THE MECHANICAL BEHAVIOUR OF HYDRAULIC FRACTURED, POSSIBLY SATURATED MATERIALS

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Abstract

The influence of a fluid pressure load on the extensile fracturing of mortar and sandstone has been investigated. A fluid pressure in the (initiating) fracture stimulates both fracture initiation and propagation and may be as effective as a directly applied uniaxial tensile stress. The efficiency of the fracture pressure depends on the degree of saturation. For the saturated materials, a pore pressure is generated under loading which counteracts the applied stress. The effective stresses governing the mechanical behaviour of the saturated materials then are lower, giving rise to an apparent stiffer behaviour, a lower effective fracture pressure and higher fracture initiation and propagation stresses. The magnitude of the pore pressure depends, among others, on the permeability of the materials. For impermeable materials, the pore pressure increases linearly with the hydrostatic stress, while for permeable materials it is equal to the applied fluid pressure. With the increase in pore pressure, the effective stresses reduce and may even become zero when cohesion of the material is low.
Key words: extensile hydraulic fracturing, porous materials, degree of saturation, permeability

1 Introduction

A mostly neglected problem in fracture mechanics is fracturing by a fluid pressure (for instance in surface cracks in the upstream face of a dam). The fluid pressure exerts an axial splitting stress on the structure. It thereby stimulates fracture initiation, and upon penetrating the fracture, wedge the fracture further open (Fig. 1). The pressure driven fractures are called hydraulic fractures, as contrary to dry fractures in which no pressure load in the fracture exists. Neglecting the fluid pressure in the fracture will give rise to a seriously underestimation of for instance the stability of structures (Saouma et al., 1989).
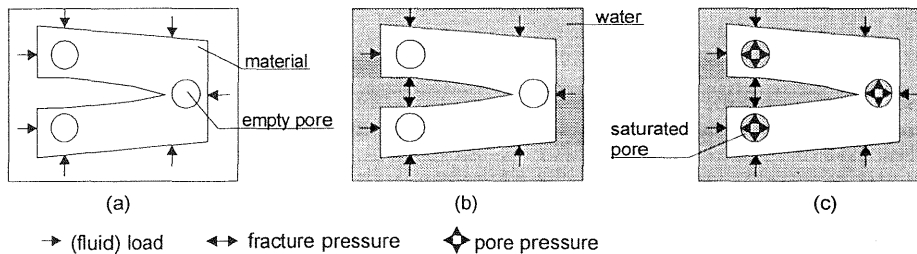
Fig. 1. Definition of fractures: dry fracture (a), hydraulic fracture in a dry material (b) and hydraulic fracture in a saturated material (c)

Porous materials in a fluid environment are often saturated. The pore water can greatly modify the mechanical behaviour of the porous materials. Loads on the saturated porous material compress the pores and thus the pore fluid. Excess pore pressures then arise which not only resist to deformation but also counteract the fracture pressure (Fig. 1c). The fracture pressure then is less efficient in a saturated porous material. The problem is further complicated by fluid flows for instance from the fracture into the material (Cheng et al., 1993).

The hydraulic fracturing process of (saturated) porous materials is one of the most complicated problems in fracture mechanics. Yet only recently, hydraulic fracturing of concrete has attained some attention. The research of hydraulic fracturing is so far limited to impermeable dry concrete (Brühwiler and Saouma, 1991, Reich et al., 1994). This is surprising since pore pressures are taken into account in the numerical modelling of the behaviour of dams (Bourdarot and Bary, 1994). To investigate the influence of the pore pressure on the hydraulic fracturing process, new hydraulic fracturing experiments have been performed on concrete and sandstone at the Stevin Laboratory.

