

An Experimental Approach to the Development of Dynamic Pressure to Improve Grout Spread

A. N. Ghafar¹ · A. Mentesisidis¹ · A. Draganovic¹ · S. Larsson¹

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Abstract Dynamic grouting is one of the methods to improve grout spread in rock that have been investigated since 1985. The results were promising, but all tests were performed under noticeable simplifications related to conditions in rock fractures. This study is an experimental approach to improve the grout spread using low-frequency instantaneous variable pressure as a new alternative with better control of filtration. The method is tested through parallel plates with constrictions of 30 and 43 μm under the applied pressures with 4 s/8 s and 2 s/2 s peak/rest periods. The results reveal conclusively the effectiveness of the method and provide a basis for further development of dynamic grouting.

Keywords Grout spread · Filtration · Erosion · Cement-based grout · Dynamic grouting · Variable pressure

1 Introduction

To achieve the required sealing in any underground infrastructure in rock, one of the key factors is to obtain sufficient grout penetration length. Cement-based grout is

one of the most commonly used materials in grouting, due to its numerous advantages from a financial, environmental, and durability point of view. However, filtration of the cement particles, which is generally defined as the separation of the suspended solid and the liquid phases of a multi-phase fluid, is an obstacle (Cheremisinoff 1998; Rushton et al. 2000). According to Eriksson et al. (2000), Eriksson and Stille (2003), and Draganovic and Stille (2011), filtration is the result of arching and plug building of the cement particles and clusters at a fracture constriction that restricts the grout spread. In addition to filtration, another parameter that influences the grout spread is the grout rheology, i.e. the viscosity and yield stress (Håkansson 1993; Schwarz 1997; Eklund 2005; Banfill 2006; Rafi 2013; Mohammed et al. 2014). Eklund and Stille (2008) also illustrated that the most significant parameters limiting the grout spread are the grout's rheological properties and filtration tendency. Several investigations over the years have therefore aimed to improve the grout spread with the focus on the grout rheology and filtration tendency.

1.1 Background

One of the main parameters influencing filtration and consequently grout spread is pressure. An increase in pressure decreases the filtration tendency and improves grout spread (Eriksson et al. 1999; Hjertström 2001; Draganovic and Stille 2011, 2014; Stille et al. 2012). According to Nobuto et al. (2008), stepwise pressure increments regulate clogging of the cement particles. The influence of dynamic pressure on improving grout spread was primarily demonstrated in the Stripa mine by Pusch et al. (1985). Borgesson and Jansson (1990) further showed that, by superimposing a high-frequency oscillating

✉ A. N. Ghafar
ali.nejad.ghafar@byv.kth.se

A. Mentesisidis
anamen@kth.se

A. Draganovic
almir.draganovic@byv.kth.se

S. Larsson
stefan.larsson@byv.kth.se

¹ Division of Soil and Rock Mechanics, Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden

pressure with large amplitude on a high static pressure of 20 bar, even a low water content cement grout can penetrate well through 100- μm artificial fractures. The mechanism of action was described by the latter as reduction in the grout viscosity due to the high-frequency oscillation, while the internal structure of the grout was disrupted and reorganized into a lower viscosity material. The results of their full-scale field tests were also satisfactory. Wakita et al. (2003) later conducted several laboratory and field tests using oscillating pressures with amplitudes of up to 5 bar superimposed on an underlying pressure of 10 bar and obtained an increase in flow rate and total volume of grout take. The mechanism of improvement was once again interpreted as being based on a reduction in grout viscosity, reducing the possibility of clog formation in a fracture. Mohammed et al. (2015) examined similar pressure and likewise reported an increase in grout spread through parallel plates with aperture sizes of 100–500 μm with the same interpretation of the mechanism of action.

1.2 Motive

The pressure examined in all previous investigations of dynamic grouting was mainly a high-frequency oscillating pressure. Other alternatives to oscillating pressure, especially at low frequencies, have not yet been investigated (Fig. 1). Furthermore, the previous laboratory experiments were all conducted on parallel plates without constriction, i.e. with no filtration along the fracture/parallel plates. This is undeniably in contrast with the geometry of a real fracture in rock having numerous constrictions. Additionally, the action mechanism of the method was consistently interpreted as reduction in viscosity due to the oscillation. It should be noticed that the nature of the resistance against grout spread through ideal parallel plates depends to a very great extent on the grout rheology. However, in view of the grout spread through a real fracture in rock, the rheology is not the only governing parameter to consider. The filtration of the cement particles should also be examined by replicating the process through parallel plates with constrictions. Earlier observations were all performed through aperture sizes $>100 \mu\text{m}$, but successful grouting in micro-fractures narrower than $70 \mu\text{m}$ is crucial in order to fulfill

the required sealing in areas with extremely high sealing demands, e.g. high-level nuclear waste repositories. This is regardless of the many other severe demands in such applications, e.g. high fluidity, rapid hardening, and extremely high durability and erosion resistance, which were extensively investigated by Mohammed et al. (2013, 2014, 2015) among others.

1.3 Scope

This study is a novel experimental approach to improve grout spread using a low-frequency instantaneous variable pressure as a new alternative with better control of filtration. In this project, manufactured fissures in the form of steel parallel plates having constrictions with apertures of 30 and 43 μm were used. The scope was to replicate the filtration within artificial fractures to examine the influences of the method on filtration and subsequently on grout spread more realistically and under fully controlled conditions. It was also to investigate the corresponding efficiency within micro-fractures narrower than $70 \mu\text{m}$. The examined pressures were based on two compositions of the peak/rest periods, i.e. 4 s/8 s and 2 s/2 s, to determine the one with better control of filtration with respect to the selected materials and test conditions and to understand the corresponding reasons (Fig. 2). It was finally to follow the filtration evolution within the cycles along the entire experiments to identify the most critical cycles in terms of filtration in order to better control them as a means to improve grout spread.

1.4 Why Instantaneous Variable Pressure?

To effectively control the filtration and improve the grout spread in dynamic grouting, the acceleration and magnitude of the pressure variation and the durations at maximum and minimum pressure (the peak and rest periods) are probably the key parameters. These parameters depend on the shape of the applied pressure, the geometry of the slot/fracture, the limitations of the pressure variation system (e.g. rate of pressure relief), and the rheological properties of the grout. The idea is to increase the acceleration and magnitude of the pressure variation as much as possible.

