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Rock joint sealing experiments using an ultra fine cement grout

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ABSTRACT: Rock joint sealing experiments have been conducted in a laboratory using a bi-axial coupled shear- flow test apparatus (CSFT). The laboratory test programme was designed to investigate the penetrative potential of a grout using different water/cement ratios on joints having different joint roughness (JRC) and joint conducting aperture in different stress conditions (total normal stress, joint water pressure and grouting pressure). The results indicate that joints with a conducting aperture (e) as small as approximately 25 microns can be grouted using a stable mixture of superfine cement, water and a super plasticizer (dispersing agent). The penetration capacity of a specific cement grout depends, in addition to the joint's characteristics, on the maximum grain size, the water/cement ratio and the injection pressure used. The tests reveal that the minimum physical aperture (E) that can be grouted corresponds to approximately four times the cement's maximum grain size.

1 INTRODUCTION

In many cases water leakages are governed by flow along the joints. An understanding of how the groundwater moves in rocks is one of the most important factors in the solution of rock engineering problems. This is especially true with regards to the planning and design of tunnels, storage caverns and underground waste disposals. Concerning nuclear waste repository safety a key aspect is the confidence of being able to successfully seal underground excavations and demonstrate methods of reducing the permeability of adjacent rock by sealing joints and fissures.

This paper describes the laboratory sealing experiments conducted on rock joints using a unique testing equipment designed by NGI. The equipment, called coupled shear flow temperature testing (CSFT) apparatus, has basically been used to derive the experimental data needed to quantify the effect of joint deformation on joint conductivity (Fig. 1). With the CSFT apparatus, joints can be closed, sheared and dilated under controlled normal stress conditions and at the same time cold or hot fluids can be flushed through the joint. Deformations, flow rate and stresses are recorded simultaneously. The CSFT test is designed to simulate as closely as possible the in situ state of critical joints and its modification by increases or decreases in normal and/or shear stress. In the present series of tests cement grout mixture was injected in the joint samples with increasing injection pressures. The rate of grout flow and the injection pressure versus time were recorded simultaneously to study the penetrability of a grout.

2 PENETRATION POTENTIAL OF GROUT MIXES

From a rheological point of view, a grout mix corresponds to a Bingham body exhibiting both cohesion and viscosity. A stable grout mix is defined as a mix having virtually no sedimentation e.g. less than 5% sedimentation in 2 hours (Lombardi, 1985). Water on the other hand follows Newton's law and is therefore a Newtonian body due to its viscosity and its lack of cohesion. A Newtonian fluid is represented by the following equation:

$$\tau = \eta \ \mathrm{dv}/dx \qquad (1)$$

where τ=shear stress (Pa); η= kinematic viscosity (Pa·sec), dv/dx= strain rate (sec^{-1})

A Bingham body or a stable mix is represented by the following equation:

$$\tau = c + \eta \ \mathrm{dv}/\mathrm{dx} \qquad (2)$$

where c= cohesion (Pa)

Unstable mixes of cement and water will show intermediate rheological properties compared to the two cases mentioned above.

By decreasing the water content in the mix, either by decreasing the initial water-cement ratio or by loss of excess water during grouting, the mix may be so dry that it will have an internal friction angle and the rheological law of such a body will be (Lombardi, 1985):

$$\tau = c + \eta\, dv/dx + p \cdot \tan\varphi \qquad (3)$$

where τ= shear stress (Pa); c= cohesion (Pa); η= kinematic viscosity (Pa·s), dv/dx= strain rate (1/s), p= internal pressure (Pa), φ= internal friction angle (°)

Even if the internal friction angle is assumed to be small in such a mix the potential travel distance will be only a fraction of that of a Bingham body for a given pressure gradient and joint aperture. This mix will form a "plug" in a joint at a very short distance from the grout hole (or even in the grout pipes or hole itself).

This form of "plugging" or "pressure filtration" may occur even with a thin, unstable grout. Grouts with high water content and low viscosities are thought to have higher penetrative potential than the thicker mixes - the limit being the grain size of the grout compared to the joint opening, and the setting ability. When the larger grains become stuck in the joints, the gradient and pressure drop across this plug increases and the excess water will be pressed out of suspension. Penetration tests on natural or artificial joints have been performed by several authors using different cement and/or bentonite based suspensions (see e.g. Ran and Daemen, 1992, Widman, 1991 and Håkansson et al. 1992). It is a general opinion that cement grout suspensions may penetrate rock joints with an aperture varying from about of 0.1 to 0.5mm.