2 Experiments

The extensile hydraulic fracturing experiments have been performed on cylindrical specimens in a Hookean cell which allows for independent application of an axial force and a radial fluid pressure. The cylindrical specimens contain a circular notch in which the radial fluid pressure is applied as well. The notch thus serves as controllable hydraulic fracture initiator. All experiments were performed in axial deformation control. Loading of the specimens occurs by first applying a certain hydrostatic stress and next by either decreasing the axial compressive stress or by increasing the radial fluid pressure (Fig. 2). For both load paths, tensile failure of the specimen is obtained, with the fracturing plane perpendicular to the axis of the cylinder. A detailed discussion of the experiment performance is given in Visser and Van Mier (1994).
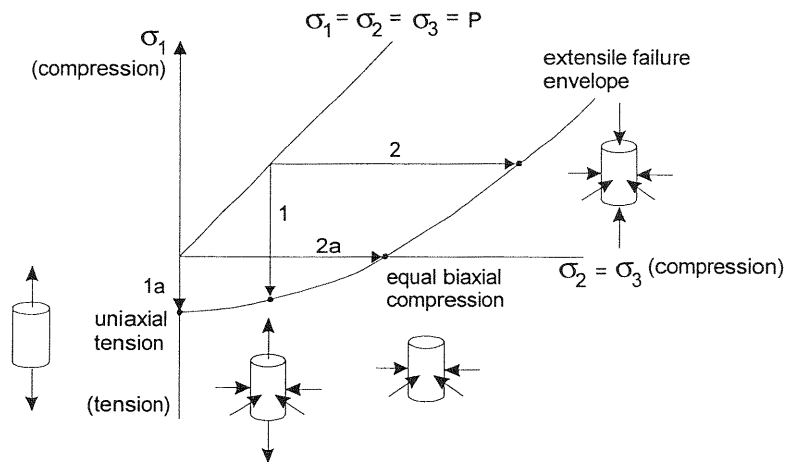

Fig. 2   Load-paths in the extensile hydraulic fracturing experiments

3 Hydraulic fracturing of the impermeable unsaturated mortar

To investigate the influence of the fracture pressure on the extensile hydraulic fracturing behaviour of porous materials, a first series of experiments has been performed on an impermeable unsaturated mortar. In the unsaturated mortar, the pores contain highly compressible air so that no pore pressure is built-up under loading. A highly viscous oil is used as fracturing fluid in the Hookean cell to which the mortar is impermeable. The only difference with dry-fracturing is the fracture pressure in the

circular notch and in the fracture once it is initiated. Fig.3a shows some stress-deformation curves of the hydraulic fracturing experiments at a constant radial stress (load-path 1, Fig. 2). In addition, also some stress-deformation curves of a dry-fractured unsaturated sandstone are shown. Dry-fracturing has been performed in the Hookean cell as well, by closing the notch and sleeving the specimen. Fig.3b shows the same curves translated to the stress and deformation after hydrostatic pre-loading. Negative stresses indicate tensile stresses.
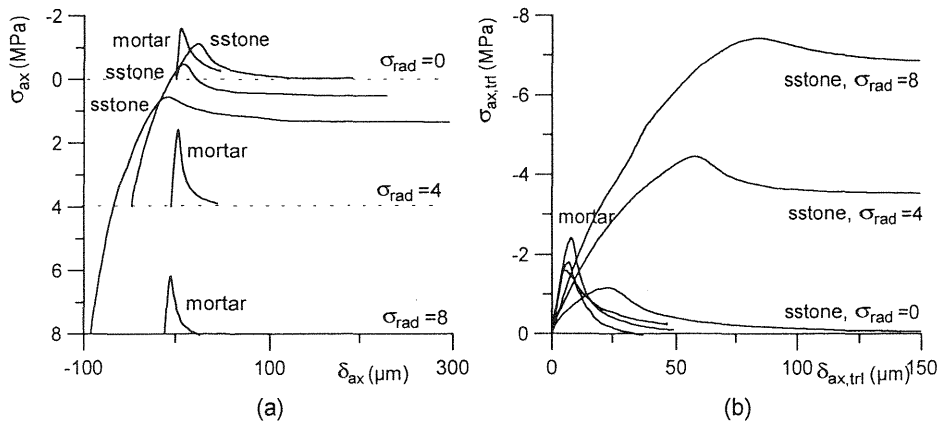