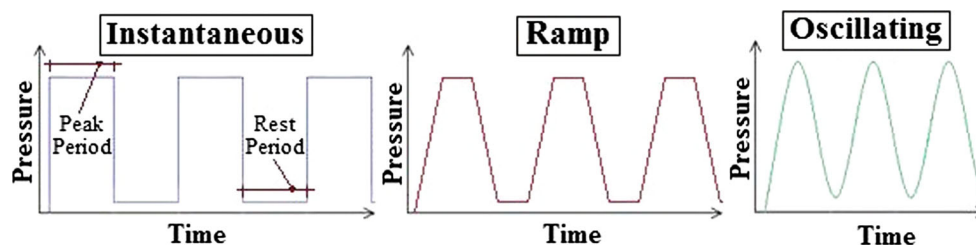


Fig. 1 Different alternatives of the dynamic pressure

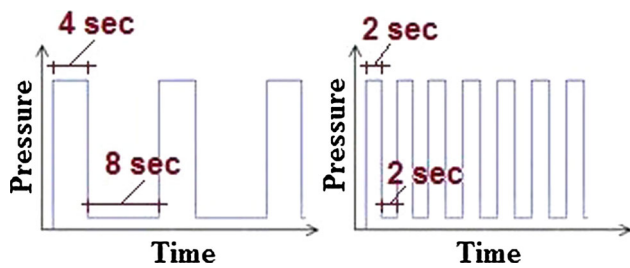


Fig. 2 Instantaneous variable pressure with peak/rest periods of 4 s/8 s and 2 s/2 s

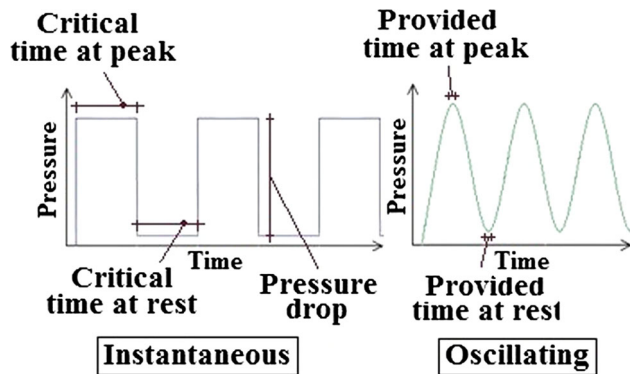


Fig. 3 Critical and provided times at peak and rest during the oscillating and instantaneous variable pressures

Second, the durations of the peak and rest periods seem to have certain critical limits, above which a filter cake is expected to appear and expand over the constriction that can no longer be eroded, and below which the durations will probably be insufficient to obtain effective pressure variations (Figs. 3, 4). This suggests that the durations of the peak and rest periods should also be kept as close as possible to the critical limits. In a comparison between oscillating, ramp shape, and instantaneous variable pressures, the latter is expected to be the best option to fulfill all the required conditions for maximizing the efficiency of dynamic grouting (Fig. 1).

1.5 How to Select the Peak and Rest Periods?

To assess the critical peak and rest periods corresponding to our selected materials and test setups, a few preliminary tests were conducted under static and dynamic pressure conditions. In the static pressure tests, the filtration process was observed to initiate mainly after 4 s. Thereafter, in the dynamic ones, it was realized that duration of approximately 8 s is required to obtain a relatively low pressure during the rest period. In order to prevent filtration before initiation and to obtain sufficiently low pressure during the rest period, the first preference for the peak and rest periods was therefore chosen to be 4 and 8 s, respectively (Figs. 2,

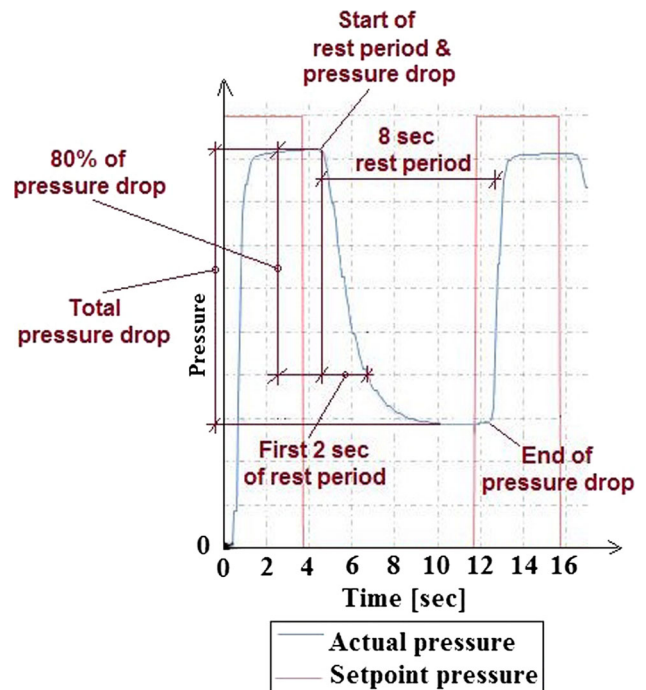


Fig. 4 Instantaneous variable pressure, details of the peak and rest periods

4). Later, in the dynamic pressure tests with 4 s/8 s peak/rest period, gradual accumulation of filtration was observed during the peak periods in progressive cycles. In addition, over 80 % of the pressure drop during the rest period in each cycle was observed to occur along the first 2 s. In order to better regulate the accumulated filtration and the duration of the process, the second preference for the peak and rest periods was established as 2 and 2 s, respectively (Fig. 2). Reduction of the peak and rest periods below a certain limit (e.g. <2 s) for the selected materials and test setups is, however, expected to be unproductive. This is because the remaining time for grouting after obtaining the maximum pressure during the peak period (≤ 1 s) would probably be insufficient. Likewise, the time provided during the rest period (if it is ≤ 2 s) is expected to yield an insufficient pressure drop (Fig. 4). Hence, the critical limits for the peak and rest periods corresponding to the selected materials and test setup were considered to be approximately 2 and 2 s, respectively.

2 Materials and Methods

2.1 Materials and Mixing Process

The mix design used in the present study is one of the most commonly used in Swedish infrastructure projects. It is composed of INJ30 with (d_{95}) of 30 μm (i.e. at least 95 %

by weight of the cement particles are $<30\ \mu\text{m}$) from Cementa AB, together with iFlow-1 from Sika AB as superplasticizer with 0.5 % concentration, using a water–cement ratio (w/c) of 0.8. The mixing process begins with premixing using a hand mixer. An (SR) rotor–stator dispersion system from VMA-GETZMANN GMBH operated at 10,000 rpm is then utilized to thoroughly disperse the cement particles within the mixture. The 4-min mixing period begins with adding the weighted cement to the required amount of water. After 1 min of mixing, the superplasticizer is added to the mixture. The grout container is then filled directly after the mixing with the prepared grout (approximately 2.8 l), and the test is run immediately.

2.2 Test Apparatus and Procedure

The test apparatus consists of a 2.6-l grout tank suspended from a steel frame by means of an S-shaped load cell, RSCC C3/50 kg from HBM. The load cell is to register the grout weight over time. The required pressure for the experiment is provided by a high-pressure (200 bar) gas tank using a pressure regulator to adjust it to a static pressure of 15 bar. A pressure transducer, P15RVA1/20BAR from HBM, is connected to the grout tank at the top to register the tank pressure. A ball sector valve from Ramón AB, controlled by a PID control unit from Bronkhorst High-Tech, is connected to the grout tank at the bottom. A second pressure sensor, a Vegabar 83, is added to the system to measure the grout pressure over time at the entrance to the attached short slot using the Flow Plot software from Bronkhorst High-Tech (Fig. 5).