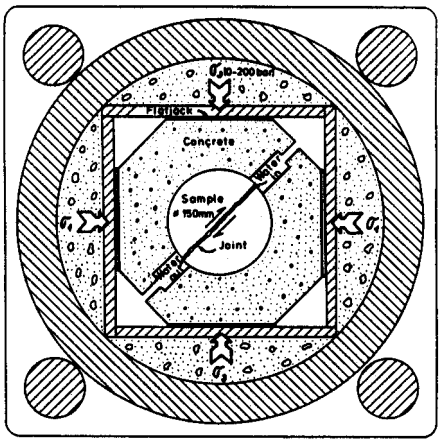

Figure 1 NGI's biaxial apparatus for CSFT testing of joints

3 PROPERTIES OF THE GROUT USED

In the present rock joint sealing experiments an ultra fine cement grout, in which 98% of the material was finer than 12 microns, has been used to study the penetrative potential of grout mixes with different water cement ratios. The grout mixture comprised of cement (Spinor A), tap water and dispersing agent (Mighty 150). The dispersing agent (corresponding to 2% of the weight of cement) was added to the water and mixed for 1 minute. Then the water and cement was carefully mixed by hand before the grout was thoroughly mixed for approximately 10 minutes using an ULTRA-TURRAX T25 mixer with a 17mm diameter rotor. The rotor speed was set at 8000 rpm and gradually increased to 24000 rpm. The injection test was started immediately after the mixture was prepared in order to avoid any hardening of the grout.

A Marsh funnel calibrated to an outflow of one quart (946 cm^3) of fresh water at a temperature of approximately 21°C per 26 seconds was used to measure the viscosity of the grout at different water/cement ratios. Table 1 shows the results of the tests at water/cement ratios of 0.6, 0.8 and 1.0; with and without a dispersing agent.

A sample of each mixture was cured under cover. The apparent bleed of the grout mixture with the dispersing agent was considered as negligible and no cracking was observed in the cured samples.

Table 1 Results of Marsh Funnel Tests on Grout Mixtures

Water/Cement Ratio	Time, Seconds	
	Dispersing agent	No dispersing agent
0.6	38.9	∞
0.8	31.5	46.3
1.0	28.9	36.8
Water	26	

4 DESCRIPTION OF ROCK JOINT SAMPLES

Three different rock joint samples were used for injection testing in the CSFT apparatus. The joint samples were procured from the field in mated condition and were prepared such that the horizontal length of the joint plane was around 85 mm. All the samples were characterised and profiled using the method described by Barton and Choubey, 1977. Table 2 shows the joint characterisation of the individual samples. Figure 2 shows a rock joint sample (sample 2) used for the injection tests. In one of the parts of the sample a hole of approximately 15 mm diameter is bored through the sample to facilitate injection of the grout mixture. The re-assembled

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joint sample is then cast in a reinforced epoxy block (see Figure 1).

Table 2 Rock joint samples used for the injection tests

Sample No.	Rock Type	JRC	Joint Description
1	Sandstone	5-7	Slightly stepped joint surface
2	Welded tuff	3-6	Rough planar with <1mm calcite infill, rough uneven
3 -	Welded tuff	8-12	Rough uneven with haematite coating, rough planar

Figure 2 Photo of the tested joint (sample 2)

All the three joint samples were tested in NGI's CSFT apparatus. In this apparatus by applying the same oil pressure to all four flatjacks, only normal stress is applied over the joint. From the two compartments adjacent to the sample in the epoxy block a back pressure is applied to simulate insitu ground water conditions The volume of material injected, total normal stresses, back pressure, injection pressure and joint conductive aperture were measured for all tests.

The following sequential order was adopted for the injection tests.

1) Saturation of the sample in water for at least 24 hours before testing.

2) Performance of water injection tests for measuring joint conductive aperture at different normal stresses (not carried out for sample 2).

3) Measurement of the joint conductive aperture at the normal stress selected for the injection test by measuring the amount of fluid that passes through the joint starting with a low injection pressure.