Fig.3   Stress-deformation curves (a) and translated curves (b) of the hydraulically fractured impermeable unsaturated mortar and dry-fractured unsaturated sandstone at a constant radial stress

The behaviour of the impermeable unsaturated mortar in the hydraulic fracturing experiments is indifferent to the hydrostatic pre-loading. It proved also to be independent of the load-path. Consequently, the elasticity parameters, the differential failure stress (failure stress minus hydrostatic pre-loading stress), the differential residual stress (stress at the tail of the response curve minus the hydrostatic pre-loading stress) and fracture energy are independent of the loading. The dry-fractured unsaturated sandstone is however not independent of the hydrostatic pre-loading.

During hydrostatic loading and at the onset of the tests, the effect of the pressure in the notch can be neglected so that the stresses on the two materials are similar (Visser, 1998). The differences in behaviour then are due to differences in material properties alone. The differences in peak stress and strain and the residual stresses, however, are mostly a consequence of the difference in extensile fracture mode (dry or hydraulic). Dry-fracture initiation of the unsaturated sandstone requires a tensile axial stress up to a radial compressive stress of 6 MPa (Fig. 4). Since there exists no notch pressure, extensile failure under radial compression alone is

brought about by local tensile splitting stresses which are generated at the contact of the aggregates. These local tensile splitting stresses are in general much smaller than the local tensile stress generated by a directly applied uniaxial tensile stress. Thus, a much higher stress is required to cause extensile failure under radial compression than under uniaxial tension.
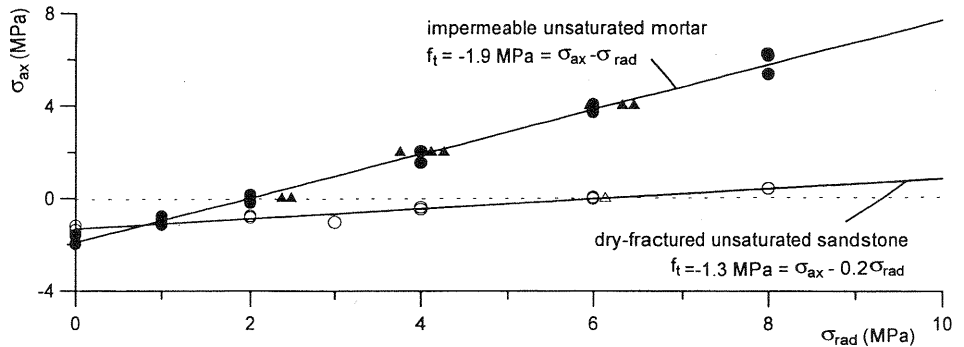

Fig. 4 Extensile failure envelopes for the dry-fractured unsaturated sandstone and the hydraulically-fractured impermeable unsaturated mortar. Dots and triangles denotes the failure stresses at a constant radial stress and axial stress respectively

For the hydraulically fractured mortar, extensile failure occurs at a constant differential stress (axial stress minus radial stress) of 2 MPa (Fig. 4). The contribution of the radial compressive stress to fracture initiation thus is 100%. This extremely high apparent contribution of the radial compressive stress to failure is mostly a consequence of the high pressure in the notch. The pressure in the notch is similar to the radial fluid pressure and exerts an axial tensile splitting stress on the specimens, as illustrated in Fig. 5 for radial compression. The axial tensile splitting stress thus promotes fracture initiation. The contribution of the radial compressive stress on the circumference is estimated to be similar to that of the dry-fractured unsaturated sandstone, about 20% (Visser, 1998). The hydraulic pressure in the notch, serving as controlled hydraulic fracture initiator, is thus 80%.

