# Rock Breaking Using Supercritical Carbon Dioxide (SC-$CO_2$) Technology – A Safe, Efficient, and Sustainable Approach

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## ABSTRACT

Rock breaking by drill and blast using chemical explosives has been a dominant method in construction. However, blasting is hazardous and risky in nature: it involves the use of Category 1 Dangerous Goods; and it induces ground vibration and risks of fly rocks and air over pressure. Mechanical rock breaking, chemical expansion agent, and hydraulic fracturing techniques, complemented with hole drilling, wedging or splitting, are sometimes used as alternatives to drill and blast for rock breaking. However, these methods are extremely slow to match with construction progress and are also costly. In particular, mechanical rock breaking brings about continuous noise, dust and nuisances to the surroundings. As more and more construction works nowadays are in congested urban region, the construction industry needs to adopt a safe, efficient, and sustainable rock breaking approach. In view of this, rock breaking using supercritical carbon dioxide (SC-$CO_2$) technology has been developed recently, and it has successfully been applied to numerous real projects.

**Keywords:** SC-$CO_2$, Rock Fracturing, Sustainable, Safe, Tensile Fracture

## 1 Introduction

### 1.1 Conventional Rock Breaking

Rock breaking is commonly practiced in mining as well as civil and building engineering for site formation, tunnelling, cofferdam excavation, and foundation construction. There are various methods of rock breaking, such as drill and blast, mechanical breaking, the use of chemical expansion agents, and hydraulic fracturing techniques. Drill and blast involves drilling of holes into the rock mass for placing chemical explosives. It is a highly effective method of rock breaking. In Hong Kong, explosives are classified as Category 1 Dangerous Goods under the Law Cap. 295 Dangerous Goods Ordinance, and the storage and transportation are subjected to stringent control. Besides, in view of the engineering risks of explosives, comprehensive precautionary and preparatory measures must be implemented before the execution of blasting works, such as identifying sensitive receivers, conducting blast assessment, planning delivery schedule and route of explosives, devising instrumentation and monitoring plan, determining alert-action-alarm levels of ground vibrations, assessing the risk of fly rock and air over pressure, designing and erecting blast doors and blast covers etc. Adequate time and resources have to be allowed for these measures.

Mechanical rock breaking is comparatively simple, it involves the use of hydraulic breaker and wedge splitter or piston splitter. The hydraulic breaker is often mounted on backhoe (Figure 1). During breaking, high level of noise in the range of 95 to 105 dB(A) would be generated. Labourers exposed to continuous noise over long-term may suffer from hearing impairment, and the noise would also cause nuisance to the public in surroundings. Wedge and piston splitters rely on splitting stresses for rock breaking. Figure 2 shows a wedge splitter mounted on backhoe; whereas Figure 3 depicts rock splitters

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which exert pressure on rock by pistons (Figure 3(a)) and by wedging (Figure 3(b)), both powered by hydraulic power unit, i.e. power pack. Unlike backhoe-mounted wedge splitter, these rock splitters need to be relocated from one place to another by lifting plants. Another alternative method of rock breaking involves the use of chemical expansion agents which are non-explosive nor blasting agent. The expansion agents are usually proprietary products and different choices are available. For example, a product described as cracking agent uses an electric shock to induce gas expansion, and a product described as demolition agent comprises inorganic compounds and make use of solid expansion of calcium hydroxide hydrates. It should be noted that the use of wedge splitter, piston splitter, and chemical expansion agents requires prior drilling of holes for insertion of splitter or filling of chemical agent. Overall speaking, the productivity, i.e., the rate of rock breaking by mechanical method or by chemical expansion agents is rather low, and this often becomes the constraining factor to the construction progress.