4) Injection of the cement grout mixture in the joint with increasing injection pressures.

5) Flushing of the cement grout mixture with water.

Repetition of Steps 2 to 5 with increasing normal stress.

The above procedure has been carried out for different water/cement ratios.

For all the tests joint conducting apertures were calculated from the flow through the joint assuming laminar flow between parallel plates using the following equation:

$$e = \sqrt[3]{\frac{Q \cdot 12 \cdot \upsilon}{g \cdot w \cdot i}} \qquad (4)$$

where w= width of flow path (m); e= conducting aperture assuming parallel-plate flow(m); ν= kinematic viscosity (m^2/s); Q= flow rate (m^3/s); i= hydraulic gradient; g= gravity acceleration m/s^2

The results of water injection tests for measuring joint conductive aperture at different normal stresses for the samples 1 and 3 are shown in Fig. 3. This figure indicates that in sample 1 (sandstone), the joint conducting aperture is reduced from approximately 45 µm to 25 µm as a result of an increase in effective normal stress of approximately 35 bars. In sample 3 (welded tuff), the joint conducting aperture is reduced from approximately 220 µm to approximately 100 µm as a result of an increase in effective normal stress of approximately 60 bars. As stated earlier, the hydraulic conducting aperture is calculated assuming laminar flow between parallel plates.

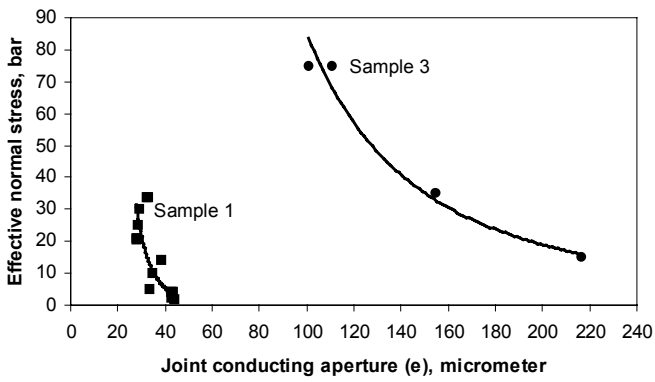

Figure 3. Conducting apertures as a function of effective normal stress for samples 1 and 3

5 INJECTION TEST RESULTS

The injection test results for the three samples are summarised in Table 3. This table shows the joint conducting apertures obtained for the water injection

tests for different normal stresses. The results from grout injection tests are also summarised in this table. During the tests, the rate of grout flow and the injection pressure versus time were recorded automatically. Typical results of these recordings for sample 1 are shown in Figures 4, 5 and 6. Figure 4 indicates that an injection pressure of 5.05 bars, which is slightly above the back pressure of 5 bars, was needed for penetration of the grout into the joint (water/cement ratio = 0.6). In this case the joint conducting aperture was 47 microns at a total normal stress of 10 bars (see Table 3). Figure 5 shows that, when the normal stress was increased to 20 bars, no grout penetrated the joint, even when the injection pressure was increased to 15 bars. This is presumably due to the decrease in joint conducting aperture (25 microns) as a result of increased normal pressure. However, as Figure 6 shows, once the water/cement ratio was increased from 0.6 to 1.0, the grout was very slowly penetrating the joint at an aperture of 25 microns. It is clearly evident from the figures that the injection pressure required for penetrating the grout depends on the water cement ratio and the normal stress across the joint. The results from samples 2 and 3 are summarised in Table 3 with similar trends.

As mentioned earlier, the cement used in the tests has a grain size distribution curve that indicates that 98% of the particles are finer than 12 microns. It may be seen from Table 3 that the minimum conducting aperture for sample 1 is approximately 25 microns and for sample 2 it is between 50 and 60 microns. For sample 3, no limiting aperture could be registered. These theoretical smooth wall apertures (e) can be converted to the real mechanical apertures (E) between the irregular joint walls. Generally, E is larger than e, implying that a rough-wall joint requires a larger aperture than a smooth-wall joint for the same water capacity. Wall friction and a tortuous path are considered responsible for flow losses.

