Effect of Pressurized Oil on the Mechanical Properties of Reactive Powder Concrete

Yanbin Zhang¹ and Zhe Wang²*

Abstract

Considering the low-permeability of reactive powder concrete (RPC) and the influence of pressurized liquid on crack development, this paper studies the mechanical properties of sealed and unsealed prismatic RPC samples under different confining pressures. It is determined that the stress-strain relations of sealed and unsealed RPC samples are almost consistent before the stress reaches its proportional limit, but the pressurized oil greatly accelerates the failure of the unsealed sample after this point. The strength loss of unsealed samples increases with an increase in the confining pressure. The failure patterns of the sealed RPC samples change with the confining pressure, but those of the unsealed samples are almost same. The unsealed samples are split by a vertical crack under every confining pressure. Additionally, it is determined that the crack development leads to a difference in the lateral strains in the perpendicular directions for sealed and prismatic samples, and the difference between the lateral strains at the peak stress in different directions increases linearly as the confining pressure increases. In contrast, for unsealed samples the lateral strains at the peak stress in the perpendicular directions are close.

1. Introduction

Concrete structures, such as some dams, mines, and offshore oil production platforms, are often in a state of three-dimensional compression. Due to the high compressive strength, self-consolidating workability and very low permeability, ultra-high-performance concrete (UHPC) is often used in these engineering applications. Many studies have been conducted on UHPC to investigate the behaviour of sealed samples under conventional triaxial compression (with pressurized oil around the specimen and an applied axial mechanical load). The experimental results showed that the ductility (Fantilli et al. 2010), the peak axial stress (Williams et al. 2010; Vankirk et al. 2019; Sovják et al. 2013) and the corresponding axial strain (Noori et al. 2015; Ren et al. 2016) increased with the confining pressure. In some papers, power-law failure criterion (Noori et al. 2015; Ren et al. 2016; Sovják et al. 2013) and Willam-Warnke failure criterion (Noori et al. 2015; Ren et al. 2016) were used to develop the empirical relations to predict the peak axial stress as a function of the confining pressure for UHPC. Yu et al. (2012) and Wu et al. (2018) analysed the mechanical properties and failure patterns of sealed RPC cylinder samples under conventional triaxial compression and found that the confined strength and the corresponding axial strain of sealed RPC cylinder samples increased with a rise in the confining pressure. Yu et al. (2012) divided the axial stress versus the axial strain curve into four stages. However, the samples used in these studies were all sealed samples.

Admittedly, in engineering applications, the concrete is often exposed to water, oil or another pressurized liquid, and the influence of the pressurized liquid on the ultimate bearing capacity and deformation capacity of unsealed concrete structures is different from that of sealed ones. Therefore, a study on sealed UHPC samples cannot well reflect the mechanical properties and deformation characteristics of UHPC structures in some real environment. The influence of the pressurized liquid on cracks and the ultimate bearing capacity of RPC cannot be ignored.

For normal-strength concrete, some experimental results have shown that the triaxial compressive strength and failure modes of unsealed samples were remarkably affected by the liquid around the samples (Clayton 1998; Wang et al. 2016; Bjerkeli et al. 1993; Chen et al. 2010). Wang and Li (2007) divided the unsaturated concrete into three zones: the saturated zone, the unsaturated zone, and the dry zone, where only the saturated zone had an effect on the mechanical properties of concrete. Considering the low-permeability, the influence of the pressurized liquid on the crack development of unsealed UHPC is different from that of normal-strength concrete. However, research on conventional triaxial compression of unsealed UHPC is rare.

As a type of UHPC with a better performance, RPC was originally developed as a homogeneous, high-strength material with a low water-to-cement ratio (Richard and Cheyrezy 1995). A reduction in the size of coarse aggregates and a decrease in the water-to-cement ratio

¹Ph.D. student, School of Civil Engineering, Beijing Jiaotong University, No. 3 Shangyuancun, Haidian District, Beijing 100044, China.
²Professor, School of Civil Engineering, Beijing Jiaotong University, No. 3 Shangyuancun, Haidian District, Beijing 100044, China.
*Corresponding author, E-mail: zhwang@bjtu.edu.cn
contribute to reducing the permeability of RPC, and the addition of silica fume also helps decrease the porosity as its particles fill empty spaces between the aggregates and cement paste (Aïtcin 2016; Scrivener et al. 1988, 2004). Tam et al. (2012) and Roux (1996) reported that the permeability coefficient of RPC was typically lower than that of normal strength concrete by one or two orders of magnitude. Li and Huang (2005) stated that RPC was impermeable. Therefore, a comparative study of the mechanical properties of sealed and unsealed RPC samples can effectively testify the influence of pressurized oil on the mechanical properties of UHPC in a real liquid environment.

