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Influence of stress state on water flow through rock mass joints

M.I. Álvarez-Fernández, D.J. Guerrero-Miguel & C. González Nicieza
DinRock Research Group, University of Oviedo, Mieres, Spain
inma@dinrock-uniovi.com)

I. Escobal-Marcos
Viuda de Sainz, S.L.

A. Rabat
University of Alicante, Alicante, Spain

Abstract

The flow of water through the joints of a rock mass is, clearly, an anisotropic phenomenon, which is governed by the roughness of these joints, but also by the stress state in which it is found. The present work describes the results obtained by means of a new laboratory test that allows to evaluate the anisotropy in the flow through a joint as a function of its roughness, the fluid pressure and the mean normal stress on the joint. In addition, by means of photoelasticity, it is verified how the stress distribution along the joint is not homogeneous. Three PMMA joints with different JRC are tested and is demonstrated that heterogeneous distribution of stresses is hardly dependent of JRC. This fact indicates that there are irregular contacts and apertures along the joint and how this phenomenon affects the fluid movement is discussed.

In this way, it is demonstrated that roughness plays a fundamental role in establishing the existence of preferred directions and how these can be affected by fluid pressure and by normal stress on joint. The laboratory tests presented here demonstrate the anisotropy of injection flow in a rock mass, making clear the limitations of current models, which attempt to predict a radius of influence of the injection.

Keywords

Water flow, joint roughness, anisotropic flow, fluid pressure.

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1 Introduction

Predicting the behaviour of a fluid through a rock joint is of particular interest in civil engineering and underground applications, as it allows optimisation of fluid injection parameters in the rock mass (waterproofing, ground improvement). Another application of growing interest is the geothermal field, as the exploitation possibilities of a potential reservoir are defined by the fluid flow capacity through the rock mass.

The opening of the joint plays a decisive role in the flow across the surface. The greater the distance between the lips of the seal, the easier it is for the fluid to flow through, as there is enough space to be able to ignore the effects that occur at the interface between the fluid and the surface. However, when the opening is small (or even non-existent), the roughness plays a decisive role by imposing restrictions on the transit of the fluid, which is forced to advance by adapting to the geometry of the opening. It is therefore necessary to properly characterise and classify the roughness of the joint in question and its interaction with the flow through it.

Two main factors stand out in this regard: asperities, irregularities of the joint on a scale of millimetres or less, and undulations, geometric irregularities of orders of magnitude decimetric or metric. Both are randomly distributed along the surface defining the actual rock joint.

Currently, the roughness is determined by using a spiked comb to reproduce the surface of the rock joint on paper and then comparing the drawing obtained with the table proposed by Barton and Choubey (1977), and assigning the JRC (*Joint Roughness Coefficient*) value that has the closest visual resemblance.

At present, there are no standards for analysing and characterising the flow through a rock joint. However, there are abundant bibliographical references that deal with this subject in the field of scientific and technical research. In this regard, it should be noted that the methodology is similar in all of them. Here, that one proposed for Xiong et al. (2018) is described. First of all, either a real rock sample is taken or a specially created sample with prismatic geometry. Subsequently, the roughness of the surface to be tested is determined and the lateral faces are sealed to prevent water from escaping through them. Those faces perpendicular to the direction of the roughness are used to inject the fluid at one end and collect it at the other.

In this way, it is only possible for the injected fluid to advance along the direction of the considered roughness, without the possibility of emanating from any of its lateral faces. However, due to the anisotropy of rock joints, imposing a single direction of advance can cause significant deviations in the behaviour of the fluid analysed at laboratory scale from that which actually develops in the natural environment. Therefore, adequately predicting the behaviour in real conditions would imply understanding how different roughnesses interact in the presence of a fluid that has sufficient freedom to advance through any of them.

In this paper the anisotropic flow through a joint is analysed and justified on the basis of the anisotropy of the lip contact in a joint. Two experimental campaigns are carried out for this purpose. The first one consists of the analysis, by means of photoelasticity techniques, of the homogeneity of the contact in joints with different roughness. The second consisted of injecting water at different pressures (2, 3 and 5 bar) into a joint subjected to stresses of 0.5 and 1.0 MPa.