Defining the pressure set points, i.e. the magnitudes and durations of the peak and rest periods in the form of a control script, is the first step in each test. After filling the grout tank with the prepared grout mix, a static pressure of 15 bar is applied to the system, while valves 10 and 14 are fully closed (Fig. 5). By running the control script, valve 10 is entirely opened. The grout flow is then initiated through the slot under 15 bar pressure and maintained over the peak period. At the end of the peak period, the valve is completely closed. The result is a sharp pressure drop, followed by a gradual pressure reduction over the rest period. This process is repeated until either the entire grout volume has passed through the slot or the flow stops due to complete filtration of the cement particles at the slot's constriction.

2.3 Experimental Program

The experimental program consists of six test groups shown in Table 1. In the experiments conducted in test groups C1 and C2, all samples were examined under

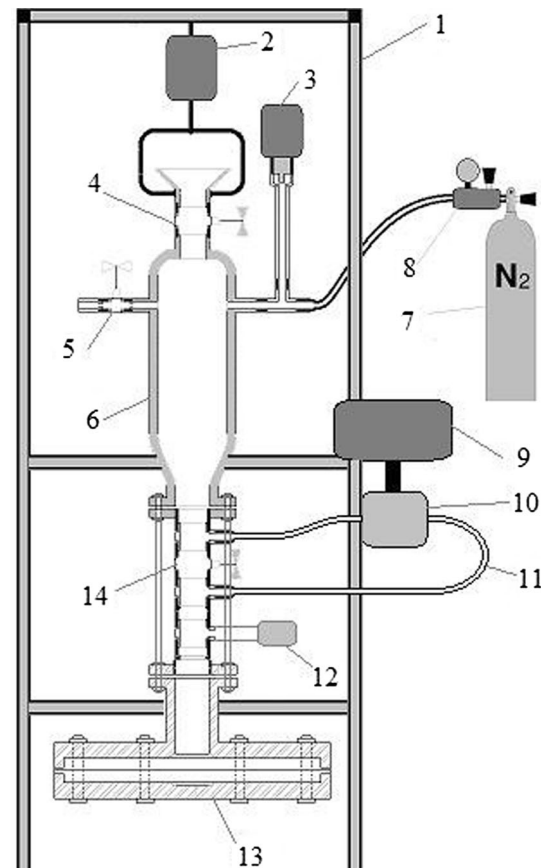


Fig. 5 Schematic depiction of the test setup. 1 Steel frame, 2 load cell, 3 pressure transducer, 4 inlet valve, 5 flushing valve, 6 grout tank, 7 gas tank, 8 pressure regulator, 9 PID controller, 10 ball sector valve, 11 high-pressure hose, 12 pressure sensor, 13 short slot, 14 gate valve

application of a static pressure of 15 bar to replicate the grouting pressure condition in the field. In the experiments performed in test groups V1 and V2, an instantaneous variable pressure with a maximum of 15 bar was applied to the materials with peak and rest periods of 4 and 8 s, respectively. Finally, in the experiments conducted in test groups V3 and V4, similar pressure was tested but with peak and rest periods of 2 and 2 s, respectively.

2.4 Evaluation Methods

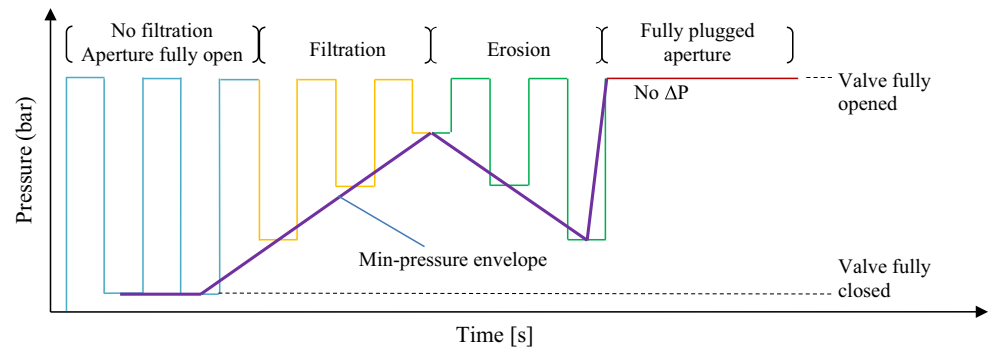
Four different methods were used in the present study to evaluate and better understand the influence of the instantaneous variable pressure and compare the obtained results with those from the static pressure tests. The details of the methods together with a summary of their benefits and drawbacks are prioritized starting from the simplest one as described below:

1. The total weight of passed grout was the simplest method with the aim of quantifying the differences.

Table 1 Test plan

Test group	Number of tests	Slot size (μm)	Pressure type	Peak/rest period (s)
C1	3	43	Static	–
C2	3	30	Static	–
V1	3	43	Dynamic	4/8
V2	3	30	Dynamic	4/8
V3	3	43	Dynamic	2/2
V4	2	30	Dynamic	2/2

Fig. 6 Illustration of the min-pressure envelope, filtration and erosion



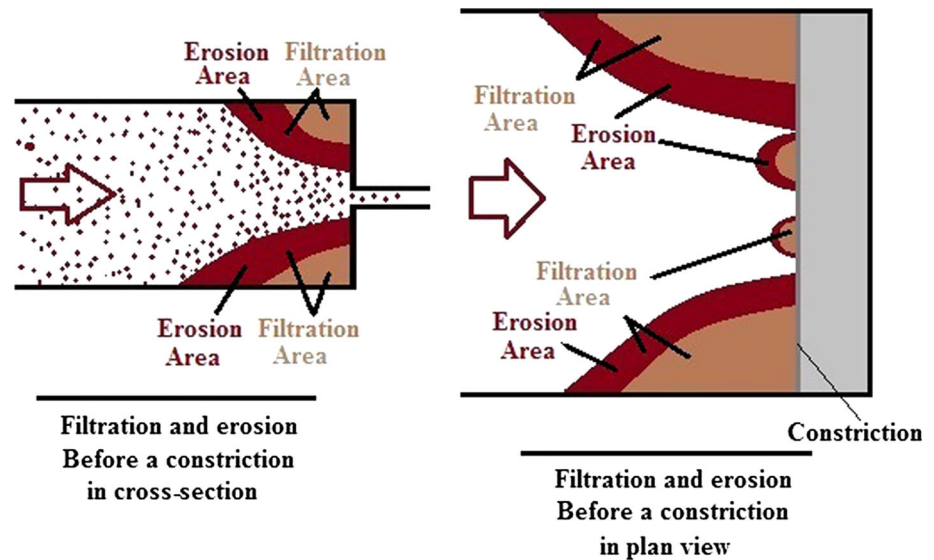
- The main drawback of the method, however, was the lack of observation of the filtration and erosion processes over time.
- The weight–time measurement developed by Draganoic and Stille (2011) was the second method, with the purpose of monitoring the filtration during the experiment. The disadvantage of the method, however, was unclear distinction between the filtration and erosion processes. In this approach, a linear relation between weight and time was an indication of no filtration, whereas a nonlinear relation represented filtration.
 - The third method was the measure of pressure over time accompanied by a min-pressure envelope intended to visualize both the filtration and erosion processes along the experiments (Fig. 6). However, the method was unable to quantify the influences of the filtration and erosion processes in each cycle. The min-pressure envelope was a polyline connecting the consecutive vertices of the minimum pressure levels of all cycles along the pressure–time diagram (Fig. 6). Any positive (upward) trend along the min-pressure envelope was considered to be an indication of filtration, whereas any negative (downward) trend represented erosion. As explained in Fig. 4, after the peak period, the grout pressure tends to zero during the rest period. Because of the remaining pressure, the grout flow continues with a gradual trend. Due to accumulation of cement particles during the filtration process in each cycle, the size of the slot’s opening is