In addition, due to the difficulty of sealing prismatic samples in a pressurized liquid, tests on UHPC prismatic samples are rare under conventional triaxial compression. Therefore, it is generally assumed that the lateral strains in two directions are consistent ($\varepsilon_2 = \varepsilon_3$) under the same lateral pressure ($\sigma_2 = \sigma_3$). Under the same lateral pressure, a study on the difference between the lateral strains in two directions would provide effective data for improving the mathematical model and finite element analysis.

In this paper, sealed and unsealed prismatic RPC samples were tested under conventional triaxial compression, and their mechanical properties, deformation characteristics and failure patterns were compared.

2. Material and methods

2.1 Samples preparation
Considering the internal size of the triaxial cell and the size of the extensometers, the prismatic RPC samples were designed to be $70.7 \text{ mm} \times 41 \text{ mm} \times 175 \text{ mm}$. All samples were made of the same RPC mortar mixture. The samples were made of the following materials: (1) Ordinary Portland cement P.O.52.5R (an average diameter of 14.5 $\mu$m, a density of 3120 kg/m$^3$, and a specific surface area of 3850 m$^2$/kg); (2) Silica fume (a diameter of 0.1 to 0.3 $\mu$m, a density of 2214 kg/m$^3$, and a specific surface area of 23310 m$^2$/kg); (3) Quartz sand (a diameter of 0.16 to 0.63 mm and a stacking density of 1750 kg/m$^3$) used as fine aggregates; (4) Quartz powder (an average diameter of 10 $\mu$m and a stacking density of 240 kg/m$^3$); (5) Sika 3301 MH polycarboxylate superplasticizer as a water reducer; (6) De-foamer used to reduce air bubbles in mortar; and (7) Tap water. In this study, specified material proportions were provided in Table 1. The prismatic samples were cast in metal moulds, and demoulded after 24 hours. To quicken the reaction rate of the materials, the specimens were placed in a steam curing box with a temperature of 90°C for 120 hours and stored in a fog room until testing.

### Table 1 Mass ratio of reactive powder concrete.

| Cement materials | Silica fume | Quartz powder | Quartz sand | Water | Water reducer | Defoamer |
|------------------|-------------|---------------|-------------|-------|---------------|---------|
| Cement           | 1           | 0.18          | 0.27        | 1     | 0.2           | 0.018   | 0.001   |

2.2 Testing program

Three pieces of Teflon with a thickness of 0.1 mm were placed between the sample and every indenter, with a lithium-based lubricant added between the Teflon to fully reduce the friction. The assembly of the measuring device is shown in Fig. 1a. The sealed samples were wrapped with a heat-shrinkable sleeve, to isolate the pressurized oil (No. 10 aviation hydraulic oil) thoroughly from the samples. The unsealed samples were also wrapped with a heat-shrinkable sleeve, but 4 square openings (with 5 mm sides) were left in the sleeve to allow the pressurized oil to contact the samples directly, and the extensometers for measuring the lateral strain were directly clamped on the unsealed samples through the openings in the sleeve. There were 5 layers of crocus cloth lining on the inside of the openings to prevent the slag from flowing into the outside pressurized oil. However, the extensometers were clamped on the outside of the sleeve for sealed ones, as the gap between the sealed sample and the sleeve could be compacted by the confining pressure. Two LVDT sensors were fixed symmetrically to the lateral side of the indenters to measure the axial strain.

This test was conducted on an XTR-01 computer-controlled triaxial testing machine at Beijing Jiaotong University, and the triaxial cell of the machine has a self-balancing function. The axial load on the samples was the superposition of the load ($q$) applied by the plunger and the confining pressure ($p$) applied via pressurized oil. The axial stress corresponding to $l_1$, the lateral stress corresponding to $l_2$ and the lateral stress

![Fig. 1 Measuring device assembly and force diagram of the RPC sample.](image-url)

(a) Measuring device assembly.  
(b) Force diagram of the sample.  