2 Assessment of contact homogeneity in joints

Three PMMA samples have been prepared to evaluate the contact between the sealing surfaces and to define their influence on the fluid circulation. To this aim, 15x16 cm plates with a thickness of 1 cm were used, on which two blocks representing the lips of a joint were separated by means of high-precision laser cutting. To define the roughness, three JRC levels were chosen: 0-2 (corresponding to a smooth joint), 4-6 (corresponding to a joint of medium roughness) and 16-18 (characteristic of a very rough joint). This is an important difference respect previous works of researcher as Wang et al (2022). Plates cut according to the above-mentioned patterns can be seen in Fig. 1.

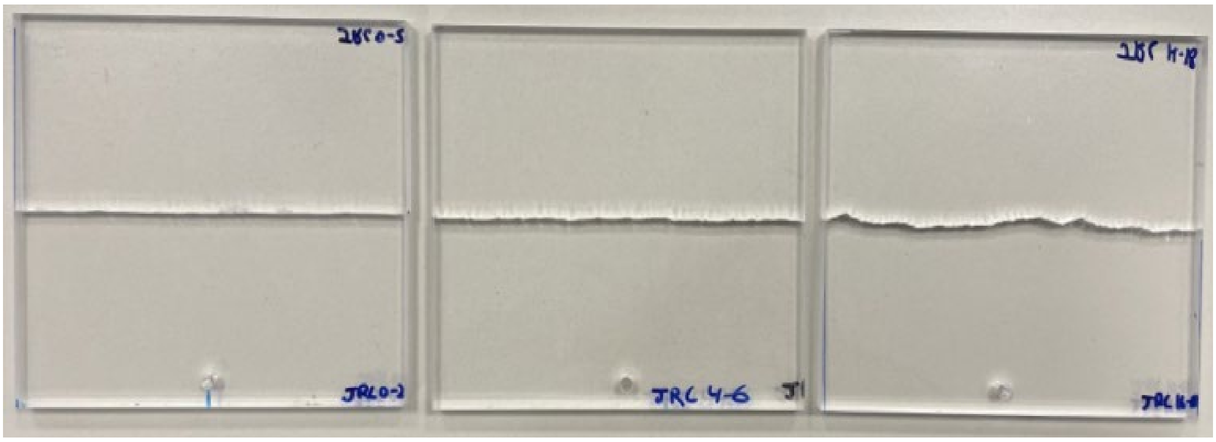

Fig. 1 Plates with JRC of 0-2, 4-6 and 16-18 respectively

Next, a qualitative study of the stress distribution in different roughness profiles has been carried out in order to determine whether the contact along all the lips of the joint is uniform or whether there are areas where stresses are concentrated, thus demonstrating that there is unequal contact along them. The layout of the different elements and equipment during the tests can be seen in Fig. 2. It was decided to apply, through a universal press, a load of 20 kN in order not to damage the plates and joints.

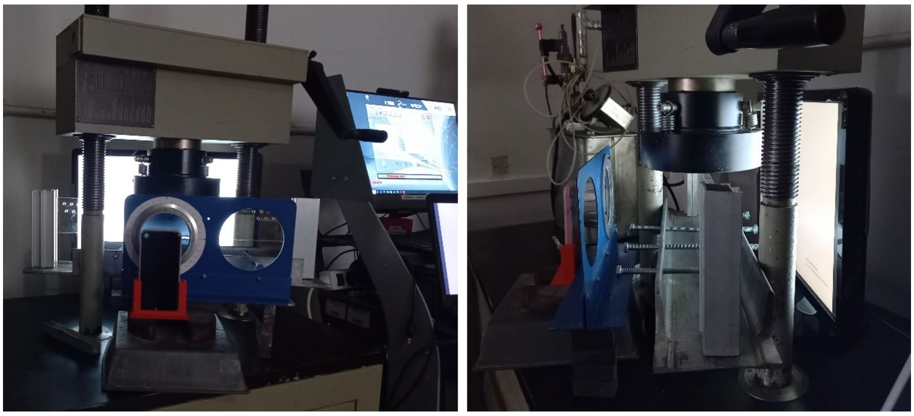
Fig. 2 Arrangement of equipment in photoelasticity tests

The stress fields in the different roughness profiles at the moment of maximum load application (20 kN) are shown in Fig. 3. In this figure, each colour represents a stress value, in such a way that the areas in which there is great chromatic variety indicate greater stress gradients, while the more chromatically homogeneous areas indicate uniform stresses. Small-scale behaviours were analysed near the joint asperities and in the central area of the plates, which are less affected by the edge and stiffness effects caused by the press platens (i.e. details in Fig. 3b)). However, the level stress is uniformly distributed in fringe number 1, as can be seen in the legend to the right of the figure.

