	1	70	200
SS	W	15	26	50

OFP ordinary filter pump,
MFP modified filter pump,
MPM modified
penetrability meter,
SS short slot, *T* total
volume of passed grout,
W weight–time,
P pressure–time

Fig. 9 Penetrability evaluated by ordinary filter pump with 26–90 μm mesh filters using the weight–time measurement

measurement evaluation are presented in Figs. 10 and 11. The experiments with 35 and 43 μm mesh filters illustrated negligible passed grouts and

immediate flow stop due to the instant filtration (Fig. 10). The value of b_{min} was therefore evaluated as 43 μm . However, the measurements with 54 μm

Fig. 10 Penetrability evaluated by modified filter pump with 35–104 μm mesh filters using the weight–time measurement

Fig. 11 Penetrability of samples (based on recipe 1) evaluated by modified filter pump with 61–104 μm mesh filters using the weight–time measurement

mesh filter showed limited grout flow and partial filling of the instrument capacity followed by flow stop due to filtration. The measurements with 61–104 μm mesh filters revealed approximately similar mass flow rates, showing a better repeatability compared with ordinary Filter pump. Considering the total volume of passed grout to evaluate the

values of b_{crit} , the result would be 61 μm , since the whole instrument capacity was completely filled in all experiments with the 61–104 μm mesh filters. However, a fair estimation of the b_{crit} will possibly be greater than 61 μm , i.e. 77 μm , using the weight–time evaluation method, due to the visualized filtration in the results of 61 μm mesh filter (Fig. 11).

Fig. 12 Penetrability evaluated by modified penetrability meter with 35–144 μm mesh filters using the weight–time measurement

3.2 Penetrability Measurement Using Penetrability Meter

The results of the experiments examined by modified Penetrability meter using the weight–time measurement are presented in Fig. 12. The experiments with 35 and 43 μm mesh filters showed negligible passed grouts and immediate flow stop due to the instant filtration, while the efforts with 54 μm mesh filter disclosed some minor grout flows. The value of b_{min} was therefore evaluated as 43 μm . Subsequently, the experiments with 77 μm mesh filter presented no sign of filtration in less than 1.0 kg of the passed grout with a satisfactory repeatability. The experiments with 90–122 μm mesh filters further displayed no sign of filtration in less than 1.5 kg of the passed grout, whereas after this limit the nonlinear graphs represent the filtration. The measures with 144 μm mesh filter examined with 2.0 and 4.0 kg of the passed grout, however, illustrated a minor non-linearity in the graphs, representing a slight filtration. This implies that the value of b_{crit} is greater than 144 μm , approximately 200 μm , provided that the amount of passed grout is between 2.0 and 4.0 kg.

The results of the experiments examined by modified Penetrability meter using the pressure–time measurement evaluation are depicted in Fig. 13. The attempts with 35 μm mesh filter, presenting a negligible pressure drop of less than 0.1 bar with no grout flow, were representative for the value of b_{min} . However, in the experiments with wider openings/mesh sizes where accompanied by considerable grout flows, the pressure drops were no longer negligible and rose progressively in successive tests. Subsequent to the balance point, the pressure drop returned back to its initial zero value in the attempts with 35–104 μm mesh filters, representing the filtration. The time period to obtain the pressure drop back to zero from the balance point was also increased by enlarging the mesh filter (Fig. 13). The minor reductions in pressure drop after the balance point, depicted in the results of the experiments with 144 μm mesh filter, were an indication of filtration, which were all interrupted by reaching the driving gas to the outlet. However, in the experiment with 200 μm mesh filter the interruption occurred at the balance point before appearance of any filtration. The value of b_{crit} was therefore evaluated as 200 μm .

Fig. 13 Penetrability evaluated by modified penetrability meter with 35–200 μm mesh filters using the pressure–time measurement

3.3 Penetrability Measurement Using Short Slot

The results of the experiments performed with Short slot with 1 bar grout pressure using the weight–time evaluation are shown in the left diagram in Fig. 14. The experiments with 70 μm aperture size showed a negligible passed grout and immediate flow stop due to the instant filtration. The value of b_{min} was therefore

evaluated as 70 μm . The experiments with 169 and 177 μm aperture sizes, however, illustrated non-linear relations, representing considerable filtration. This implies that the value of b_{crit} is evaluated greater than 177 μm , e.g., approximately 200 μm .

The results of the experiments performed with Short slot with 15 bar grout pressure using the weight–time evaluation are presented in the right diagram in Fig. 14.

Fig. 14 Penetrability evaluated by short slot under 1 bar (left) and 15 bar (right) pressures, using the weight–time measurement

The experiments with 43 μm aperture size showed a nonlinear relation with considerably quick filtration followed by the flow stop after 1.3 kg of the passed grout. Therefore, a fair estimation for the value of b_{min} will definitely be lower than 43 μm . The attempts with 50 and 70 μm aperture sizes, however, illustrated linear relations with similar trends, representing no filtration at all. The value of b_{crit} is therefore evaluated as 50 μm .