\( l_1 = 0.175 \text{m}; \ l_2 = 0.041 \text{m}; \ l_3 = 0.0707 \text{m}; \ q = \text{Axial load}; \ p = \text{Confining pressure}. \)
corresponding to \( l_1 \) were recorded as \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) respectively (see Fig. 1b). Their relationship could be expressed as \( \sigma_i = p + q \cdot \varepsilon_i = p \cdot \varepsilon_i \geq \sigma_3 = \sigma_1 \), where \( \varepsilon_1, \varepsilon_2 \) and \( \varepsilon_3 \) are the strains corresponding to \( l_1, l_2 \) and \( l_3 \) respectively. In this paper, the strains do not contain the strain produced by confining pressure \( (p) \).

Six confining pressure levels (0, 5, 10, 20, 40 and 70 MPa) were used in this study. The experimental procedure was as follows. First, the designated hydrostatic pressure was applied in the cell, and then the axial load increased at a constant plunger displacement rate of \( 5 \times 10^{-6} \) m/s. The tests were terminated at an axial strain of 10\%. If the sample completely lost its strength, the test was terminated as well. After each test, the sample was removed from the cell and the failure patterns were recorded. For this experimental procedure, please refer to the experimental method of Wu et al. (2018). For the sealed or unsealed samples, the experimental data of the three samples were used at each confining pressure, but the data collection of the two samples failed.

3. Results and discussion

Before the test was conducted on the unsealed samples, five samples were exposed for two hours in pressurized oil at 70 MPa. It was determined that the surface layer infiltrated with oil was less than 1 mm, and the interior of the samples was still dry. All the experiments requiring data acquisition require less than half an hour. Therefore, it could be considered that the samples were impermeable during the experiment.

3.1 Stress-strain relationship

On the basis of fracture development, the pre-peak failure of sealed brittle materials can be divided into four stages (Wang and Li 2007; Martin and Chandler 1994; Zhao et al. 2018; Ren and Ge 2004; Li et al. 2017), as shown in Fig. 2: fracture closure (stage I), linear region (stage II), stable extension of micro-cracks (stage III), and accelerating extension of cracks (stage IV). In stage I, the existing micro-cracks in the samples tend to be closed gradually, and this process depends on the initial crack density and the crack geometry. In stage II, the samples are assumed to be a linear, homogeneous material. In stage III, a large number of new micro-cracks are generated, and the micro-cracks extend stably. In stage IV, the cracks penetrate into one another, and the damage develops rapidly. The above four stages have been observed using acoustic emission or scanning electron microscopy in some previous literature (Huang et al. 2019; Zhang et al. 2018).

Figure 3 illustrates the deviatoric stress versus the axial strain curves of the sealed and unsealed RPC samples under different confining pressures. The pre-peak failure of the sealed RPC samples (see Fig. 3a), like other brittle materials, can be divided into four stages. However, the axial deformation measured in this test includes the deformation of the anti-friction layers, which are located between the samples and the indenters. If the deformation of the anti-friction layers is removed, stage I is almost negligible, as there are few micro-defects in the RPC (Liu and Song 2007). The course of crack development (stage III and stage IV) of sealed RPC samples becomes more prominent with an increase in the confining pressure, but Fig. 3b shows that the...
unsealed sample course is much shorter. This indicates that the deformation capacity of sealed samples increases with an increase in the confining pressure, but the deformation capacity of the unsealed sample is greatly reduced because the pressurized oil can enter into the cracks and accelerate the crack development. In contrast, the pressurized oil can hinder the crack development of the sealed sample.

For unsealed normal-strength concrete, the brittleness of the samples decreases due to the pore pressure, so the decrease in the triaxial compressive strength at the peak point is not sudden (Bjerkeli et al. 1993). However, as shown in Fig. 3b, the deviatoric stress of unsealed samples drops rapidly after reaching its peak and the load-carrying capacity of the unsealed samples is almost completely lost instantaneously. Thus, it can be seen that the unsealed sample will be quickly destroyed once the cracks are generated. However, the triaxial compressive strength of the sealed specimens continues to increase after the cracks are generated and there is some residual strength left.