**Figure 1:** Hydraulic breaker mounted on backhoe

**Figure 2:** Wedge splitter mounted on backhoe

(a) (b)

**Figure 3:** (a) Piston-type rock splitter & (b) wedging-type rock splitter

### 1.2 Hydraulic Fracturing

The hydraulic fracturing technique is commonly used in rock drilling for petroleum extraction. Basically, this technique is to inject a pressurized hydraulic fluid into the end of the borehole, which may be at a depth greater than 1000 m, to fracture the rock. The hydraulic fluid (also called fracturing fluid) serves two purposes: (a) to wedge-open and extend a fracture hydraulically; and (b) to transport and distribute the proppant along the fracture (Ishida et al. 2004). Hydraulic fluids used include oil-based fluids, water-based fluids and alcohol-based fluids. In recent years, liquefied and pressurized carbon dioxide, especially supercritical carbon dioxide, has become popularly used as the hydraulic fluid due mainly to its much lower viscosity (Kizaki et al. 2012; Liu et al. 2014; Bennour et al. 2015).

Ishida et al. (2004) had studied the influence of fluid viscosity on the hydraulic fracturing mechanism by fracturing granite blocks using viscous oil or water, and found that viscous oil tends to generate thick and planar cracks with few branches while water tends to generate thin and wavelike cracks with many secondary branches. Hence, a less viscous fluid would penetrate more deeply to produce thinner cracks with more secondary branches. Bennour et al. (2015) later compared viscous oil, water and liquid carbon dioxide (L-CO$_2$) as hydraulic fluids in fracturing of shale, and observed that with the use of L-CO$_2$, which has the lowest viscosity, the cracks formed tend to be widely extended with many branches. The effects of using supercritical carbon dioxide (SC-CO$_2$), which has an even lower viscosity, will be explained later in this paper.

The hydraulic fracturing technique is also being applied to rock breaking for excavation (Ishida et al. 2012; 2013; Zhang et al. 2018), although the rock blasting technique of using a chemical explosive is still dominant. It may appear at first sight that hydraulic fracturing may not be powerful enough to break strong rocks like granite and volcanic tuff. But actually, the breaking power is just a matter of the quantity of hydraulic fluid injected into the borehole, the pressure applied to the hydraulic fluid, and the penetrability of the hydraulic fluid into fine cracks to wedge-open and extend the cracks (i.e. to extend the fracture). In the case of using liquefied and pressurized gas (e.g., CO$_2$) as the hydraulic fluid, the breaking power is dependent also on the amount of heat applied to gasify and cause rapid expansion of the gas in the borehole.

### 1.3 Overview of the Study

As will be explained later, with SC-CO$_2$ used as the hydraulic fluid, the rock breaking can be accomplished at a much lower breakdown pressure (also called fracturing pressure or explosion pressure), meaning that much less shock would be generated during rock breaking. In theory, the hydraulic fracturing technique without using any explosive should be much safer to use than the rock blasting technique using an explosive.

At the outset, it should be pointed out that SC-CO$_2$ is not solid, liquid or gas, but has certain properties favouring rock drilling and rock breaking. In the following, it will be explained how and why liquid L-CO$_2$ used in rock drilling for petroleum extraction is being replaced by SC-CO$_2$. Then, it will be discussed how SC-CO$_2$ could be applied to rock breaking for excavation. For rock breaking, SC-CO$_2$ is used like a chemical explosive, but actually is not an explosive and thus is safer to use. Lastly, the advantages and disadvantages of using SC-CO$_2$ will be discussed and application examples will be presented.

## 2 Supercritical Carbon Dioxide

### 2.1 Basic Properties of Supercritical CO2

For most materials, its phase transforms between solid, liquid or gas as the temperature and/or pressure changes. However, for some materials, there could be the fourth phase. For instance, supercritical carbon dioxide (SC-CO$_2$) is not solid, liquid or gas, but is of the fourth phase. Carbon dioxide will be transformed into a supercritical state when its temperature and pressure exceed those at the critical point (critical temperature = 31.1°C and critical pressure = 7.38 MPa), as shown in Figure 4 (Roland & Wagner 1996; Lv et al. 2013).