Table 3 Summary of water and grout injection tests results for the rock joint samples 1, 2 and 3

Sample No.	Test No.	Total Normal Stress (bar)	Back Pressure (bar)	Injection Test		Joint Cond. Aperture (μm)
				Pressure (bar)	Penetration	
1	a) Water Injection	10	5	a) 5.06	-	47
	b) Grouting Test 1			b) 5.05	GOOD	
JRC=5-7	1: (W/C=0.6)					
	a) Water Injection	20	5	a) 5.50	-	25
	b) Grouting Test			b) 15.0	NO	
	2: (W/C=0.6)					
	a) Water Injection	20	5	a) 5.56	-	25
	b) Grouting Test			b) 15.0	GOOD	
	3: (W/C=1.0)					
2	a) Water Injection	10	5	a) 5.50	-	66
	b) Grouting Test			b) 12.65	GOOD	
JRC=3-6	1: (W/C=0.6)					
	a) Water Injection	10	5	a) 5.50	-	61
	b) Grouting Test			b) 5.50	GOOD	
	2: (W/C=0.8)					
	a) Water Injection	20	5	a) 5.50	-	50
	b) Grouting Test			b) 15.0	MINOR	
	3: (W/C=0.8)					
	a) Water Injection	20	5	a) 5.50	-	45
	b) Grouting Test			b) 15.0	MINOR	
	4: (W/C=1.0)					
	a) Water Injection	40	5	a) 5.50	-	43
	b) Grouting Test			b) 20.0	MINOR	
	5: (W/C=1.0)					
3	a) Water Injection	20	5	a) 5.10	-	137
	b) Grouting Test			b) 5.05	GOOD	
JRC=8-12	1: (W/C=0.6)					
	a) Water Injection	40	5	a) 5.09	-	111
	b) Grouting Test			b) 5.05	GOOD	
	2: (W/C=0.6)					
	a) Water Injection	80	5	a) 5.14	-	90
	b) Grouting Test			b) 5.05	GOOD	
	3: (W/C=0.6)	75	0	c) 0.43	-	22
	c) Water Injection after Grouting	75	0	c) 0.47	-	15

It may be noted that the equivalent smooth-wall aperture (e) and the physical aperture (E) are related to the joint roughness coefficient (JRC) in the following manner (Barton, 1982):

$$e = \frac{JRC^{2.5}}{(E/e)^2} \tag{5}$$

The above empirical relationship is illustrated in Fig. 7.

Using equation 5, the physical aperture (E) for sample 1 (JRC=6, e=25 µm) is calculated as 47 µm. For sample 2 (JRC=4.5, e= 50 µm) the physical aperture (E) is close to the limit value of E=e, i.e. 50 µm (see Fig. 7). The above values correspond roughly to 4 times the maximum grain size of the cement.

The tests support the surprising notion that a joint with a lower Joint Roughness (JRC) will be less easily penetrated than a rougher joint, the hydraulic joint aperture being equal. At a physical aperture of 47 microns, Sample 1 is easily grouted using a water/cement ratio of 0.6 and an excessive grouting pressure of 0.05 bar while Sample 2, having a smoother surface and a 50 micron physical aperture, is not groutable using a water/cement ratio of 1.0 and a grouting pressure of 10-15 bars. The tests support the predictions of Barton et al. 1985 and Barton and Quadros (1997) and support findings of Widmann (1991) and others that the grouting efficiency seems to be increased by an increase in the grouting pressure. There is of course the possibility of hydraulic jacking here.

Figure 8 shows the result of the grouting for Sample 3, Test3. Approximately 50 % of the area is covered by grout material. This indicates that even a 80-100 micron joint is not 100% effectively grouted using the super fine (Spinor) cement. The effective hydraulic aperture has been reduced to about one fourth. If one assumes parallel plate flow (laminar), the hydraulic conductivity has been reduced 64 times.