- reduced (Fig. 7). The grout flow and the resulting pressure drop consequently decrease during the consecutive cycles. The minimum obtained pressures during the rest periods in successive cycles therefore increase. The result is an upward trend along the min-pressure envelope during the filtration process. In the case of erosion, however, the size of the slot’s opening increases, resulting in a higher grout flow and pressure drop (Fig. 7). The minimum obtained pressures during the rest periods in successive cycles therefore decrease. The result is a downward trend along the min-pressure envelope during the erosion process (Fig. 6).
- The min-pressure envelope presented in the previous method illustrates the filtration and erosion processes graphically. However, to quantify them in each cycle and to better distinguish between the influence of different peak and rest period durations, a parameter called cycle mean flow rate (CMFR) was introduced as a fourth method. The CMFR, defined as the mean value of the volumetric flow rate of the passed grout in each cycle, can be calculated as:

$$CMFR = \frac{V}{T} \tag{1}$$

where V is the volume of grout passed per cycle determined based on the registered weight of grout passed per cycle and the measured grout density using a mud balance, and T is the cycle duration.

Fig. 7 Filtration and erosion at a constriction



3 Results

3.1 Test Results Using the Total Weight of Passed Grout

Results from the experiments using 43- and 30- μm slots considering the total weight of passed grout are summarized in Tables 2 and 3, respectively. During the static pressure tests with a 43- μm slot (test group C1), the grout tank was never empty at the end of the experiments, whereas the weight of passed grout was repeatedly reported as less than half the capacity of the grout tank (Table 2). During the dynamic pressure tests with the same slot (test groups V1 and V3), the grout tank was consistently empty at the end of the experiments, showing an average weight of passed grout more than double that the case of static

pressure application. The method, however, was unable to differentiate between the influences of 4 s/8 s and 2 s/2 s peak/rest periods on regulating the filtration.

In the next effort, a smaller aperture size of 30 μm was examined with the same peak/rest periods. Test groups C2, V2, and V4 resulted in a flow stop before the grout tank was empty in all the experiments (Table 3). Application of dynamic pressure, however, showed a significant difference, i.e. a substantially higher amount of passed grout compared with static pressure application. Test group V2 with a peak/rest period of 4 s/8 s showed an increase in the average weight of passed grout approximately 2.6 times greater than in the static pressure case, whereas test group V4 with a peak/rest period of 2 s/2 s showed considerable improvement, approximately 11 times greater than in the case of static pressure.

Table 2 Comparison of total weight of passed grout for test groups C1, V1, and V3, using a 43- μm slot

Test group	Test no.	Peak/rest period (s)	Weight of passed grout (kg)	Final tank condition	Average weight of passed grout (kg)	Improvement compared with the static pressure condition
C1 (static)	1	–	1.339	Not empty	1.932	–
	2	–	2.055	Not empty		
	3	–	2.402	Not empty		
V1 (dynamic)	1	4/8	4.189	Empty	4.271	2.2
	2	4/8	4.302	Empty		
	3	4/8	4.321	Empty		
V3 (dynamic)	1	2/2	4.093	Empty	4.072	2.1
	2	2/2	4.177	Empty		
	3	2/2	3.947	Empty		

Table 3 Comparison of total weight of passed grout for test groups C2, V2, and V4, using a 30- μ m slot

Test group	Test no.	Peak/rest period (s)	Weight of passed grout (kg)	Final tank condition	Average weight of passed grout (kg)	Improvement compared with the static pressure condition
C2 (static)	1	–	0.441	Not empty	0.299	–
	2	–	0.181	Not empty		
	3	–	0.275	Not empty		
V2 (dynamic)	1	4/8	0.852	Not empty	0.786	2.6
	2	4/8	0.824	Not empty		
	3	4/8	0.684	Not empty		
V4 (dynamic)	1	2/2	2.679	Not empty	3.190	10.7
	2	2/2	3.702	Not empty		

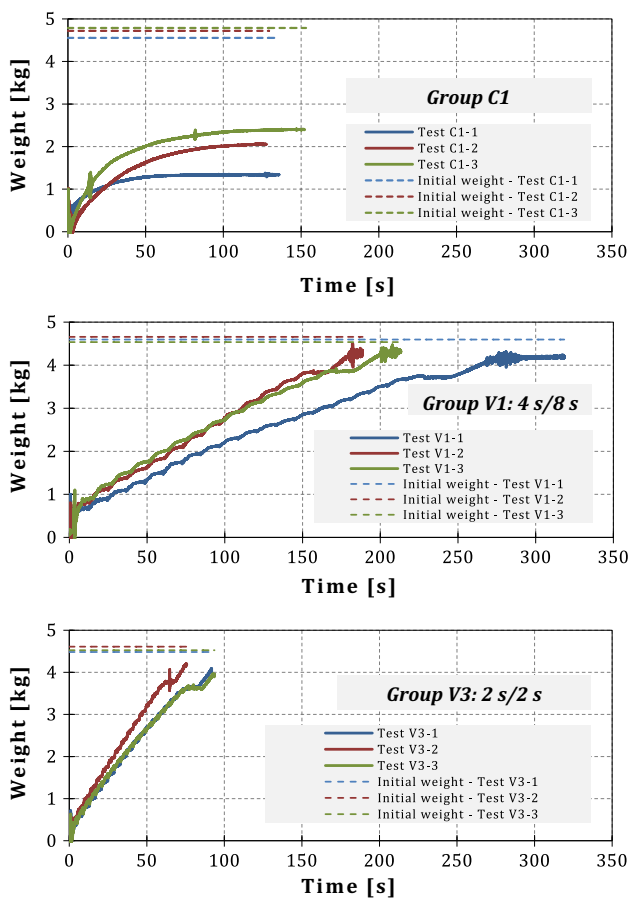


Fig. 8 Weight–time measurements for test groups C1, V1, and V3 using a 43- μ m slot with peak/rest periods of 4 s/8 s and 2 s/2 s

3.2 Test Results Using the Weight–Time measurement

Results from the experiments using 43- and 30- μ m slots considering the weight–time measurement are presented in Figs. 8 and 9, respectively. During the static pressure tests using a 43- μ m slot (test group C1), the results clearly

illustrated the filtration process along the experiments by relatively quick variations in the gradient of the weight–time measurements (Fig. 8). However, during the dynamic pressure tests (test groups V1 and V3), the results showed some minor/negligible variations in gradient, indicating slight degrees of filtration along the experiments. During the static pressure tests using a 30- μ m slot (test group C2), the results showed a small amount of passed grout accompanied by rapid filtration. During the dynamic pressure tests, however, test group V4 in particular, the results showed gradual accumulation of filtration followed by a flow stop. The flow stop was observed in test V4-1 after approximately 350 s and in test V4-2 after 500 s (Fig. 9).