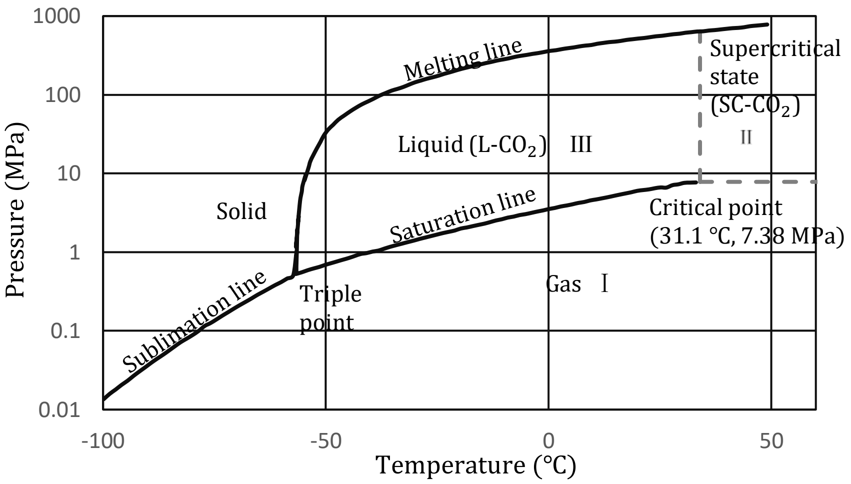

**Figure 4:** Phase diagram of $CO_2$

In the supercritical state, $CO_2$ has a relatively high density like liquid but a very low viscosity close to gas, thus allowing a large quantity of $CO_2$ to be filled into the container or borehole and the $CO_2$ to penetrate into very fine gaps (Kizaki et al. 2012). In fact, the very small inter-molecular forces, zero surface tension and very strong mobility of SC-$CO_2$ (these are the properties causing the SC-$CO_2$ to have a very low viscosity) would enable the SC-$CO_2$ to penetrate into any space larger than the size of $CO_2$ molecules (Liu et al. 2014; Wang et al. 2017). Therefore, SC-$CO_2$ can penetrate into micro-fractures that most other hydraulic fluids, including L-$CO_2$, cannot. This allows the SC-$CO_2$ to penetrate into the very fine crack tips to keep on wedge-opening the cracks and extending the fracture once initiated.