As shown in Fig. 4, the deviatoric stress versus the axial strain curves of sealed and unsealed samples under the same confining pressure are generally consistent before the curves reach stage III. At each confining pressure, the peak stress of the unsealed samples is close to the proportional limit (the end point of stage II) of the sealed specimen. Due to the low-permeability of RPC, the stress distribution of sealed and unsealed samples is almost identical before the pressurized oil flows into the cracks. As the axial stress reaches the proportional limit, the confining pressure can continue to impede the cracks extension for the sealed samples. However, the pressurized oil flows into the cracks of unsealed samples near the proportional limit, so the confining pressure can no longer restrain the crack development. In contrast, the pressurized oil can promote the crack development as it reaches the tips of cracks. Therefore, the unsealed samples will accelerate the failure and quickly lose strength.

In addition, when the confining pressure is between 20 MPa and 70 MPa, the lateral strains (ε_u) of the unsealed samples increase significantly before the samples lose their strength, whereas the lateral strains (ε_u) do not. This is caused by the pressurized oil promoting crack development and the direction of cracking makes the lateral strain of the two directions different (see Table 4).

### 3.2 Strength and failure criterion

The strength of the samples corresponding to 0 MPa in Table 2 is the uniaxial compressive strength in air. The uniaxial compressive strength of sealed and unsealed samples is the same set of data.

For normal-strength concrete, the triaxial compressive strength of sealed samples increases with the confining pressure, but that of unsealed ones decreases due to the pore pressure (Clayton 1998; Wang et al. 2016; Bjerkeli et al. 1993; Chen et al. 2010). The triaxial compressive strength of sealed and unsealed RPC samples increases as the confining pressure increases, as shown in Table 2. To compare the experimental data with those predicted by the existing failure envelopes, the curves obtained with the power-law failure criterion (Li and Ansari 2000; Noori et al. 2015; Ren et al. 2016; Sovják et al. 2013) are represented in Fig. 5.

As an improved model of the Mohr-Coulomb failure criterion, the power-law failure criterion is more suitable for high-strength concrete (HSC) (Li and Ansari, 2000) and UHPC (Noori et al. 2015; Ren et al. 2016; Sovják et al. 2013). The power-law failure criterion can well fit the relationship between their triaxial compressive strength and confining pressure. The RPC samples used in this paper lack coarse aggregate and steel fibre, compared with the HSC and UHPC samples in the studies of Li and Ansari (2000), Ren et al. (2016), and Noori et al. (2015). However, the material ratio of the RPC samples studied in this paper is similar to the UHPC samples of Sovják et al. (2013). The power-law failure criterion for RPC can be expressed as:

\[
\frac{\sigma}{f_c} = 1 + k \left( \frac{\sigma}{f_c} \right)^a
\]

(1)

In this equation, \( k \) and \( a \) are empirical parameters, and \( f_c \) is the uniaxial compressive strength. For both sealed and unsealed RPC samples, the experimental data in Fig. 5 shows similar trends as the data for the power-law failure criterion. In this study, the compressive meridian of sealed samples can be expressed as:

\[
\frac{\sigma}{f_c} = 1 + 2.74\left( \frac{\sigma}{f_c} \right)^{0.66}, \quad R^2 = 0.9912
\]

(2)
And the compressive meridian of unsealed samples can be expressed as:

\[
\frac{\sigma_{c u}}{f_c} = 1 + 1.77\left(\frac{\sigma_t}{f_c}\right)^{0.66}, \quad R^2 = 0.9659
\]  

Compared with the equation of HSC and UHPC, the empirical parameters \(k\) and \(a\) in the equation of RPC are most similar to those in the paper of Sovják et al. (2013), whose material ratio of the samples is similar to the RPC samples studied in this paper. It can be seen that the empirical parameters \(k\) and \(a\) are related to the material ratio. If all the compressive meridian data points of both sealed and unsealed samples obtained in this study are put together (see Fig. 5), the power-law failure criterion applied to both sealed and unsealed samples can be determined. The only difference between Eqs. (2) and (3) is the parameter \(k\). The difference between the triaxial compressive strength of sealed and unsealed samples represents the strength loss of unsealed samples due to the pressurized oil flowing into the cracks, and it can be seen from Fig. 5 that the strength loss of the unsealed samples increases as the confining pressure increases.