According to Eklund (2005), a rule of thumb in hard rock grouting developed by Crawford and Graskopf (1984) suggests that the aperture size of a groutable fracture should be at least three times the maximum grain size (d_{95}) of the used cement. However, this rule is mainly applicable on old grout recipes without additives and admixtures (e.g. super-plasticizers) using coarse grained cements (e.g. $d_{95} > 30 \mu\text{m}$) with low water-to-cement ratios and is not consistent with the results obtained in this study.

4 Discussion

The presented results can be reconsidered and further discussed with respect to the most governing origins of the uncertainties in grout penetrability measurement using the aforementioned instruments. The uncertainties are principally induced by either of or a combination of the applied pressure, the grout volume, the constriction geometry and the evaluation methods.

4.1 Uncertainties Induced by the Applied Pressure

One of the deficiencies of ordinary Filter pump is the operator dependency of the applied pressure, which might generate different penetrability for identical

grout samples. Uneven and unequal mass flow rates, shown in different repeats with the 54, 61 and 77 μm mesh filters in Fig. 9, are due to the non-uniform and dissimilar applied pressures along an experiment and in different repetitions. Comparison with the results of modified Filter pump in Figs. 10 and 11 revealed that the adjustment on the instrument and method undeniably reduced the uncertainties in measurement.

Comparing the values of b_{min} and b_{crit} evaluated from Short slot tests with 1 bar pressure (70 and 200 μm) with those under 15 bar pressure (<45 and 50 μm) suggests that diversity in the applied pressure is one of the most governing sources of contradiction in the results of penetrability measurements conducted by different penetrability measuring instruments as expected.

When grouting a fracture in rock, the grout pressure in the vicinity of the borehole is the maximum. Due to the pressure loss during the penetration, the driving pressure which can be mobilized at the grout front decreases. Depending on the grout rheology and the number of the constrictions in the fracture the pressure loss can be substantial. Since penetration at a constriction is dependent on the pressure, it is essential to measure the penetrability with both the high and the low pressures. This implies that, measuring the grout penetrability using Short slot only at high pressure does not yield a satisfactory result applicable in the field. Therefore, evaluating the b_{crit} at both the low and the high pressures (e.g. 1 and 15 bar) is crucial to determine the upper and the lower limits of the fracture aperture in rock that a specific grout can penetrate without filtration.

Fig. 15 Penetrability evaluated by modified penetrability meter with 144 μm mesh filter using both the weight–time and the pressure–time measurements

The quality of the grout passed through a constriction mainly depends on the size of the constriction and the rheological properties of the injected grout. If the constriction size is larger than b_{crit} , there will be no filtration and therefore no change in the quality of the grout passed through the constriction. If the constriction size is between b_{min} and b_{crit} , filtration of the cement particles occurs at the constriction. The smaller the constriction size the higher the filtration and therefore the lower the quality of the grout passed through the constriction. This is due to the fact that the number of cement particles passed through the constriction will be lower and therefore the grout passed through the constriction will be thinner with lower density, apparent viscosity, and yield stress. Similar result is expected when the injected grout is thicker. The higher the density, viscosity, and yield stress, the more the filtration of the cement particles in the same constriction size (if the constriction size is between b_{min} and b_{crit}) and consequently the lower would be the quality of the passed grout through the constriction.

4.2 Uncertainties Induced by the Grout Volume

In the experiments with modified Penetrability meter using the weight–time measurement evaluation, the value of b_{crit} is evaluated as 90 μm , provided that the amount of passed grout was between 1.0 and 1.5 kg (Fig. 12). It could also be evaluated as 77 μm , if the amount of passed grout was less than 1.0 kg. The latter is similar to the results of ordinary and modified Filter

pump with 0.3 L of the passed grout (less than 1.0 kg). This implies that one of the other principal origins of the contradiction in the results of different test instruments is the amount/volume dependency of the grout penetrability that suggests the higher the designated grout volume, the greater the value of b_{crit} .

The required grout volume for a proper evaluation of grout penetrability can be determined based on the needed grout volume to inject a real fracture in rock. According to Grøv and Woldmo (2012), a key point to a successful grouting is to focus the injection on the surrounding area of the tunnel edge limited to a radius of 5–10 m. This suggests a minimum penetration length of approximately 5 m around the tunnel. Assuming disk shape fractures with the apertures of 50, 100, and 200 μm and the radius of 5 m around a grouting borehole, their required grout volume can be calculated as 3.9, 7.8, and 15.7 L respectively with an average of nearly 10 L. Dividing this disk into four quarters gives the required grout of approximately 2.5 L. The reason for dividing the calculated volume of a disc shaped fracture by four is to obtain a rough estimation of the grout volume that is required to fill that fracture in 1D direction. This will possibly be a reasonable proposal for the designated grout volume in penetrability test instruments that definitely needs further investigation. It should be noticed that the volume of the grout container in Short slot (approximately 2.6 L) is very close to this value, whereas the designed grout volume in ordinary and modified Filter pump as well as ordinary penetrability meter is 0.3 and 1 L respectively. This once again contributes to underestimate the values of the b_{min} and the b_{crit} .