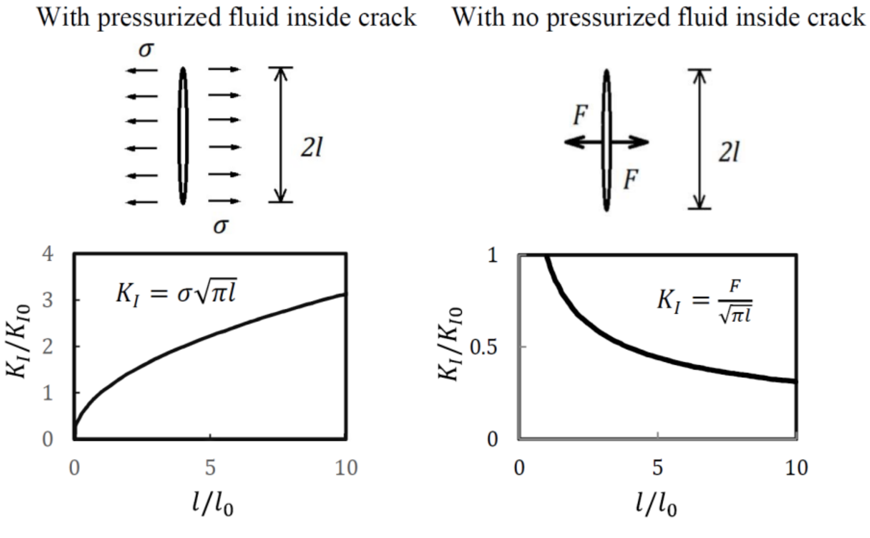

**Figure 5:** Stress intensity factor at crack tip

To better understand the importance of the hydraulic fluid penetrating into fine cracks, it should be noted that the hydraulic fluid does not just fracture the rock by exerting pressure onto the borehole wall. Ishida et al. (2004) fractured granite blocks by injecting a pressurized fluid (water or oil) directly into the borehole or inflating a urethane sleeve inserted into the borehole, and found that with direct fluid injection, the cracks formed propagated away from the borehole but with pressurization via the urethane sleeve (no fluid penetrating into the fracture), cracks were only formed in the vicinity of the borehole. Moreover, the breakdown pressure due to pressurization via the urethane sleeve was about three times that due to direct fluid injection. Ishida et al. (2004) explained this phenomenon by considering the stress intensity factor at the crack tip, as depicted in Figure 5. With a pressurized fluid inside the crack (direct fluid injection), the stress intensity factor increases with the crack length and thus the crack would propagate once formed. With no pressurized fluid inside the crack (pressurization via urethane sleeve), the stress intensity factor decreases with the increase in crack length and thus the crack would not propagate.

Moreover, Ishida et al. (2012) had conducted hydraulic fracturing experiments using SC-$CO_2$ (at temperature higher than the critical temperature) and L-$CO_2$ (at temperature lower than the critical temperature) in granite blocks, and revealed that SC-$CO_2$ tends to generate cracks extending more three dimensionally while L-$CO_2$ tends to generate cracks along a flat plane. More importantly, the breakdown pressure with the use of SC-$CO_2$ is lower than that of L-$CO_2$. They attributed such differences to the lower viscosity and higher compressibility of SC-$CO_2$ compared to L-$CO_2$. Ishida et al. (2013) had also conducted hydraulic fracturing experiments using SC-$CO_2$ and water in granite blocks under triaxial stresses, and revealed that the lower viscosity SC-$CO_2$ (viscosity of SC-$CO_2$ is only 5% of that of water) would induce more three dimensionally and widely spreading cracks under lower breakdown pressure than water. Putting these results together with their previous results, they concluded that the breakdown pressure is higher when the viscosity of the hydraulic fluid is higher and lower when the viscosity of the hydraulic fluid is lower.

## 2.2 Utilisation of SC-$CO_2$ in Rock Drilling

In rock drilling, the hydraulic fluid is pumped into the bottom of the borehole to pressurize the borehole at the bottom end and fracture the rock there. The hydraulic fluid is continuously injected into the bottom of the borehole through a packer with a seal to confine the hydraulic fluid for building up the pressure needed to fracture the rock. As the hydraulic fluid is injected through the packer, the pressure of the hydraulic fluid increases until it reaches the breakdown pressure at which the rock is fractured and then due to expansion of the hydraulic fluid into the cracks and voids formed, the pressure rapidly drops, as shown in Figure 6 (Kizaki et al. 2012).