3.3 Test Results Using the Min-Pressure Envelope

The min-pressure envelopes obtained from the pressure–time measurements using 43- and 30- μ m slots are shown in Figs. 10 and 11, respectively. As can be seen from the results from test group V1, there are cycles with upward trends in the min-pressure envelopes, showing dominant filtration, versus cycles with downward trends, indicating dominant erosion, distributed without any prevailing tendency throughout the experiments (Fig. 10). The results from test group V3, however, are more stabilized with a gradual upward trend, indicating consistent compensation between the filtration and erosion with minor accumulated filtration in successive cycles. As can be seen from Fig. 11, all the min-pressure envelopes obtained from the experiments in test group V2 showed a sharp upward trend just through the first few cycles, illustrating rapid and dominant filtration ending with a flow stop. In the experiments conducted in test group V4, the steep upward trend in the min-pressure envelopes during the first 25 s was an indication of significant filtration at the beginning, followed by some random filtration and erosion, which kept the slot open for a longer period.

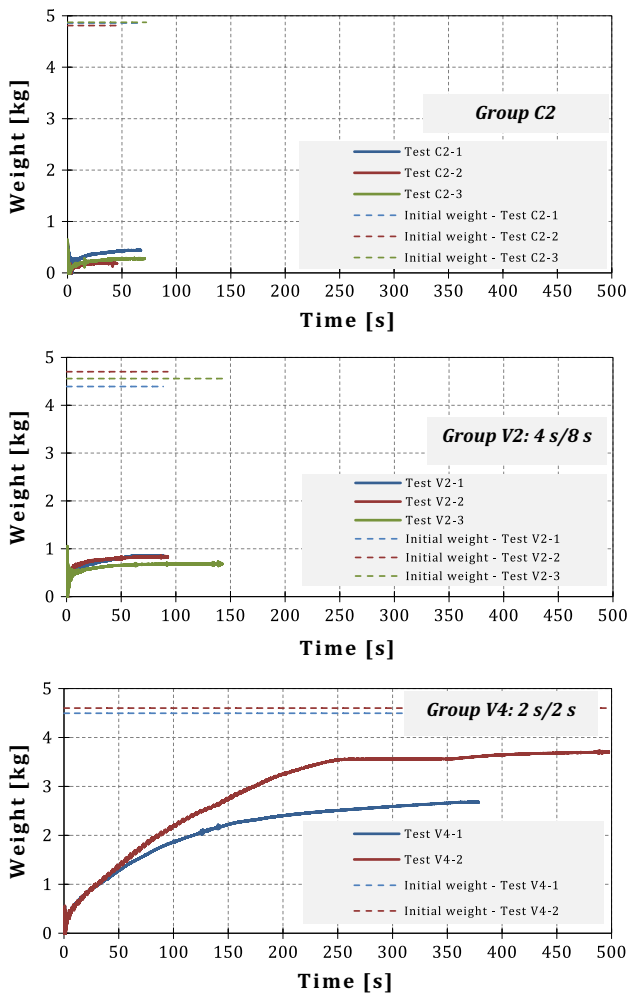


Fig. 9 Weight–time measurements for test groups C2, V2, and V4 using a 30- μ m slot with peak/rest periods of 4 s/8 s and 2 s/2 s

3.4 Test Results Using the Cycle Mean Flow Rate (CMFR)

The results of the experiments using 43- and 30- μ m slots considering the CMFR, along with the average CMFR of all cycles, are presented in Figs. 12 and 13, respectively. As shown in Fig. 12, the average CMFR for all the experiments conducted with a peak/rest period of 4 s/8 s was lower than with 2 s/2 s. The mean value of the average CMFRs for the three experiments performed with 4 s/8 s peak/rest period was 0.72 l/min, compared to 1.76 l/min for the tests conducted with 2 s/2 s, showing an approximately 2.4 times higher average for the latter. In Fig. 13, the CMFR value in the first cycle of the experiments with 4 s/8 s peak/rest period was approximately half the corresponding values in experiments with a 2 s/2 s peak/rest period. Furthermore, in the former case the flow stop occurred quickly,

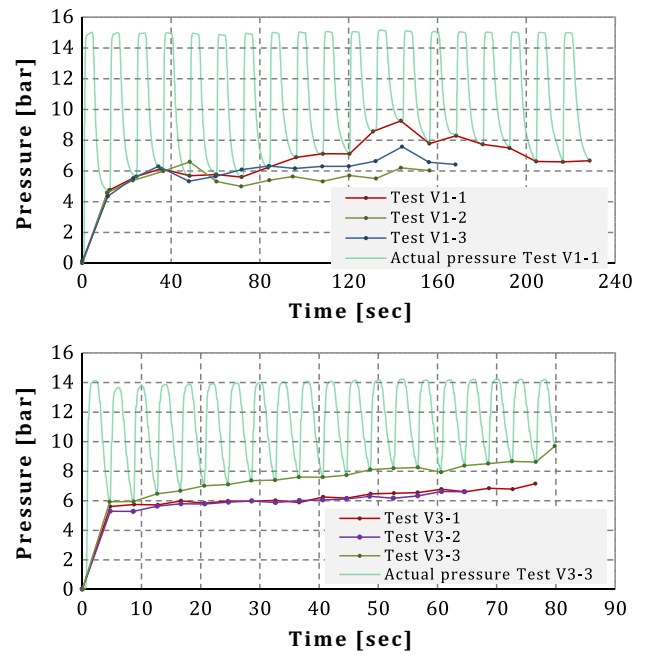


Fig. 10 Min-pressure envelopes for test groups V1 and V3 using a 43- μ m slot with peak/rest periods of 4 s/8 s and 2 s/2 s