Fig. 4 Comparison of the deviatoric stress-strain curves of sealed and unsealed prismatic RPC samples each confining pressure.

\(\varepsilon_{c2}\) = Lateral strain corresponding to \(l_2\) of the sealed samples; \(\varepsilon_{n2}\) = Lateral strain corresponding to \(l_2\) of the unsealed samples;
\(\varepsilon_{c3}\) = Lateral strain corresponding to \(l_3\) of the sealed samples; \(\varepsilon_{n3}\) = Lateral strain corresponding to \(l_3\) of the unsealed samples.
3.3 Failure patterns

According to the previous results (Nemat-Nasser and Horii 1982; Horii and Nemat-Nasser 1985, 1986), for the samples under uniaxial compression, the tips of the larger existing defects nucleated first as the axial load increased, and the direction of the cracks was parallel to the axial load, whereas the smaller defects did not nucleate. As the axial load continued to increase, the fracture continued until the samples failed. When the samples were subjected to a certain confining pressure (no pressurized liquid made direct contact with the sample), the tips of the larger existing defects nucleated first as the axial load increased, and the cracks generated earlier grew in the direction of the axial load. However, the cracks were soon arrested because of the confining pressure, and as the axial stress continued to increase, the tips of the smaller defects nucleated. When the axial stress was large enough, the cracks in the shear band grew spontaneously and simultaneously, finally leading to a fault.

The failure patterns of sealed samples under different confining pressures are shown in Table 3. When the confining pressure is 0 MPa, the samples under uniaxial compression are split into several vertical columns. The reason for this failure pattern is that the lateral tensile strain exceeded the ultimate tensile strain of the samples. Under a confining pressure of 5 MPa, the samples fail with several short vertical cracks instead of an inclined crack. This is because the confining pressure is so weak that the cracks generated from the larger defects could sufficiently extend, and before the inclined crack is formed, the end of the sample is crushed. This experimental result well confirms the conclusion of (Nemat-Nasser and Horii 1982; Horii and Nemat-Nasser 1985, 1986).

When the confining pressure is between 10 MPa and 40 MPa, the failure modes of the samples are typical shear failure mode. The reason for this failure pattern is that the confining pressure is large enough to arrest the vertical cracks generated from the larger defects. Then, the tips of the smaller defect nucleate. When the shear stress \( \frac{\sigma_3 - \sigma_1}{2} \) is higher than its ultimate shear stress, the cracks in the shear band grow spontaneously and simultaneously.

The sealed samples under a confining pressure of 70 MPa are destroyed with an inclined crack and many other short cracks in different directions. After the test was completed, the sample could be broken into small pieces by hand. This is because the cracks were fully developed before the stress reached its peak (the crack propagation stage is large enough under this confining pressure, as shown in Fig. 2).

The absence of coarse aggregates and the decrease in the water-to-cement ratio makes the fracture surfaces of the unsealed RPC samples smooth, which is different from the unsealed normal strength concrete under triaxial compression (Wang et al. 2016; Chen et al. 2010). The failure patterns of unsealed RPC samples under different confining pressures are shown in Table 4. The unsealed samples are all split by a vertical crack under every confining pressure (the crack does not extend to the bottom for samples under a confining pressure of 10 MPa). The reason for this failure pattern is that the existing larger

| Confining pressures | 0 MPa | 5 MPa | 10 MPa | 20 MPa | 40 MPa | 70 MPa |
|---------------------|-------|-------|--------|--------|--------|--------|
| Front side correspond to \( l_1 \) | | | | | | |
| Right side correspond to \( l_2 \) | | | | | | |

![Fig. 5 Experimental data and the curves fitted with the power-law failure criterion.](image)
defects nucleate first (Nemat-Nasser and Horii 1982; Horii and Nemat-Nasser 1985, 1986) and the cracks generated first are parallel to the axial load. Once the crack is generated, the pressurized oil flows into them rapidly, and the cracks are no longer restrained by the confining pressure. In contrast, the pressurized oil promoted the development of the crack as it reached the tips of the crack. After the vertical crack extends to the end of the sample, the sudden increase in the slenderness ratio results in a decrease in the bearing capacity of the sample. Before the smaller defects nucleate, the sample has been destroyed. Thus, there is only one vertical crack in the sample.