A similar highly efficiency of the fracture pressure can be observed in the tails of the response. For the hydraulically fractured mortar, the residual stress returns to the axial hydrostatic pre-loading stress axis, while the residual stresses of the dry-fractured unsaturated sandstone remains close to zero axial stress axis (see Fig.3). In the hydraulic fracture experiments, the fracture oil is free to penetrate the fracture, thereby exerting an additional
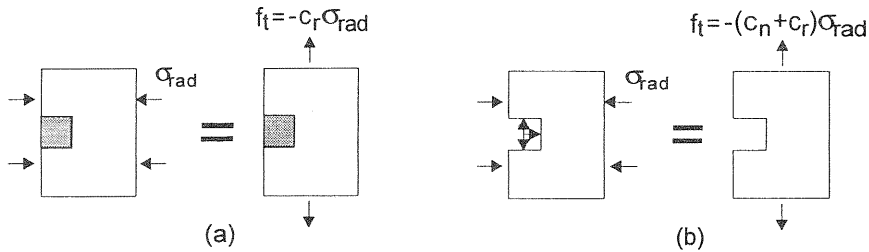
Fig. 5 Superposition principle for dry-fracture initiation (a) and hydraulic fracture initiation (b) under radial compression; c_r and c_n are the contributions of the radial stress on the circumference and in the notch respectively

stress on the fracture faces. Since the fracture surface is perpendicular to the axial stress, the fracture pressure also serves as an axial tensile stress, promoting fracture propagation. Near the end of the tests, the fracture pressure is as effective as a directly applied uniaxial stress. Contrary, for the dry-fractured sandstone where no pressure is exerted on the fracture, a high differential residual stress is required to propagate the fracture.

4 Hydraulic fracturing of the impermeable saturated mortar

To investigate the influence of the degree of saturation on the mechanical behaviour of the mortar in hydraulic fracturing, experiments have been performed on the impermeable saturated mortar. Due to the impermeability no fluid can drain or penetrate from the mortar. Fig.6 shows some results.
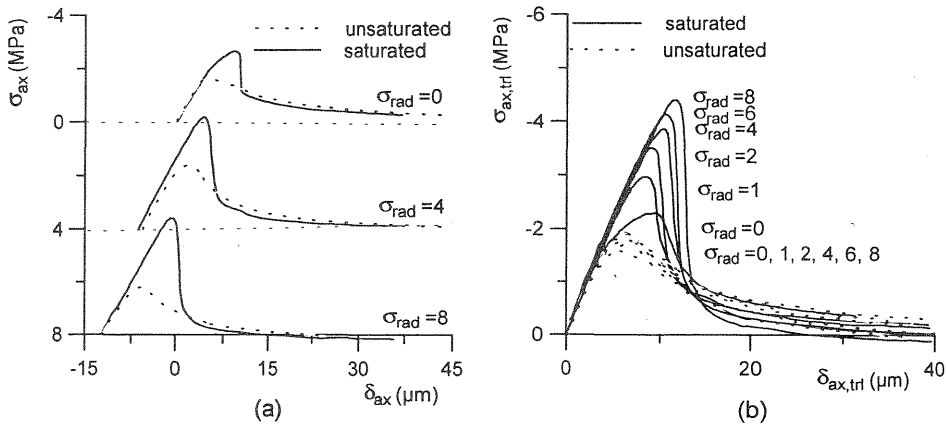

Fig.6 Stress-deformation curves (a) and translated curves (b) of the hydraulically fractured impermeable mortar

The most notable differences in behaviour between the unsaturated and saturated mortar are the higher stiffness and higher uniaxial tensile strength of the saturated mortar. Moreover, while the unsaturated mortar was indifferent to the hydrostatic loading, the results of the saturated mortar show an increase in differential failure stress with increase in radial stress.

The behaviour of the saturated mortar under hydraulic extensile stresses is greatly influenced by pore pressures. When the saturated mortar is compressed, the pore water is compressed as well. The compressed pore water exerts a stress on the mortar which counteracts the applied stress. The pores thus cannot be compressed as easily as in the unsaturated mortar, where the pores contain highly compressible air. The effective stresses governing the mechanical behaviour of the impermeable saturated mortar then are smaller than the applied stresses. Thus, the deformation of the saturated mortar is stiffer.