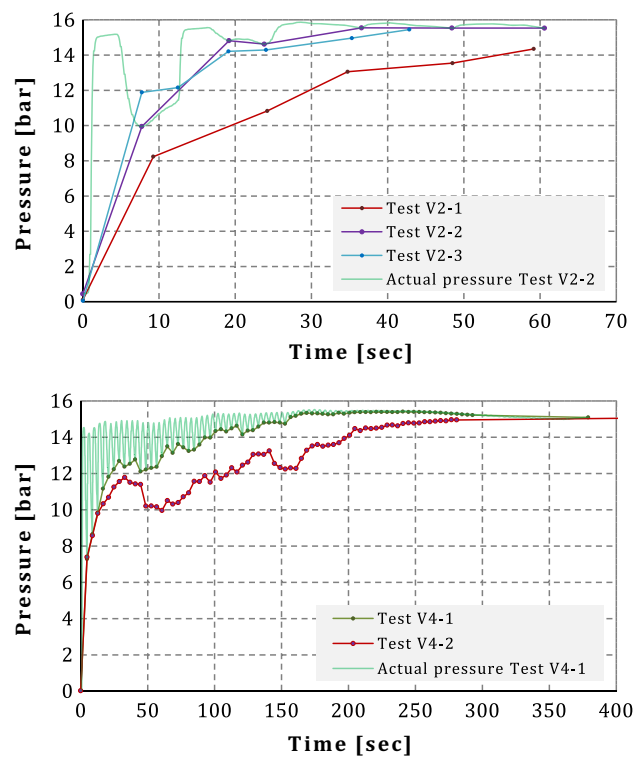
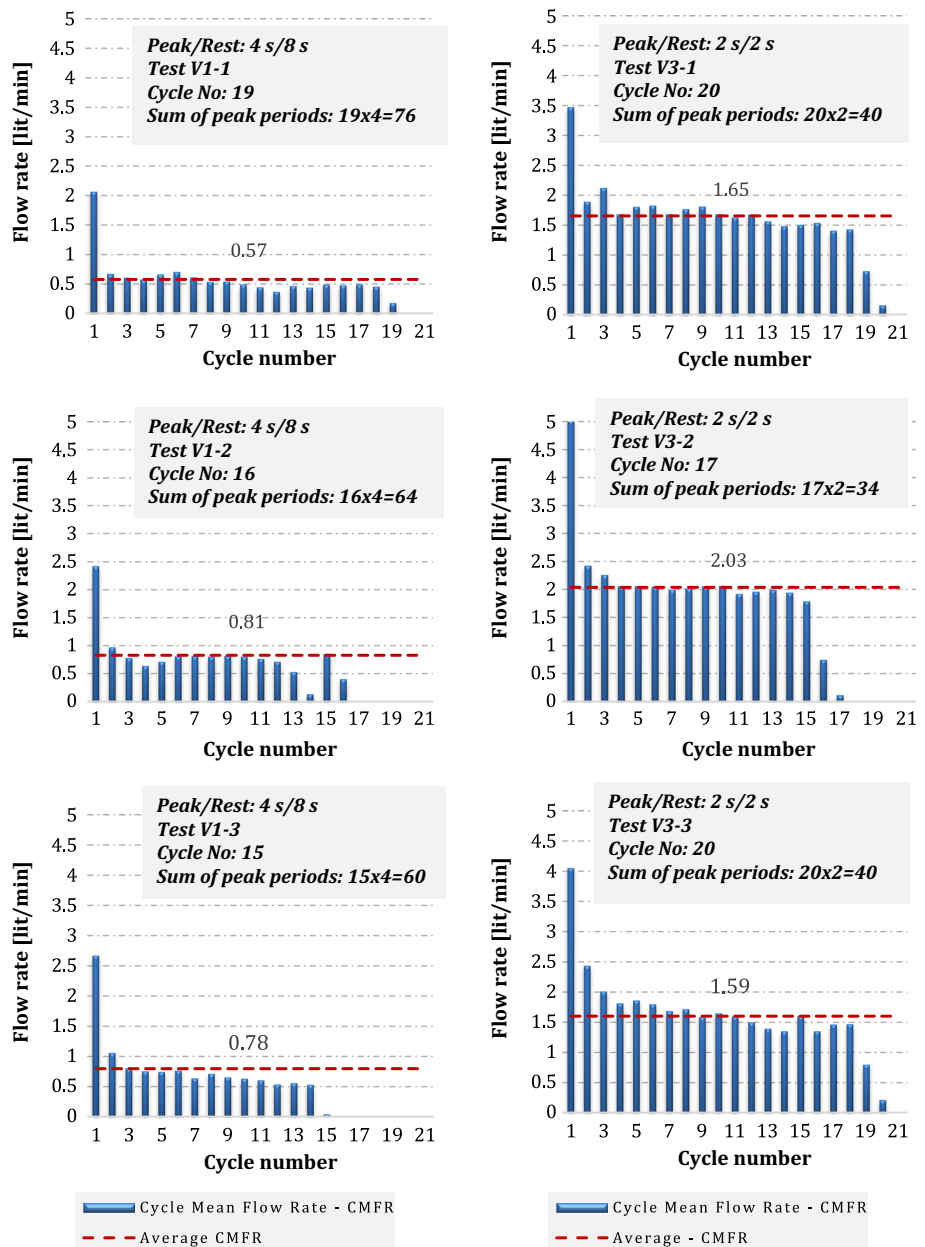


Fig. 11 Min-pressure envelopes for test groups V2 and V4 using a 30- μ m slot with peak/rest periods of 4 s/8 s and 2 s/2 s

after only a few cycles, whereas in the latter the selection of the peak/rest period was more effective and kept the slot open longer.

Fig. 12 Cycle mean flow rates (CMFRs) and average CMFRs for the test results using a 43- μ m slot with peak/rest periods of 4 s/8 s and 2 s/2 s



4 Discussion

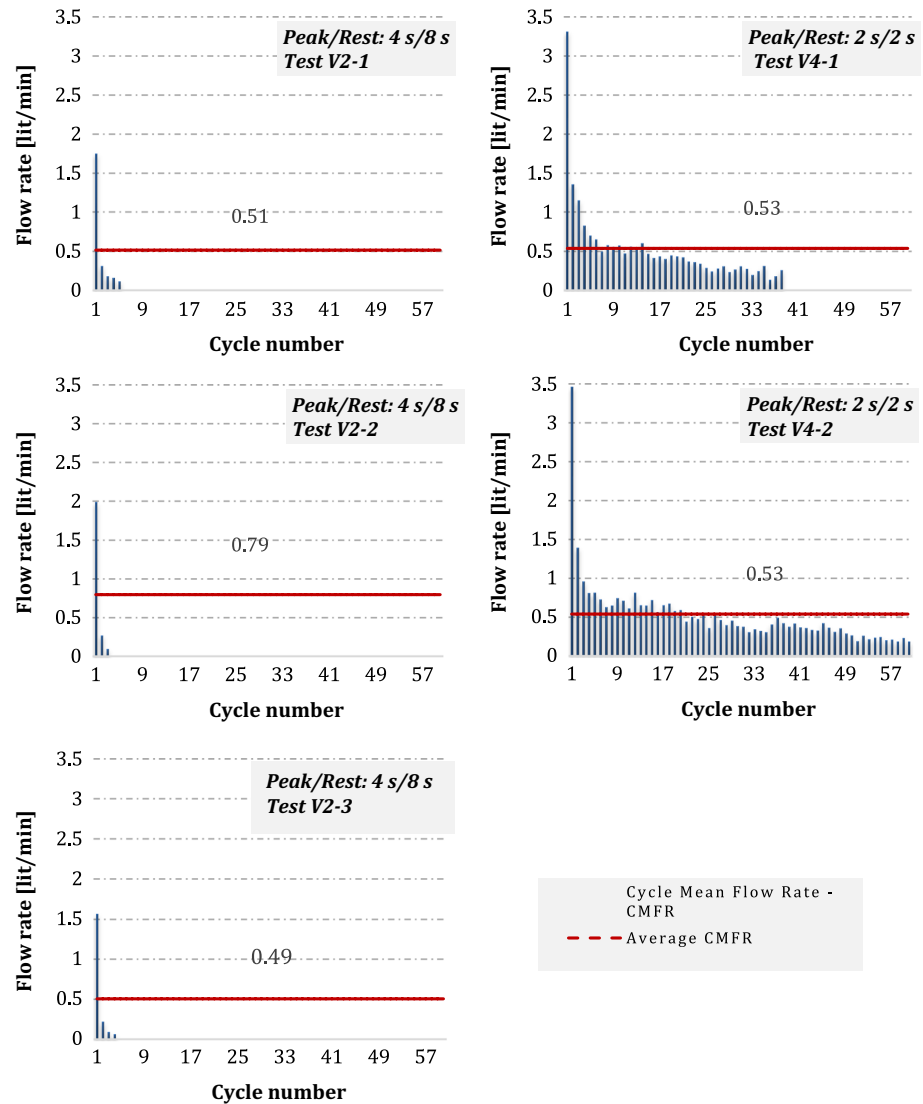
4.1 The Influence of the Method on Grout Spread in a 43- μ m Slot