6 CONCLUSIONS

The laboratory tests on rock joint sealing have concentrated on the penetration capacities of a superfine cement grout with respect to different conducting apertures. It has been shown that grouts with a maximum particle size of 12 microns have the capacity of penetrating joints with a corresponding joint conducting aperture of 25 microns. Although the penetration capacity of a cement grout depends on the maximum grain size, the water/cement ratio and the injection pressure used, the tests do not conclusively support the thesis that a joint with a lower joint roughness will be more easily penetrated than a rougher joint, the hydraulic joint apertures being equal. For nuclear waste repository safety, such tests,

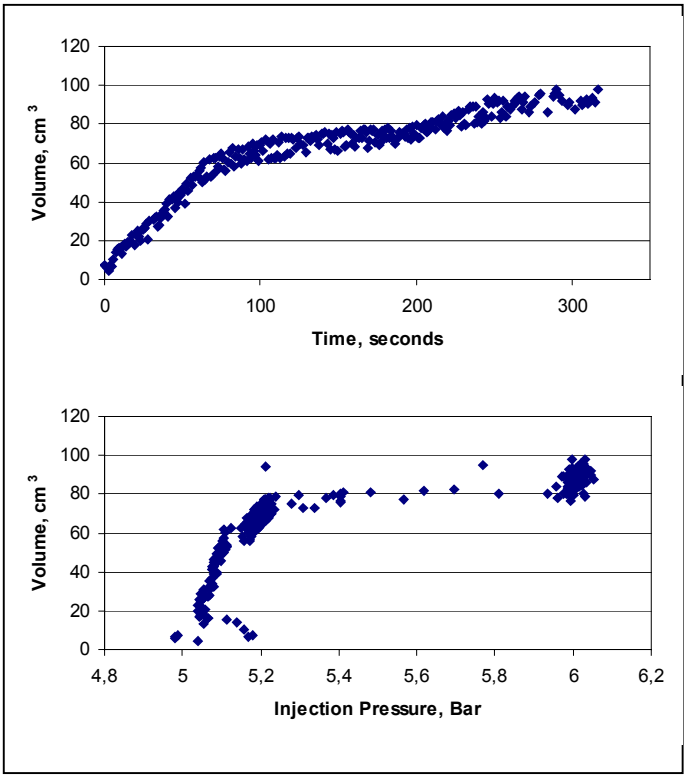

Figure 4 Injection test for Sample 1 with water/cement ratio= 0.6, total stress = 10 bar.

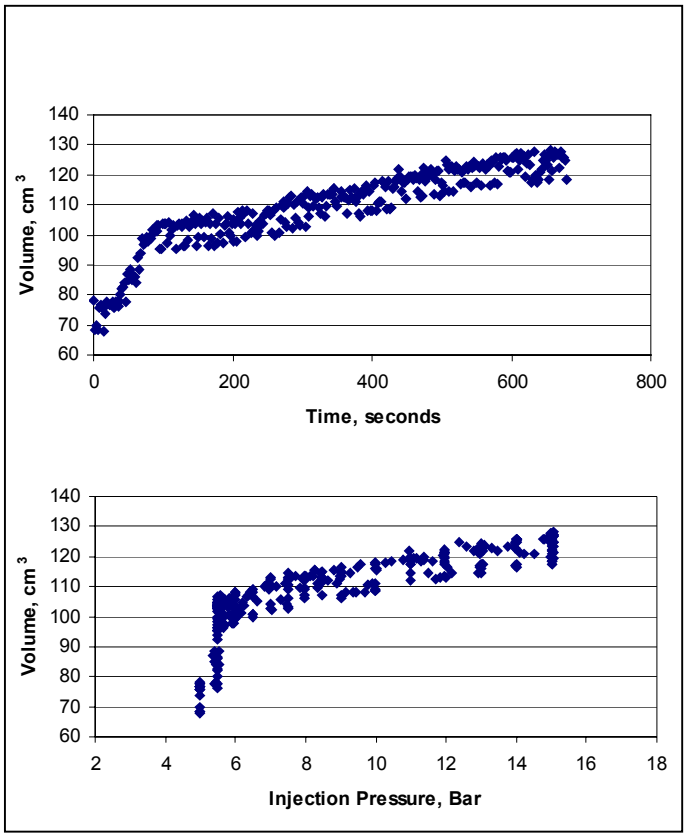

Figure 5 Injection test for sample 1 with water/cement ratio=0.6, total stress=20 bar

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which can be site specific, provide not only guidance for conducting in-situ test programmes but give recommendations for selecting appropriate grout mixtures.