In the case of asperities, their influence can be examined by looking at the results of the JRC 0-2 and JRC 4-6 patterns, due to their reduced undulation. It can be seen that they cause an important redistribution of stresses in their vicinity. The lighter areas indicate lower stresses and the coloured areas higher stresses, showing the different degrees of contact along the both roughness profiles.

In the profile with JRC 16-18, the undulation of the joint has a great influence and causes a more irregular distribution of stresses.

Therefore, it can be seen that the roughness generates an anisotropy in the contacts that does not disappear with the application of normal loads on the joint, quite the opposite, and that will have a great influence on the fluid flow. There are areas with a more intimate contact (more closed joint sections) and others with almost no contact (minor stress transmission is observed) through which fluids will flow more easily.

This effect is magnified when the joint lips have a relative displacement, as can be seen in Fig. 4 which corresponds to 5 mm relative displacement. In this case, on the lips of the joint it is possible to see from black colours (absence of stress) to fringe number 4, which indicates an important concentration of stresses in some areas with respect to others.

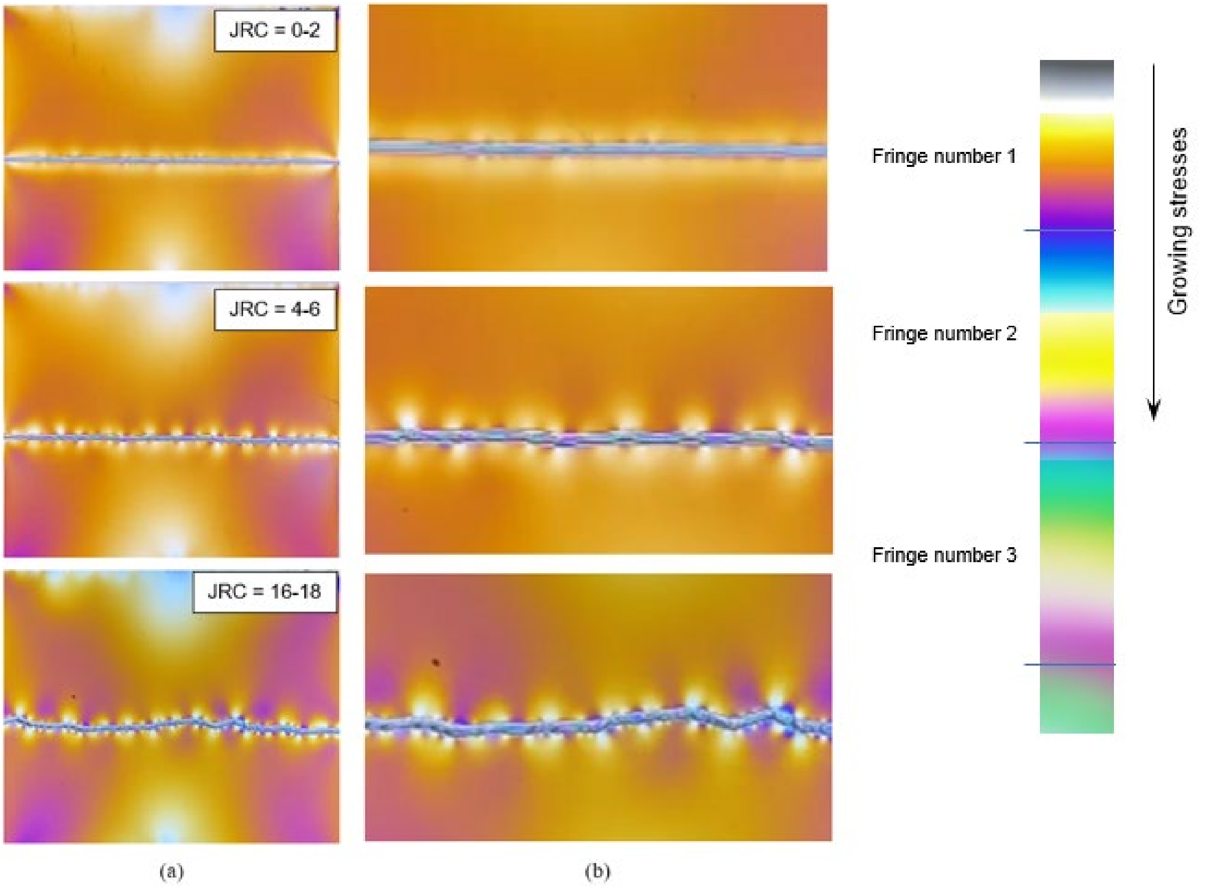

Fig. 3 Stress distribution in the three tested joints: a) general view; b) details

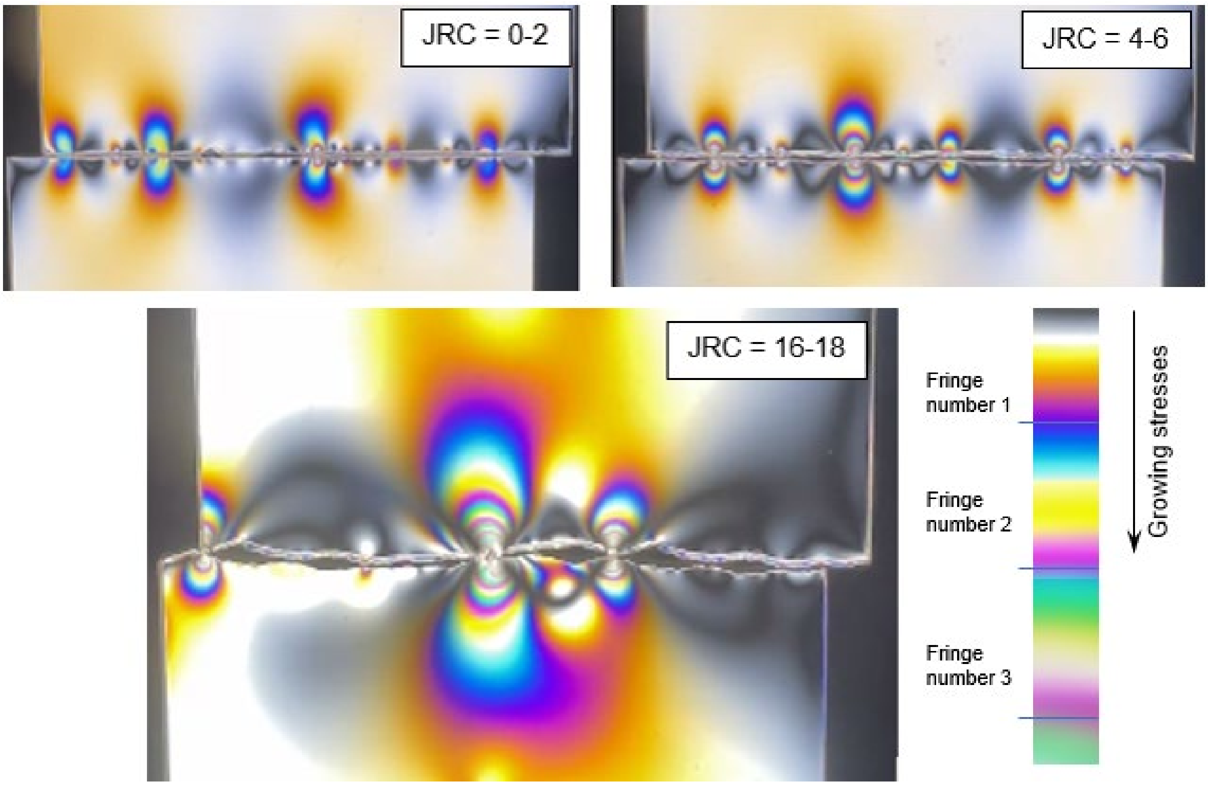

Fig. 4 Stress distribution in the three tested joints with relative displacement of 5 mm between lips

3 Water injection tests

According to tests carried out by Guerrero-Miguel et al. (2018) and Escobal-Marcos (2022) on rock joints injected with water at different pressures, the water flow does not pass through the joints uniformly, even at high fluid pressures, and regardless of the normal load applied. Water flows out at discontinuous points along each edge of the joint.