The average weights of the passed grout obtained from the experiments with 4 s/8 s and 2 s/2 s peak/rest periods were more than double those from static pressure application (Table 2). This was a clear indication of the effectiveness of instantaneous variable pressure for improving grout spread through a slot with 43 μ m aperture size. However, there was no clear distinction between the two peak/rest periods of 4 s/8 s and 2 s/2 s. The results from the weight-

time measurements presented in Fig. 8 further showed some minor filtrations during those experiments, whereas the min-pressure envelopes revealed the progress of filtration and erosion within the cycles. The cycles with dominant filtration and/or erosion were distributed without any prevailing tendency during the experiments with 4 s/8 s peak/rest period; however, the ones from the 2 s/2 s peak/rest period were more stabilized with a gradual upward trend, showing minor accumulation of filtration within successive cycles (Fig. 10).

Flow rate is a parameter directly related to the opening size of the slot under identical conditions. The wider the opening size, the higher the flow rate, while the opening

Fig. 13 Cycle mean flow rates (CMFRs) and average CMFRs for the test results using a 30- μ m slot with peak/rest periods of 4 s/8 s and 2 s/2 s



size itself is substantially affected by the filtration. The greater the filtration, the narrower the opening that remained. Two alternatives can thus be considered as the time for the pressure to act: first, the entire cycle period but with different mean flow rates during the peak and rest periods, and second, the duration of the peak period as the governing one disregarding the rest period. The results presented in Fig. 12 were with consideration of the first alternative. As can be seen, the value of the average CMFR of 1.76 l/min ($[1.65 + 2.03 + 1.59]/3$) obtained from the tests with a 2 s/2 s peak/rest period was approximately 140 % higher (2.4 times) than the 0.72 l/min ($[0.57 + 0.81 + 0.78]/3$) obtained in the tests with 4 s/8 s. This clearly shows that the accumulation of filtration in the tests with a 2 s/2 s peak/rest period was better controlled and considerably lower than the 4 s/8 s case. Additionally, the time required to empty the grout tank was approximately 140 % shorter for the former.

Considering the second alternative, the effective pumping time in 1 min of the experiments was 30 s for 2 s/2 s and 20 s for 4 s/8 s. One might expect a higher flow rate with 2 s/2 s, provided that the average opening sizes of the slot in both cases were identical. In our experiments, the cross sections in both cases were initially identical, but due to uneven filtration after some grout flow the openings that remained were expected to be unequal. On the other hand, in Fig. 12 the mean values of the sum of all the peak periods in the tests with 4 s/8 s and 2 s/2 s peak/rest periods were determined to be 66.7 s ($[76 + 64 + 60]/3$) and 38 s ($[40 + 34 + 40]/3$), respectively. This resulted in 76 % more time being taken for the pressure to act in the case of 4 s/8 s peak/rest period, corresponding to rationally 76 % higher volume of the passed grout. However, the volumes of passed grout in both cases were similarly equal to the grout tank capacity (Table 2). Dividing identical grout volumes by 76 % shorter time for the 2 s/2 s case

resulted in a higher average flow rate of 76 % in the tests with a 2 s/2 s peak/rest period.

On close examination of the CMFRs presented in Fig. 12, the first cycle in each test clearly shows the highest value compared with the following ones. The significant difference between the CMFRs in the first and second cycles is an indication of severe filtration during the first cycle. This has a huge impact on the remaining opening size of the slot and consequently on further development of the flow rates. Subsequently, the results obtained from the experiments with 2 s/2 s showed higher CMFRs in the first cycles compared to the results of 4 s/8 s tests. This is an indication of a lower degree of filtration over the first cycles in the tests with 2 s/2 s compared to 4 s/8 s peak/rest period, showing once again that the peak/rest period of 2 s/2 s is closer to the critical ones, resulting in better control of filtration and improved grout spread.

4.2 Influence of the Method on Improving the Grout Spread in a 30- μ m Slot

The average weights of the passed grout obtained from the experiments with 4 s/8 s and 2 s/2 s peak/rest periods showed approximately 2.6 and 11 times improvement compared to those from the static pressure application, respectively (Table 3). This is a clear indication of effectiveness of the instantaneous variable pressure on improving the grout spread through a slot with 30 μ m aperture size. One can conclude directly that filtration was controlled better with a 2 s/2 s peak/rest period than with 4 s/8 s in experiments using 30- μ m slot.

Regarding the weight–time measurement presented in Fig. 9, the evolution of filtration during the static pressure tests in experiments using a 30- μ m slot was extremely fast, followed by a flow stop after a limited amount of passed grout. During the dynamic pressure tests with a 4 s/8 s peak/rest period, the growth of filtration was still rapid. In the case of a 2 s/2 s peak/rest period, however, the results showed gradual accumulation of filtration followed by a flow stop over a much longer period (Fig. 9).

The results of the min-pressure envelope illustrated once more that using a 2 s/2 s peak/rest period was effective enough to keep even a 30- μ m constriction open for a longer period (Fig. 11). In addition, the method visualized cycles with dominant erosion throughout the experiments as the main reason for reopening the partially plugged constrictions, as shown in Fig. 11.

The considerable difference between the CMFRs of the first and second cycles in each test is once again an indication of significant filtration during the first cycles (Fig. 13). Moreover, the lower values of the CMFRs in the first cycles in the tests with 4 s/8 s peak/rest period compared to the ones in the tests with 2 s/2 s are an illustration

of lower filtration during the first cycles in the tests with a 2 s/2 s peak/rest period. This shows further that the peak/rest period of 2 s/2 s is closer to the critical ones, resulting in better control of filtration and improved grout spread.