The pore pressure affects the fracture initiation as well. This can be seen in Fig. 7 which shows the failure envelopes of the impermeable and permeable mortar. The extensile hydraulic failure envelope of the impermeable saturated mortar differs from the hydraulic failure envelope of the unsaturated mortar in two aspects: it has a higher uniaxial tensile strength and the contribution of the radial stress to failure is lower.
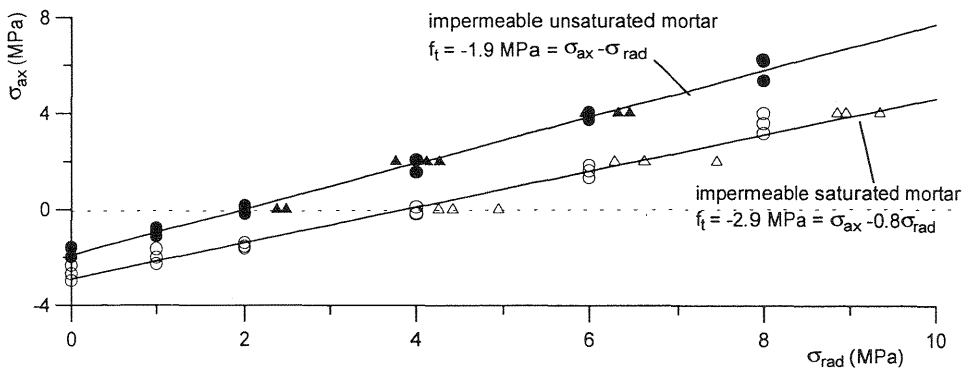

Fig. 7 Extensile failure envelopes of the hydraulically-fractured impermeable mortar. Dots and triangles are the failure stresses of the tests at a constant radial stress and constant axial stress respectively

The effect of the pore pressure on fracture initiation can again be viewed as counteracting the applied stress, so that the effective stresses on the mortar are smaller than the applied stresses. This is illustrated in Fig. 8 for radial compressive loading. The compressive pore pressure p_p increases linearly with the applied hydrostatic stress σ_c, but its effect is somewhat smaller by

the factor $\alpha<1$. The pore pressure affects the applied axial and radial stress (both on the circumference and the notch) similarly. However, due to the geometry of the experiments, the contribution of the radial stress to failure decreases.
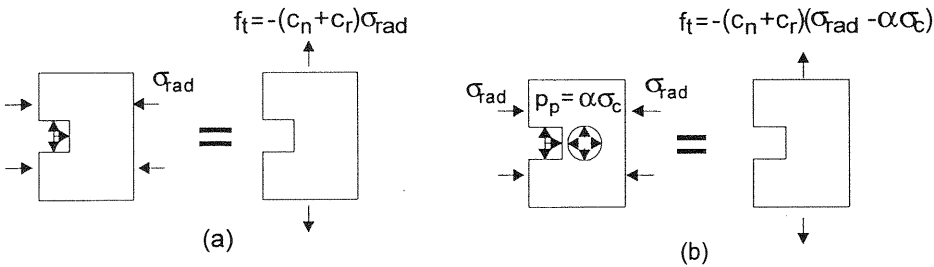

Fig. 8 Superposition principle for hydraulic fracture initiation under radial compression: impermeable unsaturated mortar (a) and impermeable saturated mortar (b); c_r and c_n are the contributions of the radial stress on the circumference and in the notch respectively

In the uniaxial tensile test, the pore pressure is 'tensile' as it resists to the pore volume increase. The tensile strength of the saturated mortar under drained conditions (i.e. no pore pressure) is equal to that of the unsaturated mortar. The uniaxial tensile failure stress for the impermeable saturated mortar thus is not equal to the tensile strength of the mortar, but equal to the tensile strength in the presence of tensile pore pressures only. In order to initiate a fracture, the tensile failure stress has to be higher than the tensile strength of the mortar.