To analyse the flow of a fluid through a rock surface on laboratory scale, it has been necessary to develop a system to regulate the inlet pressure of the fluid (P_0), the normal stress on the joint (σ) and to record the flow rates (Escobal-Marcos 2022).

In order to allow the fluid to flow freely in any possible direction in the joint, this is injected through the centre point of the discontinuity, rather than from the side. In addition, none of the lateral faces of the sample are sealed, so that the fluid can flow through any of them, collecting the flow rate that emerges on each side independently. Each of the flow rates recorded in each direction and direction will be named with the letter Q and the subscript corresponding to its location according to the graphical scheme shown in Fig. 5.

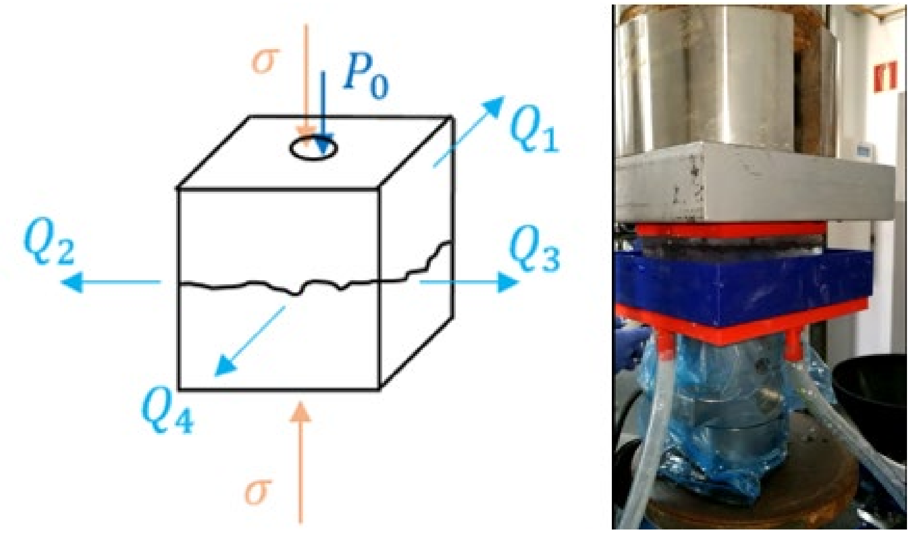

Fig. 5 Conceptual outline of the test and test disposal

The tested joints, with a surface of 10x10 cm, have been artificially created by 3D printing in transparent resin. In Fig. 6 it can be seen the 3D model that would represent an 18-20 JRC profile crossed with an identical one in the perpendicular direction. In the same figure it can be seen the printed blocks that constitute the two lips of the joint.