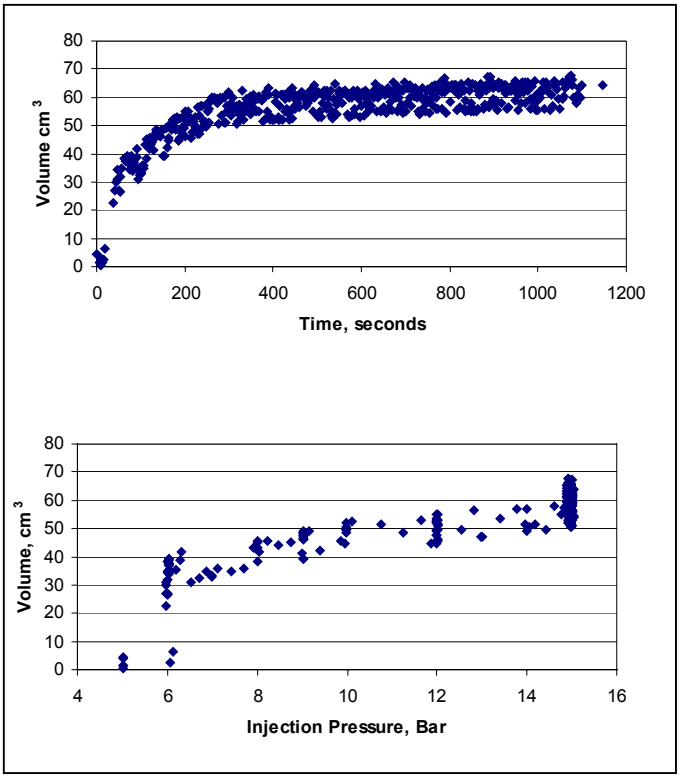

Figure 6 Injection test for sample 1 with water/cement ratio=1.0, total stress=20 bar

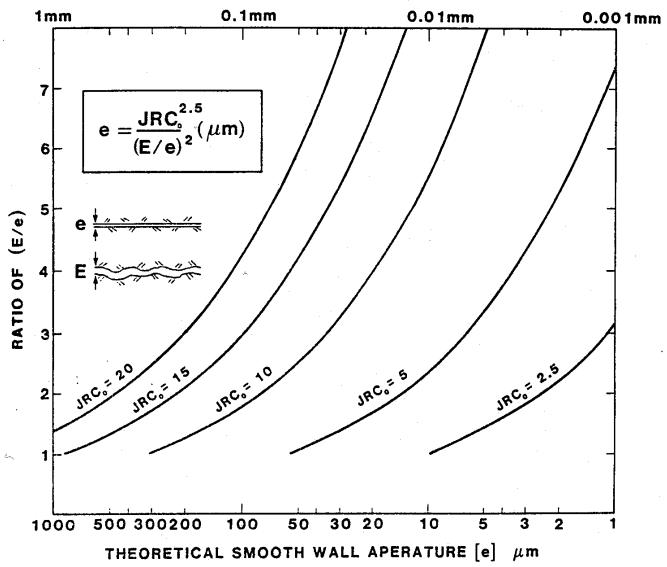

Fig. 7 Empirical relationship between the mechanical and equivalent conducting flow aperture based on the JRC-value (Barton, 1982)

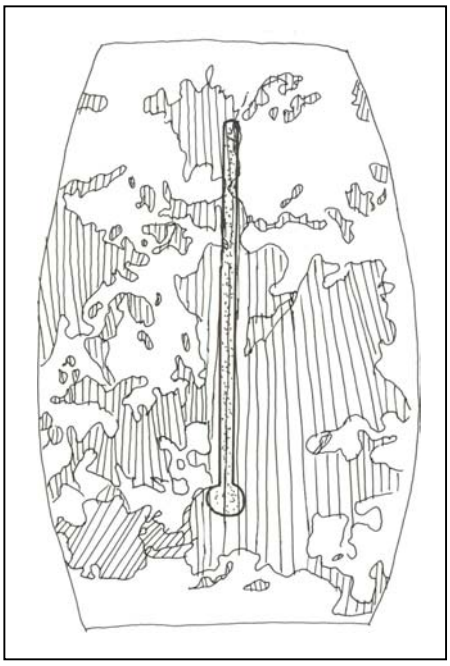

Figure 8 Grouted area of sample 3, after test 3

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