3.4 Axial strains at peak stress
The anti-friction layers can not only be pressed thinner by the confining pressure through the indenters but can also be pressed thinner directly from the pressurized oil. However, the gap between the sealed samples and the indenters can be compacted by the confining pressure, while the gap between the unsealed samples and the indenters cannot.

Figure 6 shows that the axial strains at the peak stress of sealed and unsealed samples increase linearly as the confining pressure increases. Their relationship can be expressed as:

\[ \varepsilon_{n1}^u = 2.48 \times 10^{-4} p + 0.005, \quad R^2 = 0.9170 \]  \hspace{1cm} (4)

\[ \varepsilon_{n1}^u = 9.23 \times 10^{-5} p + 0.005, \quad R^2 = 0.8690 \]  \hspace{1cm} (5)

Considering the influence of the gap between the unsealed samples, the constant term in Eq. (5) is greater than the real value.

According to the results of Section 3.2, the difference between the axial strains at the peak stress of the sealed and unsealed samples is the axial strain corresponding to the process of crack development. Eqs. (4) and (5) show that this difference increases linearly with the confining pressure.

3.5 Lateral strains at peak stress
The lateral strains at peak stress are shown in Fig. 7a. For the sealed RPC samples, it is determined that the lateral strain at the peak stress increases with an increase in the confining pressure. The lateral strains at the peak stress corresponding to the wide side \( l_3 \) are greater than the ones corresponding to the narrow side \( l_2 \), and their difference \( (\varepsilon_{u2}^s - \varepsilon_{u3}^s) \) increases linearly with an increasing confining pressure (see Fig. 7b). The relationship between the difference and the confining pressure can be expressed as:

\[ (\varepsilon_{u2}^s - \varepsilon_{u3}^s) = 2.67 \times 10^{-5} p + 8.33 \times 10^{-5}, \quad R^2 = 0.9650 \]  \hspace{1cm} (6)

Moreover, as shown in Fig. 8, the lateral strain versus the axial strain curves in two perpendicular directions are quite close before the axial stress reaches the proportional limit, and the distance between these two curves gradually increases after this point. Therefore, it is inferred that the crack development mainly contributes to the difference \( (\varepsilon_{u2}^s - \varepsilon_{u1}^s) \) of the lateral strains at the peak stress in two perpendicular directions.

Table 4 Failure patterns of unsealed samples under different confining pressures.

| Confining pressures | 5 MPa | 10 MPa | 20 MPa | 40 MPa | 70 MPa |
|---------------------|-------|--------|--------|--------|--------|
| Front side          | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) |
| Right side          | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) | ![Image](image10.png) |

| Confining pressures | 5 MPa | 10 MPa | 20 MPa | 40 MPa | 70 MPa |
|---------------------|-------|--------|--------|--------|--------|
| Front side          | ![Image](image11.png) | ![Image](image12.png) | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) |
| Right side          | ![Image](image16.png) | ![Image](image17.png) | ![Image](image18.png) | ![Image](image19.png) | ![Image](image20.png) |

Fig. 6 Relationship between the axial strain at peak stress and confining pressures.

\( \varepsilon_{u1}^s \) = Axial strain at the peak stress of sealed samples;

\( \varepsilon_{n1}^u \) = Axial strain at the peak stress of unsealed samples.
For the unsealed RPC samples, the lateral strain at peak stress increases with an increase in the confining pressure when the confining pressure is lower than 20 MPa. However, the lateral strain at peak stress hardly changes with the confining pressure when the confining pressure is larger than 20 MPa. Thus, it can be inferred that, when the confining pressure is higher than 20 MPa, the lateral deformation capacity of the unsealed samples will not change with confining pressure. In addition, the lateral strains at the peak stress in two perpendicular directions are close (except for three discrete values). This is because the samples tend to be isotropic before the cracks extend stably, and as the pressurized oil flows into the cracks once the stress reaches the proportional limit, the unsealed samples are promptly destroyed. The extremely short course of crack development contributes little to the difference \( (\varepsilon_{l2} - \varepsilon_{l3}) \) between the lateral strains in different directions.