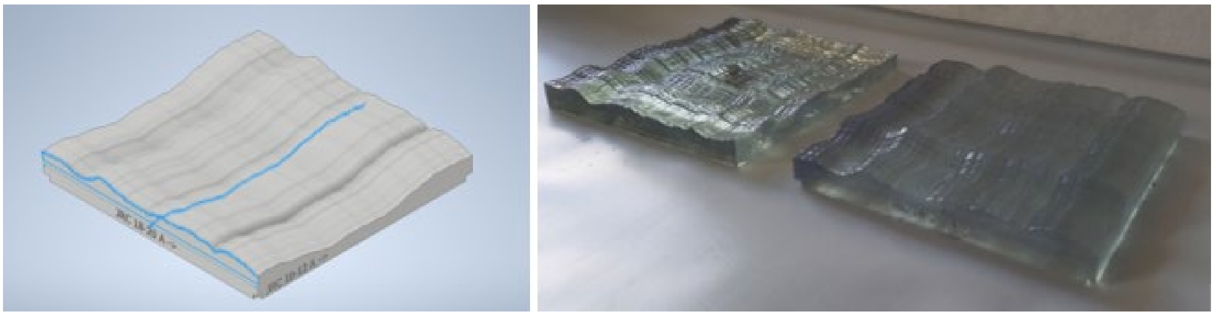

Fig. 6 View of 3D model and printed blocks

In order to analyse the shape and distribution of the asperities, the elevation of each point on the surface has been plotted and the corresponding contour lines have been drawn (Fig. 7). The blue tones would represent the valley areas, the deeper the more intense the blue. The warm tones (oranges and yellows) would be associated with the higher areas. It is presented the water injection point and the flow directions too.

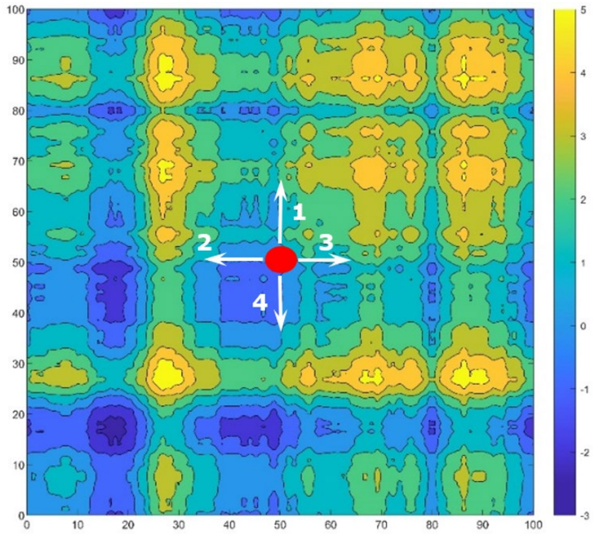

Fig. 7 Contour map of joint made with a profile with JRC 18-20 crossed with the same profile

As can be seen, from the injection point, the paths in directions 1 and 3 are similar, as is the same in directions 2 and 4. In this sense, a similar flow rate could be expected in directions 1 and 3, as well as in directions 2 and 4. However, there are large differences, as shown in Fig. 8. This figure represents the flow rates collected at each joint face in the six tests performed at a normal stress of 0.5 MPa and for injection pressures of 2, 3 and 5 bar. Notice that this is a semi-logarithmic representation.

Due to the arrangement of the asperities, the flow rates in directions 1 and 3, besides being similar to each other, should be lower than in directions 2 and 4. This is true when compared to those in direction 2 but, surprisingly, there is hardly any flow in direction 4 (when it should be of the same order as in direction 2). This is where the importance of the contact characteristics, discussed in the previous section, is demonstrated. A small anomaly or deformation can close one flow path or magnify another. In fact, in order for the fluid to flow in directions 2 and 4, a small elevation, which is marked in the figure as a critical zone, must be overcome. Any anomaly involving a slightly higher elevation or a better fit of the lips in that zone will prevent the passage of water in that direction. In addition, the average elevation of the asperities in direction 4 is slightly higher than in direction 2, which contributes to the asymmetric distribution of the water flow, favouring this last direction.