The effect of the pore pressure on the fracture propagation becomes small at large crack openings, since the residual stresses (or the tails of the stress-deformation curves) of the unsaturated and saturated mortar are nearly similar. This is caused by the indifference of the fracture propagation stress to the pore pressure at the end of the experiments. When the fracture plane perpendicular to the axis of the cylinder becomes large, the fracture propagation stress is determined by the differential stress of the fracture pressure and the axial compressive stress alone. Since the efficiency of both the fracture pressure and the axial stress decrease with the same amount by the counteracting pore pressure, the fracture propagation or differential residual stress becomes independent of the pore pressure.

The fracture energy of the saturated mortar is higher than that of the unsaturated mortar, since work has to be done against the pore pressure.

The fracture energy is however independent of the hydrostatic pre-loading or load-path (Visser, 1998).

5 Hydraulic fracturing of the permeable saturated sandstone

To investigate the influence of the permeability on the mechanical behaviour in hydraulic fracturing, experiments have been performed on a permeable saturated sandstone. Water is used as fracturing fluid in the experiments, to which the sandstone is so permeable that the flow between the water in the reservoir of the Hookean cell and the water in the pores is instant. Some results are shown in Fig. 9.
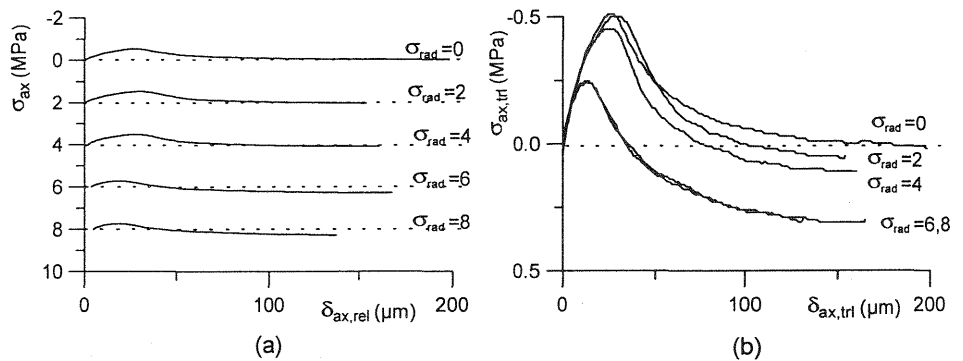
Fig. 9 Stress-deformation curves (a) and translated stress-deformation curves (b) of the hydraulically fractured permeable saturated sandstone

A first remarkable phenomena is that the uniaxial tensile strength of the saturated sandstone (i.e. the tensile failure stress under drained conditions) is more than twice as low as the tensile strength of the unsaturated sandstone. From other experiments, it was found that the cohesion of the sandstone decreases upon saturation (Visser,1998). The decrease in cohesion is due to adsorption of water in the matrix clay of the sandstone. In response to the water adsorption the distance between the (planar) sheets which together form a clay particle increases. The Van-der-Waals forces which mainly determine the cohesion of the clay decrease with distance between the clay sheets.

  Another remarkable phenomena arises for the axial deformation after hydrostatic pre-loading. Regardless the pre-loading, this deformation is zero. The permeable saturated sandstone thus behaves incompressible. From dry-fracturing experiments on drained saturated sandstone (no pore

pressure) is was found however that the actual compressibility of the saturated sandstone is even higher than that of the unsaturated sandstone. The apparent incompressible behaviour thus is a consequence of the high pore pressures. For the permeable saturated sandstone, the pore pressure increases linearly with the radial compressive stress and thus are higher than in the experiments on the impermeable saturated mortar. Moreover, the apparent incompressibility of the saturated sandstone indicates that there is no net stress at all on the specimen. The pore pressure is thus completely effective in counteracting the applied stress.