### 4. Conclusions

The purpose of this study was to experimentally investigate the effects of pressurized oil on the mechanical properties of prismatic RPC samples. Sealed and unsealed prismatic RPC samples were used under different confining pressures. Due to the low-permeability of RPC, the pressurized oil impeded the inner micro-cracks from extending before the stress reached the proportional limit, but promoted crack development in the unsealed samples after it flowed into the cracks. Because of the influence of pressurized oil on the cracks, sealed and unsealed RPC samples are different in terms strength, failure modes and deformation characteristics. The following conclusions can be drawn:

1. The stress-strain relations of sealed and unsealed samples are almost consistent before the stress reaches the proportional limit. There is some residual stress of the sealed samples under triaxial compression. However, the pressurized oil makes the unsealed RPC samples fail rapidly once the crack is generated, and there is no residual stress in the unsealed RPC samples.

2. As the confining pressure increases, the failure modes of the sealed samples change from columnar failure mode to shear failure mode, and finally to cataclastic failure mode. When the pressurized oil...
contacts the samples directly, the samples have the same failure pattern under every confining pressure; that is, they are split by a vertical crack.

(3) The triaxial compressive strength for both sealed and unsealed RPC samples increases with an increase in the confining pressure. However, the strength loss of the unsealed samples increases with the confining pressures compared with the sealed samples.

(4) For the sealed RPC samples, the lateral strains at the peak stress in two perpendicular directions are different under every confining pressure, and their difference increases linearly with an increase in the confining pressure. The crack development contributes to this difference, whereas the lateral strains at the peak stress in the two perpendicular directions of unsealed RPC samples are close.

Acknowledgement
The authors gratefully acknowledge the financial support by the National Natural Science Foundation of China (No. 51279003 and 51078024).

References:
Aïtcin, P. C.,(2016). “Ultra high strength concrete.” In: P. C. Aïtcin and R. J. Flatt, Eds. Science and Technology of Concrete Admixtures. Amsterdam: Woodhead Publishing, 503-523.

Bjarke, L., Jensen, J. J. and Lenschow, R., (1993). “Strain development and static compressive strength of concrete exposed to water pressure loading.” ACI Structural Journal, 90(3), 310-315.

Chen, Z. F. S., Hu, Y., Li, Q. B., Sun, M. Y., Lu, P. Y. and Liu, T. Y., (2010). “Behavior of concrete in water subjected to dynamic triaxial compression.” Journal of Engineering Mechanics, 136(3), 379-389.

Clayton, N., (1998). “Effect of water pressure on concrete strength.” In: O. E. Gjov, K. Sakai and N. Banthia, Eds. Concrete under severe conditions 2: Environment and loading. London and New York: E & FN Spon, 978-987.

Funtilli, A., Mihashi, H., Vallini, P. and Chiaia, B., (2010). “The ductile behavior of high-performance concrete in compression.” Archives of Civil Engineering, 56(1), 3-18.

Horii, H. and Nemat-Nasser, S., (1985). “Compression-induced microcrack growth in brittle solids: axial splitting and shear failure.” Journal of Geophysical Research, 90(B4), 3105-3125.

Horii, H. and Nemat-Nasser, S., (1986). “Brittle failure in compression: Splitting, faulting and brittle-ductile transition.” Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 319(1549), 337-374.

Huang, Y. H., Yang, S. Q. and Tian, W. L., (2019). “Crack coalescence behavior of sandstone specimen containing two pre-existing flaws under different confining pressures.” Theoretical and Applied Fracture Mechanics, 99, 118-130.

Li, D. Y., Sun, Z., Xie, T., Li, X. B. and Ranjith, P. G., (2017). “Energy evolution characteristics of hard rock during triaxial failure with different.” Engineering Geology, 228, 270-281.

Li, Q. B. and Ansari, F., (2000). “High-strength concrete in triaxial compression by different sites of specimens.” ACI Materials Journal, 97(6), 684-689.

Li, Z. and Huang, L. D., (2005). “Research on durability of reactive powder concrete with steel-fiber.” Municipal Engineering Technology, 23(4), 255-257.