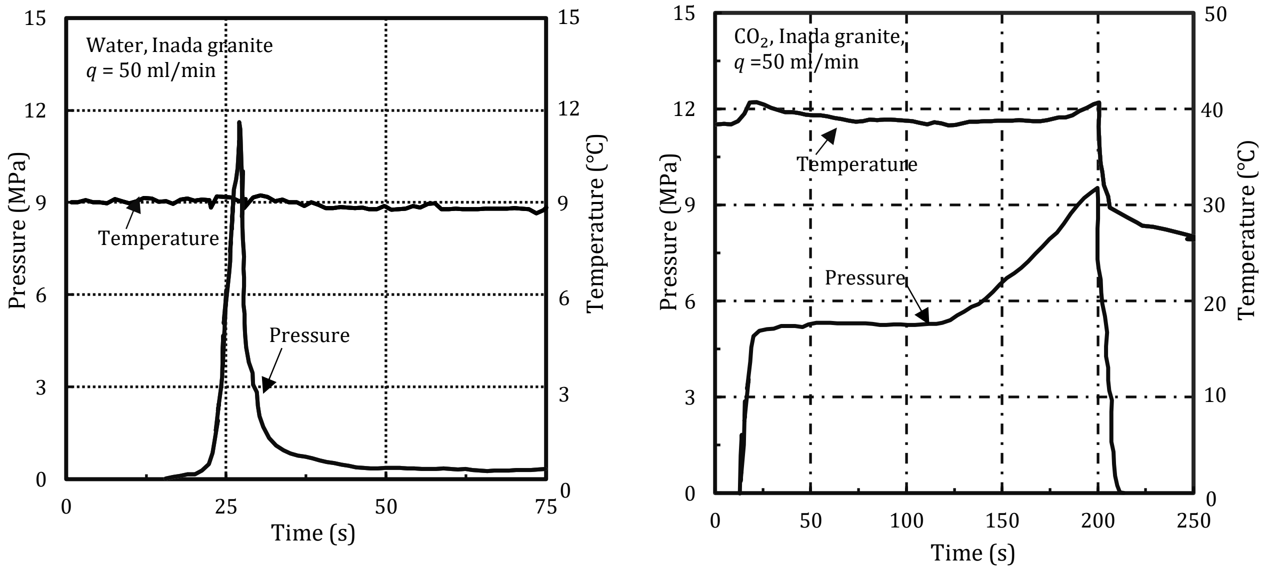

**Figure 6:** Temperature and pressure during hydraulic fracture of Inada granite

Kizaki et al. (2012) suggested that since SC-$CO_2$ has lower viscosity compared to that of L-$CO_2$, the SC-$CO_2$ has a higher tendency to permeate into fine pores and micro-cracks and is thus a better fracturing fluid in the making of a fractured reservoir with a high fracture density for applications such as carbon sequestration, geothermal energy extraction and recovery of oil and gas from depleted reservoirs. Liu et al. (2014) pointed out the problem that in deep wells, the $CO_2$ can usually reach the critical temperature to become supercritical, but in shallow wells, the $CO_2$ may not reach the critical temperature and thus heating may be required to transform the $CO_2$ to the supercritical state. They also mentioned that compared with the use of L-$CO_2$, the use of SC-$CO_2$ as the fracturing fluid can decrease the fracturing pressure and thus reduce the treatment cost. Wang et al. (2015) cited previous researches revealing that the use of SC-$CO_2$ jets to cut rock needs much shorter time and much lower threshold pressure, and to be specific, the threshold pressure for SC-$CO_2$ jet is just 2/3 of that for water jet when breaking granite and even less than one half of that for water jet when breaking shale. And, in oil drilling, SC-$CO_2$ will enhance single well production and recovery after entering the reservoir.

Apart from the above, the use of $CO_2$ also has the following advantages (Du et al. 2012): superior hole-cleaning performance, little formation damage, no reaction with clay to cause swelling of clay, can dissolve hydrocarbons and other chemicals to remove them in near-well formation etc. Added all up, there is a tendency of replacing other fracturing fluids by SC-$CO_2$.

## 3 Use Of SC-$CO_2$ for Rock Breaking

Currently, one the dominant methods of rock breaking for excavation is the drill and blast method (Persson et al. 1993; Lucca 2003). Basically, boreholes are drilled into the rock, a chemical explosive is filled into each borehole and then the explosive is detonated to trigger an explosion by which the explosive is instantaneously transformed into a hot and high-pressure gas. The sudden expansion of the explosive within a confined space produces an extreme gas pressure and imparts very large dynamic stresses to the surrounding rock. The extreme pressure exerted by the gas may exceed 1 GPa. After blasting, the borehole would be enlarged by the high pressure gas, the rock right at the borehole wall would be crushed, and the rock further away would be fractured as shown in Figure 7. Along with the violent rock fracturing, stress waves are produced, causing intensive deformation and vibration of the ground, and possibly damages to the nearby structures. There also may be air-blast and fly-rock, if the explosive was over-charged and/or the blasting area was not adequately covered. Hence, rock blasting, i.e., rock breaking using the drill and blast method, is a dangerous operation, and has to be very carefully controlled, especially in urban areas or in close proximity to sensitive receivers or green concrete, i.e. freshly cast concrete (Kwan & Lee 2000).