For both the experiments performed on a constant radial compressive stress (Fig. 9) as well as on a constant axial compressive stress, the stress-deformation curves translated to the stress after hydrostatic loading are all similar. This means that the differential failure stress is equal to the tensile strength of the saturated sandstone (Fig. 10), and that the differential residual stress or fracture propagation stress is about zero.
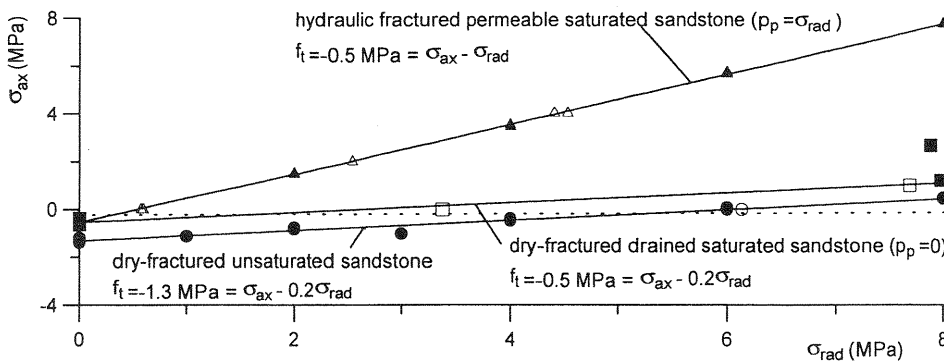

Fig. 10 Extensile failure envelopes for the dry-fractured unsaturated and drained saturated sandstone and hydraulic fractured permeable saturated sandstone. Open symbols denote constant axial stress tests, closed symbols constant radial stress tests.

The same results were found for the hydraulic fractured unsaturated mortar, yet it should be realised that the underlying mechanics are completely different. For the unsaturated mortar, a high contribution of the notch or fracture pressure was found. Contrary, for the permeable saturated sandstone, where the pore pressure completely counteracts the radial pressure, there exists no net stress either on the circumference of the cylinder nor in the notch or the fracture. Deformation, fracture initiation as well as fracture propagation then is governed solely by an
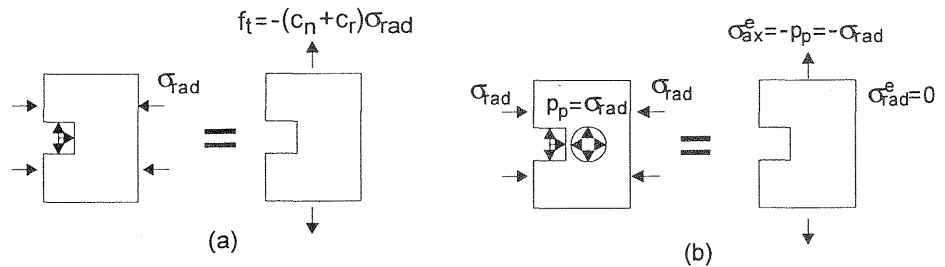
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Fig. 11 Superposition principle for the hydraulic fractured impermeable unsaturated mortar (a) and the permeable saturated sandstone (b)

effective uniaxial tensile stress, equal to the axial (compressive stress) minus the pore pressure, as illustrated in Fig. 11.

The fully effective pore pressure in the permeable saturated sandstone is partly due to the high pore pressures, partly due to its low cohesion. From similar experiments on the permeable saturated mortar, it was found that the pore pressure effect was much lower (Visser, 1998).

6 Conclusions

Hydraulic fracturing occurs under much lower stresses than dry fracturing, due to the wedge-splitting effect of the fluid pressure in the (initiating) crack. The fluid pressure can contribute as much as 80% to fracture initiation. In fracture propagation, its efficiency increases with the fracture length, being as effective as a directly applied uniaxial tensile stress near complete failure.

The efficiency of the fluid pressure to wedge a fracture depends on the degree of saturation. For saturated materials, pore pressures are generated under loading which counteract the applied stresses and thus also the pressure in the fracture. The fracture pressure is then less effective than in an unsaturated material. The magnitude of the pore pressure and thus its effect on the hydraulic fracturing depends on material properties such as permeability and cohesion. For impermeable saturated materials, the pore pressure increases linearly with the applied hydrostatic stress while for permeable materials, it increases linearly with the fluid pressure load. For the well-cemented mortar, it was found that even for testing under permeable conditions, the pore pressure did not completely counteract the applied fluid pressure load, while for the low-cohesive permeable saturated sandstone they did.

7 References

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