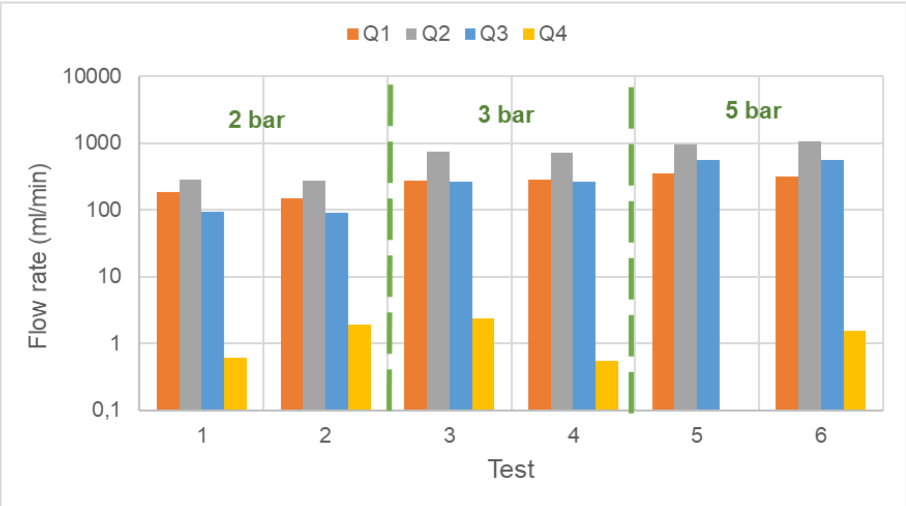

Fig. 8 Flow distribution for JRC 18-20 crossed with 18-20 (normal stress of 0.5 MPa)

The greater prevalence of direction 2 can be seen in Fig. 9, where the sum of the flows corresponding to directions that should be equivalent (i.e. 1 and 3 on the one hand and 2 and 4 on the other) have been plotted. Although, in this particular case, direction 4 does not contribute a significant flow, the flow corresponding to direction 2 exceeds the sum of the flows Q1 and Q3.

Something similar happens when the normal stress on the joint is increased to 1 MPa, although, as expected, the total flow rate is reduced (see Fig. 10). Under these conditions, the flow in direction 1 is practically closed until the injection pressure is raised to 3 bar.

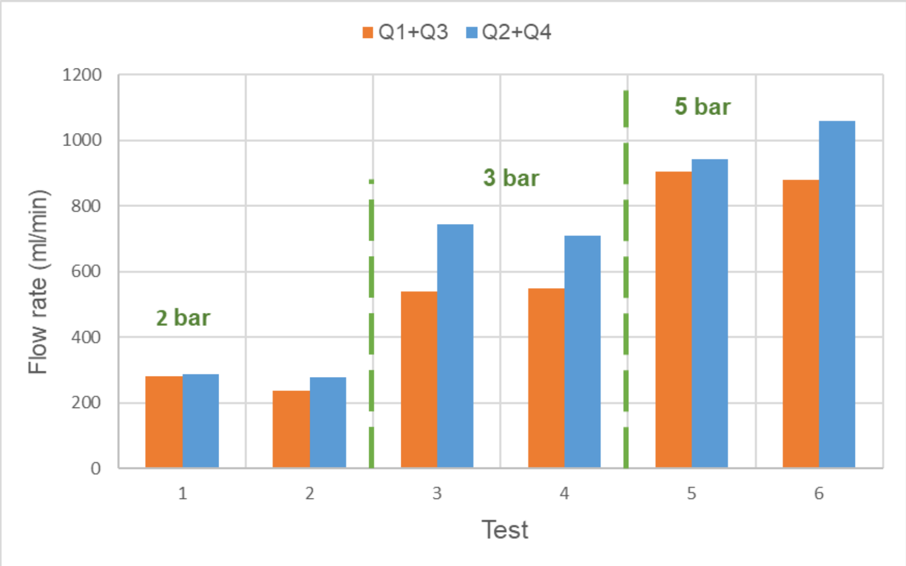

Fig. 9 Combined flow rates per direction (0.5 MPa)