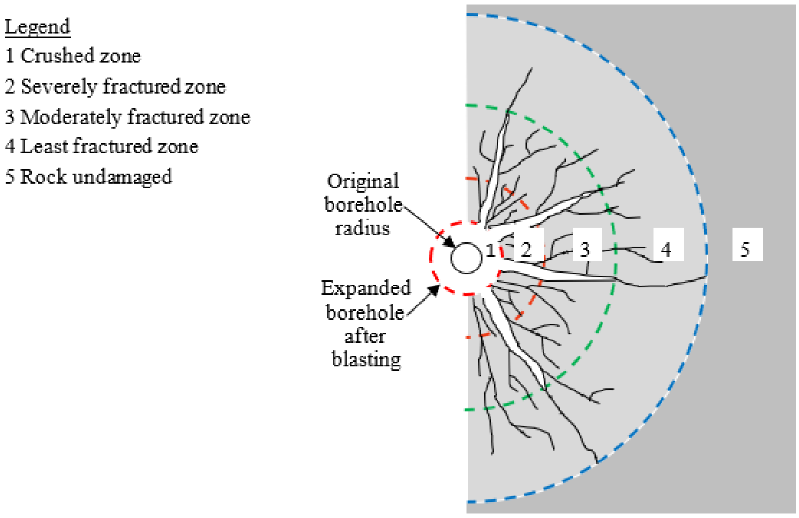

**Figure 7:** Rock mass damage after blasting

The success of hydraulic fracturing in rock drilling for petroleum extraction has gradually led to the extension of its applications to rock breaking for excavation, although some engineers are still skeptical about its ability to break strong rocks like granite and volcanic tuff. Ishida et al. (2004) applied the hydraulic fracturing technique to break granite under horizontal confining stresses of 3 MPa and 6 MPa, and found that with water or oil directly injected into the borehole, the breakdown pressure was only about 17 to 18 MPa. Kizaki et al. (2012) used water or SC-$CO_2$ as the hydraulic fluids to break granite and volcanic tuff under triaxial confining stresses of 1 MPa, 3 MPa and 5 MPa, and found that the breakdown pressure was only about 11 MPa when water was used and about 10 MPa when SC-$CO_2$ was used. Ishida et al. (2012) used SC-$CO_2$ and L-$CO_2$ to break granite under triaxial confining stresses of 1 MPa in each direction, and measured that the breakdown pressure was only 8.44 MPa when SC-$CO_2$ was used and 10.56 MPa when L-$CO_2$ was used.

Putting all the above results together, it seems that the breakdown pressure is dependent on the type of rock, the confining stresses and of course the type of hydraulic fluid used. Evidently, the use of SC-$CO_2$ as the hydraulic fluid would lead to the lowest breakdown pressure, which seems to be about 10 MPa. Compared to the extremely high gas pressure of the order of 1 GPa during blasting, which crushes the rock at the borehole wall and generates a huge shock to the ground, such a breakdown pressure during hydraulic fracturing of the order of 10 MPa is only about 1%. With the very much reduced explosion pressure (breakdown pressure) and shock produced, the ground deformation and vibration induced should be much smaller and thus the hydraulic fracturing technique using SC-$CO_2$ as the fracturing fluid should be much safer to employ than the blasting technique using a chemical explosive. Moreover, with the hydraulic fracturing technique employed, there is no explosive (which is Category 1 Dangerous Goods under the relevant Laws of Hong Kong) to be stored and delivered to the construction site. During transportation and storage, the carbon dioxide exists as liquefied $CO_2$ (which is Category 2 Class 2 Dangerous Goods (i.e. liquefied gas) under the Laws of Hong Kong), and it reaches supercritical state to become SC-$CO_2$ only during rock fracturing. Particularly, for close-in blasting (blasting within 20 feet or 6 metres as per Lucca (2003)), where there is less margin for error because of the proximity of structures affected by fly-rock and vibration effects, immediate considerations should be given to changing over to hydraulic fracturing using SC-$CO_2$.