Liu, J. H. and Song, S. M., (2007). “The influence of particle distribution to properties and microstructure of reactive power concrete.” Journal of Wuhan University of Technology, 29(1), 26-29.

Martin, C. D. and Chandler, N. A., (1994). “The progressive fracture of Lac du Bonnet granite.” International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 31(6), 643-659.

Nemat-Nasser, S. and Horii, H., (1982). “Compression-induced nonplanar crack extension with application to splitting, exfoliation, and rockburst.” Journal of Geophysical Research: Solid Earth, 87(B8), 6805-6821.

Noori, A., Shekarchi, M., Moradian, M. and Moosavi, M., (2015). “Behavior of steel fiber-reinforced cementitious mortar and high-performance concrete in triaxial loading.” ACI Materials Journal, 112(1), 95-103.

Ren, G. M., Hu, H., Fang, Q., Liu, J. Z. and Gong, Z. M., (2016). “Triaxial compressive behavior of UHPCC and applications in the projectile impact analyses.” Construction and Building Materials, 113, 1-14.

Ren, J. and Ge, X., (2004). “Computerized tomography examination of damage tests on rocks under triaxial compression.” Rock Mechanics and Rock Engineering, 37(1), 83-93.

Richard, P. and Cheyrrez, M., (1995). “Composition of reactive powder concretes.” Cement and Concrete Research, 25(7), 1501-1511.

Roux, N., (1996). “Experimental study of durability of reactive powder concrete.” Journal of Materials in Civil Engineering, 8(1), 1-6.

Scrivener, K. L., Bentur, A. and Pratt, P., (1988). “Quantitative characterization of the transition zone in high strength concretes.” Advances in Cement Research, 1(4), 230-237.

Scrivener, K. L., Crumbe, A. K. and Laugesen, P., (2004). “The interfacial transition zone (ITZ) between cement paste and aggregate in concrete.” Interface Science, 12(4), 411-421.

Sovják, R., Vogel, F. and Beckmann, B., (2013). “Triaxial compressive strength of ultra-high-performance concrete.” Acta Polytechnica, 53(6), 901-905.

Tam, C. M., Tam, V. W. Y. and Ng, K. M., (2012). “Assessing drying shrinkage and water permeability of reactive powder concrete produced in Hong Kong.” Construction and Building Materials, 26(1), 79-89.

Vankir, G., Heard, W., Frank, A., Hammons, M. and Roth, J., (2019). “Residual structural capacity of a
high-performance concrete.” Dynamic Behavior of Materials, 1, 233-236.
Wang, H. L. and Li, Q. B., (2007). “Prediction of elastic modulus and Poisson’s ratio for unsaturated concrete.” International Journal of Solids and Structures, 44(5), 1370-1379.
Wang, Q. F., Liu, Y. H. and Peng, G., (2016). “Effect of water pressure on mechanical behavior of concrete under dynamic compression state.” Construction and Building Materials, 125, 501-509.
Williams, E. M., Graham, S. S., Akers, S. A., Reed, P. A. and Rushing, T. S., (2010). “ Constitutive property behavior of an ultra-high-performance concrete with and without steel fibers.” Computers and Concrete, 7(2), 191-202.
Wu, L. C., Wang, Z., Liu, D., Zhu, H. H., Lu, Y. and Lin, L., (2018). “Effect of confining pressure and steel fiber volume content on mechanical property of reactive powder concrete.” Journal of Building Materials, 21(2), 208-215. (in Chinese)
Yu, Z. R., Qin, X. and An, M. Z., (2012). “Experimental research on the conventional triaxial compressive properties of reactive powder concrete.” China Railway Science, 33(02), 38-42. (in Chinese)
Zhang, G. B., Zhang, W. Q. and Wang, H. L., (2018). “Microscopic failure mechanism analysis of sandstone under triaxial compression.” Geotechnical and Geological Engineering, 37(2), 683-690.
Zhao, J., Feng, X. T., Zhang, X. W., Zhang, Y., Zhou, Y. Y. and Yang, C. X., (2018). “Brittle-ductile transition and failure mechanism of Jinping marble under true triaxial compression.” Engineering Geology, 232, 160-170.