4.3 Uncertainties Induced by the Constriction Geometry

The designated grout volume of 2.6 L and the applied pressure of 1 bar in Short slot were approximately identical to those in modified Penetrability meter. The remained diversity was in the constriction geometries, i.e. the slot geometry in Short slot with 10 mm of the constriction length versus the mesh geometry in modified Penetrability meter with 100 μm mesh thickness. The associated resisting friction against the grout flow along the constriction length in the mesh geometry is negligible compared with the slot geometry of the same size. This suggests that the pressure loss along the constriction in Short slot is greater than

modified Penetrability meter. Considering an identical pressure before the constriction in both instruments, a lower driving pressure will reasonably remain at the end of the constriction in Short slot which will reduce the grout penetrability. A higher value of b_{min} is therefore expected for similar grout using Short slot compared with modified Penetrability meter. The obtained results in this investigation verified that in closely identical conditions the evaluated value of b_{min} in Short slot (70 μm) was greater than that in modified Penetrability meter (35 and 43 μm) (Figs. 12, 13, 14). The similar values of the b_{crit} (200 μm) evaluated by Short slot and modified Penetrability meter imply that evaluating the b_{crit} is less influenced by the diversity in the geometry (Figs. 12, 13, 14).

4.4 Uncertainties Induced by the Evaluation Methods

In ordinary Filter pump, replacing the total volume of passed grout by the weight–time measurement to evaluate the values of b_{crit} provided the opportunity to recognize the filtration in the experiments with 77 μm mesh filter, which was not possible before (Fig. 9). In modified Filter pump, replacing the old evaluation method by the new one, once again provided the opportunity to identify the filtration in the experiments with 61 μm mesh filter, which could not be properly detected previously (Fig. 11). Therefore, the new evaluation method in both ordinary and modified Filter pump undeniably increased the accuracy in the evaluation.

In modified Penetrability meter, both the weight–time and the pressure–time evaluation methods were to reveal the same penetrability. This was verified in Fig. 15, where the start and the evolution of filtration after 1.35 s presented by both methods simultaneously. In Fig. 13, the value of b_{crit} obtained from the pressure–time method (200 μm) also verified the result of the weight–time method perfectly. However, the pressure–time evaluation appeared more sensitive than the weight–time method in evaluation of the b_{min} .

4.5 Uncertainties Induced by a Combination of Origins

The evaluated b_{min} and b_{crit} obtained from Filter pump are significantly lower than those obtained from Short slot in 1 bar pressure (Table 3). This is considered to be in association with all the aforementioned

parameters (a)–(d) in the introduction except the pressure. This makes Filter pump not suitable for measuring the b_{min} and the b_{crit} . However, it can still be used to control the cement quality, i.e., the partial hydration of cement in contact with moisture or to test the quality of mixing as described in SS-EN 14497:2004.

5 Conclusions

The most significant outcomes of this investigation are presented as follows:

- Nonuniform and unequal applied pressure was found to be one of the main governing origins of uncertainty and contradiction in the results of different penetrability measuring instruments. Evaluating b_{crit} at both the low and the high pressures, e.g. 1 and 15 bar, was found crucial to determine the upper and the lower limits of a real fracture aperture in rock that a specific grout can penetrate without filtration.
- Difference in the designated grout volume was found the second governing origin of uncertainty and contradiction in the results of penetrability measuring instruments. The experiments using modified Penetrability meter clearly illustrated that the higher the designated grout volume, the greater the value of b_{crit} . The required grout volume for proper evaluating the grout penetrability was also estimated to be approximately 2.5 L. The results of ordinary and modified Filter pump and ordinary Penetrability meter (with the designated grout volume of 0.3 and 1 L) will therefore be less than the proper values of the grout penetrability through a real fracture in rock. This makes applicability of those instruments not recommended. However, Filter pump is still useful for quality control of the cement and the mixing process as suggested by Swedish standard SS-EN-14497.
- Diversity in the constriction geometry was found as the third governing origin of uncertainty and contradiction in the results of the penetrability measurements. The evaluated value of the b_{min} in Short slot was greater than that in modified Penetrability meter in closely identical conditions. This was due to the remained differences in the constriction geometries. However, the similar values of the b_{crit} obtained from both instruments inferred that evaluating the b_{crit} is less influenced by the diversity in constriction geometry.

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