## 4 Advantages and Disadvantages

### 4.1 Advantages of using SC-$CO_2$ in Rock Breaking

The hydraulic fracturing technique for rock breaking has the main advantages as listed below:

i. No chemical explosive is used and thus there is no need to store and deliver the explosive to the construction site, which can be very dangerous, especially if the site, storage area or route of delivery is close to any fuel tanks, densely populated areas or sensitive receivers.
ii. The breakdown pressure and shock produced are much smaller and thus the ground deformation and vibration induced would be much smaller. This would help to avoid causing damages to nearby structures, utilities and sensitive receivers, and in urban areas, also reduce the number of complaints.
iii. With the pressure of the fracturing fluid rapidly decaying as the fracturing fluid expands into the fractures and voids, there should be little risk of air-blast and fly-rock (nevertheless, for added safety, it is still recommended to provide some overburden to cover the rock breaking area).
iv. Overall, for rock breaking, the hydraulic fracturing technique using a fracturing fluid should be much safer than the blasting technique using a chemical explosive.

The use of liquefied and pressurized $CO_2$ as the fracturing fluid in hydraulic fracturing has the following additional advantages:

i. $CO_2$ is by nature a gas. As the pressure drops after the initiation of rock fracture, some of the $CO_2$ would be gasified to expand up to 600 to 700 times its original liquid volume, and thus would squeeze the $CO_2$ to penetrate into fine cracks to wedge-open the cracks and thereby extend the fracture.
ii. The breakdown pressure is lower when $CO_2$ is used as the fracturing fluid than when water or oil is used as the fracturing fluid.
iii. After the rock fracturing, the $CO_2$ would return to its gaseous state and thus simply escape without leaving behind any un-detonated explosive or chemical residues that might cause any danger or contamination.

The use of SC-$CO_2$ instead of L-$CO_2$ as the fracturing fluid in hydraulic fracturing has the following additional advantages:

i. SC-$CO_2$ has lower viscosity and stronger mobility than L-$CO_2$, and thus is more able to penetrate into very fine cracks to wedge-open the cracks and thereby extend the fracture. As a result, the breakdown pressure is even lower when SC-$CO_2$ is used instead of L-$CO_2$ as the fracturing fluid.
ii. Both SC-$CO_2$ and L-$CO_2$ are 100% $CO_2$. The only process needed to convert L-$CO_2$ to SC-$CO_2$ is to apply heating to raise its temperature to well above the critical temperature of 31.1°C. Actually, the pressurization of the $CO_2$ would already slightly increase the temperature through adiabatic compression.

### 4.2 Disadvantages of using SC-$CO_2$ in Rock Breaking

Regarding the disadvantages, the major disadvantage is that the use of SC-$CO_2$ in the construction industry in Hong Kong is still new and is not supported by abundant field data. Most construction professionals are not familiar with this new rock breaking technology, albeit the use of SC-$CO_2$ in the petroleum industry is already quite common. Construction professionals are by training extremely careful and very conservative in employing any new technology, which at the beginning, does not have any job reference. In this regard, it is recommended to carry out some field trials, with the temperature and pressure of the $CO_2$, borehole pressure, shock vibration, extent of rock fracture, any air-blast and any fly-rock etc. recorded for detailed study and analysis. More basic research on this new technology, especially on the data collection and safety related issues, should also be carried out to develop guidelines so that eventually, this newer, more advanced and theoretically safer technology could be adopted in a larger scale.

## 5 Applications in Construction Projects

The SC-$CO_2$ technology has been successfully applied to numerous construction projects in real-life, as exemplified in the following. Figure 8 illustrates the application to site formation works for Zhanghua Highway construction in Hunan Province, China in year 2017-2018. The volume of rock breaking was approximately 0.2 million $m^3$ and the rock type was mainly shale. Figure 9 illustrates the application to basement excavation for a building project in Loudi, Hunan Province in 2019, with the volume of rock breaking of approximately 50000 $m^3$. Pioneering applications to special cases have been carried out and proven successful. For example, tunnel portal excavation with very limited rock overburden for Bailushi Tunnel in Yiyang, Hunan Province (Figure 10) in 2018; as well as underwater rock fracturing in Guangxi Province (Figure 11) in 2020. For the latter case, fish survey was conducted in the vicinity of works and the results demonstrated that the fishes were not harmed by the works. The experience gained from the past construction projects provides confidence and serves useful reference for extending the application of SC-$CO_2$ technology to wider project settings. After the turn of year 2020, two large-scale mining projects in Yunnan Province, China with the employment of SC-$CO_2$ technology have been ongoing.