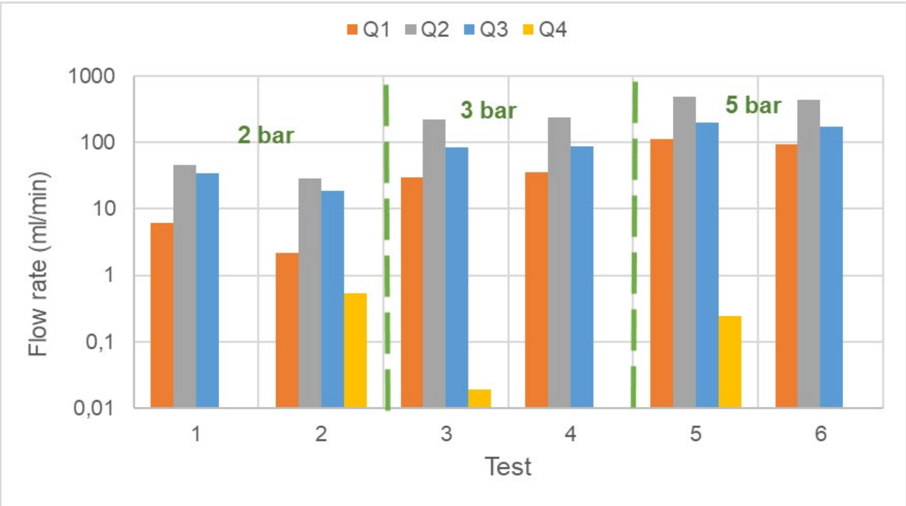

Fig. 10 Flow distribution for JRC 18-20 crossed with 18-20 (normal stress of 1.0 MPa)

Furthermore, although the distribution is similar to that for a stress of 0.5 MPa, the prevalence of direction 2 over 1 and 3 is much more pronounced, as can be seen in Fig. 11.

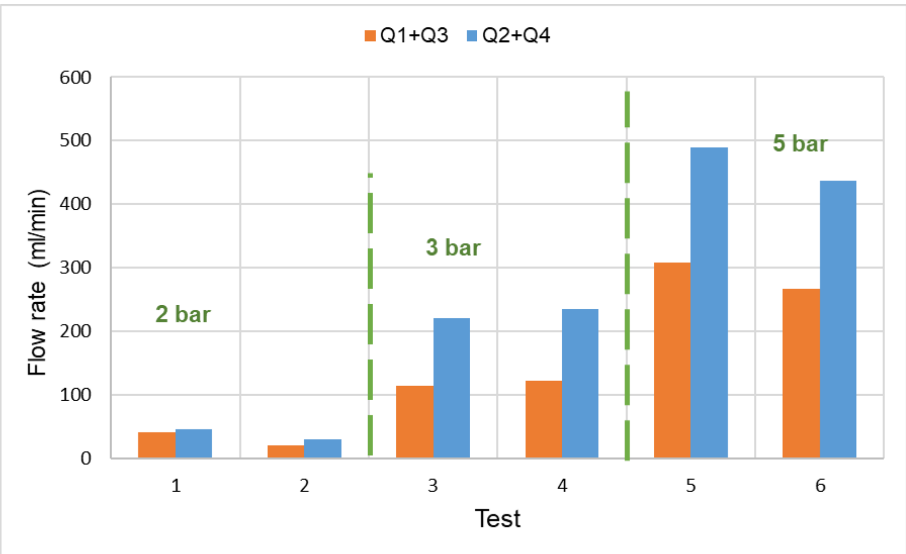

Fig. 11 Combined flow rates per direction (1.0 MPa)

If all the tests are analysed together, it can be seen that when the joint is subjected to a low normal stress, the fluid tends to flow out of its lateral faces in a fairly homogeneous manner, although with a significant difference in flow rates in each direction, demonstrating the anisotropy. However, as the stress is raised significantly, it will also be necessary to increase the fluid pressure to get the fluid across the discontinuity, with water spurting out at specific, very localised points (see Fig. 12), at high flow rates.

Fig. 12 Jet-like outflow, characteristic of high stresses and pressures

4 Conclusions

The tests developed allows to verify that the contact between the surfaces forming the joint is a determining factor in the behaviour of the fluid, this contact depending on both the roughness and the stress normal to the joint. Both factors confer a marked anisotropic character to the flow. It has been found that the less roughness and undulations are present, the more evenly the stresses tend to be distributed along the lips of the joint. Conversely, the presence of asperities and undulations causes stresses to be concentrated in certain areas, releasing others and thus facilitating the flow not to develop homogeneously in one direction, but through certain preferential channels. This has important implications also for the shear strength of the joint.

As a consequence, rougher joints allow higher injection flow rates than smooth joints, as there are areas of poorer contact through which it is easier for fluids to flow. However, the flow distribution is not homogeneous in this kind of joints. Any change in the roughness or contact of the joint lips changes the fluid distribution. As the normal stress increases, the effect of roughness as a flow conditioner gains weight and the flow becomes more poorly distributed over the entire joint surface.

The laboratory tests presented here demonstrate the anisotropy of injection flow in a rock mass, making clear the limitations of current models, which attempt to predict a radius of influence of the injection.

Acknowledgments

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