4.3 Possible Interpretation of the Mechanism of Action

To figure out how the proposed method improves the grout spread, the flow equations in laminar and turbulent conditions were employed (White 1998). The aim was to determine the flow types inside the slot at different pressures during the peak and rest periods. The calculations for the selected grout and test setups revealed a pressure of approximately 9 bar, above which the flow type was turbulent and below which laminar. On this basis, depending on the magnitude of the pressure variation within each cycle, the method's potential mechanism of action can be categorized into two conditions: the major pressure variation (between 15 and <9 bar) and the minor one (between 15 and >9 bar) (Fig. 14).

In case of major pressure variation, due to the high pressure and high flow velocity during the peak period the flow type is expected to be turbulent (Fig. 14a). During the rest period, due to a large drop in pressure and flow velocity, the flow type is anticipated to turn to laminar (Fig. 14a). The same process is repeated in subsequent cycles, whereas the change in flow type from laminar to turbulent suggests a drastic variation in flow pattern. This will possibly increase the probability of eroding any partially built filter cakes and will improve the grout spread significantly. See also the illustration of the filtration and erosion processes in Fig. 7. In case of a minor pressure variation, the flow type always remains turbulent with minor variation in the flow pattern (size and positions of the vortices), due to the minor variation in flow velocity (Fig. 14b). Slight erosion of the produced filter cakes is therefore anticipated (Fig. 14b).

The proposed mechanism of action can also be distinguished in our obtained results. In the case of dynamic pressure with major pressure variation as seen in the results from a 43- μ m slot in Fig. 10 (between 15 and \leq 9 bar), the flow type is expected to change between turbulent and laminar. A severe change in flow pattern is therefore anticipated that increases the probability of erosion of any produced filter cake. This can be seen in Fig. 8, where the severe filtration registered under application of constant pressure (C1) was totally diminished when the dynamic pressure applied with both peak/rest periods (V1–V3). This is an indication of substantial efficiency of dynamic pressure with major pressure variation. In the case of dynamic pressure with minor pressure variation as seen in the results from a 30- μ m slot in Fig. 11 (between 15 and \geq 9 bar), the

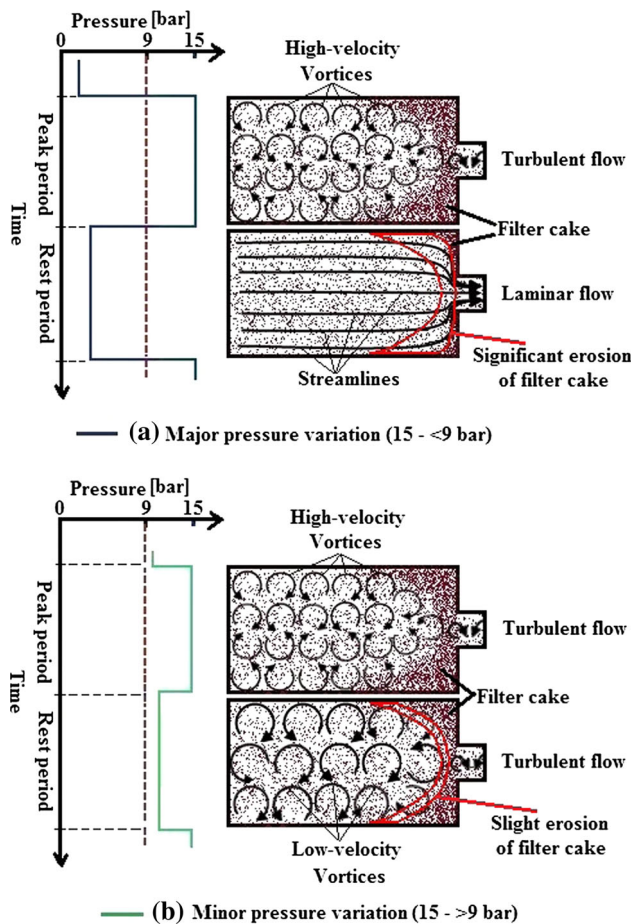


Fig. 14 Possible interpretation of the mechanism of action

flow type is expected to remain turbulent (see also Fig. 14b). A slight change in flow pattern and a limited erosion of the produced filter cake is therefore expected. This can be seen in Fig. 9, where the severe filtration recorded under application of constant pressure (C2) showed a slight improvement in the case of 4 s/8 s (V2) and a moderate improvement in 2 s/2 s case (V4). This is an indication of less efficiency of dynamic pressure with minor pressure variation compared to the major ones.

4.4 Further Research

This study shows that grouting with instantaneous variable pressure can significantly improve the grout spread inside artificial fractures in comparison with the constant pressure condition. The results also indicate the method's potential to improve the grouting process in the field. Dynamic pressure impulses are expected to have the greatest benefit for sealing the thin fractures close to the tunnel walls, whereas their influences decrease with concurrent length. Furthermore, the dissipation of the dynamic pressure impulses is expected to be greater in fractures with smaller

apertures due to the higher pressure loss. Accordingly, the following issues remain to be resolved in fully controlled condition in the laboratory before the technique can be employed in practice: How and to what extent different dynamic pressure impulses affect the grout penetrability and rheological properties? What minimum amplitude of the pressure impulse is required to significantly affect the grout rheological properties and/or penetrability? Are the amplitude and the critical peak/rest period independent? How the dynamic pressure impulses transform from the source to the grout front at different penetration distances?

5 Conclusions

The following conclusions are drawn:

- Application of low-frequency instantaneous variable pressure as a new alternative to oscillating pressure had a substantial impact on controlling the filtration evolution to improve the grout spread within parallel plates with constrictions even with very narrow aperture sizes <math><70\ \mu\text{m}</math>.
- The analysis of the total weights of the grout passed through the slot with 43 μm aperture size showed the effectiveness of instantaneous variable pressure on improving grout spread, whereas there was no clear distinction between the two choices of 4 s/8 s and 2 s/2 s peak/rest periods. However, the analysis of the cycle mean flow rates (CMFRs) revealed better control of filtration during the tests with 2 s/2 s peak/rest period, in addition to a considerably shorter time for emptying the grout tank.
- The analysis of the total weights of the grout passed through the slot with 30 μm aperture size showed a better control of filtration during the tests with 2 s/2 s peak/rest period than with 4 s/8 s. Examining the min-pressure envelopes further revealed cycles with dominant erosion during the experiments to be the main reason why the partially plugged constrictions reopened and the grout spread improved.
- The analysis of the CMFRs in the experiments with both 43- and 30- μm slots showed leading filtration over the first cycles, dominating the flow rates throughout the experiments. The results also revealed a lower degree of filtration over the first cycles in the tests with 2 s/2 s peak/rest period than with 4 s/8 s, showing that the former, which was closer to the critical peak/rest period, had better control of filtration. One of the key factors in improving the grout spread in dynamic grouting is therefore to control the filtration over the first cycle better.
- The analysis of the weight and pressure measurements over time further revealed major pressure variation

within each cycle associated with negligible filtration (resulting from considerable erosion) in the tests with a 43- μm slot versus minor pressure change associated with considerable filtration (resulting from minor erosion) in the tests with a 30- μm slot. This once again suggests that under application of instantaneous variable pressure, the greater the pressure variation the better the control of filtration.

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