**Figure 8:** Site formation for highway project using SC-$CO_2$

**Figure 9:** Basement excavation for building project using SC-$CO_2$

**Figure 10:** Tunnel portal excavation using SC-$CO_2$

**Figure 11:** Underwater rock fracturing using SC-$CO_2$

## 6 Conclusions

Rock breaking for excavation by blasting using a chemical explosive, i.e. by the drill and blast method, is potentially dangerous and risky by nature. The shock, vibration and air-blast generated during blasting may cause damages to nearby structures and sensitive receivers, and arouse complaints because ground shaking and loud noise could be scary to some people. This situation is not entirely satisfactory and sustainable. It is now about time to explore and develop a more advanced and safer method of rock breaking for excavation. On the other hand, hydraulic fracturing using L-$CO_2$ (liquid carbon dioxide) or SC-$CO_2$ (supercritical carbon dioxide) as the hydraulic fluid has been successfully applied to rock drilling for petroleum extraction and is already quite common in the petroleum industry. This hydraulic fracturing technology has also been proven to be powerful enough to break strong rocks like granite and volcanic tuff. Hence, this hydraulic fracturing technology may also be applied to rock breaking for excavation. Relatively, the use of SC-$CO_2$ would lead to a lower breakdown pressure and more extensive fracture, and thus should be a better hydraulic fluid to use. Overall, since no explosive is used and the breakdown pressure is only a very small percentage of the extremely high gas pressure of around 1 GPa during blasting, this hydraulic fracturing method should be much safer than the conventional rock blasting method. It is thus advocated here that it is time to change to adopt the more advanced and safer method of hydraulic fracturing using SC-$CO_2$. To promote the use of this new technology, it is recommended to carry out field trials in Hong Kong to gain confidence and more basic research to develop guidelines for the local industry to follow.

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## References

Bennour, Z., Ishida, T., Nagaya, Y., Chen, Y., Nara, Y., Chen, Q., Sekine, K. & Nagano, Y. 2015. Crack extension in hydraulic fracturing of shale cores using viscos oil, water and liquid carbon dioxide. Rock Mechanics and Rock Engineering, 48(4): 1463-1473.

Du, Y.K., Wang, R.H., Ni, H.J., Li, M.K., Song, W.Q. & Song, H.F. 2012. Determination of rock-breaking performance of high-pressure supercritical carbon dioxide jet. Journal of Hydrodynamics, 24(4): 554-560.

Ishida, T., Chen, Q., Mizuta, Y. & Roegiers, J.C. 2004. Influence of fluid viscosity on the hydraulic fracturing mechanism. Transactions of the ASME, 126: 190-200.

Ishida, T., Aoyagi, K., Niwa, T., Chen, Y., Murata, S., Chen, Q. & Nakayama, Y. 2012. Acoustic emission monitoring of hydraulic fracturing laboratory experiment with supercritical and liquid CO2. Geophysical Research Letters, 39: L16309.

Ishida, T., Nagaya, Y., Inui, S., Aoyagi, K., Nara, Y., Chen, Y., Chen, Q. & Nakayama, Y. 2013. AE monitoring of hydraulic fracturing experiments conducted using CO2 and water. In M. Kwaśniewski & D. Łydżba (ed.), Rock Mechanics for Resources, Energy and Environment. Taylor & Francis, 957-962.

Kizaki, A., Tanaka, H., Ohashi, K., Sakaguchi, K. & Matsuki, K. 2012. Hydraulic fracturing in Inada granite and Ogina tuff with super critical carbon dioxide. Proceedings, 7th Asian Rock Mechanics Symposium. Seoul, Korea, 1-8.

Kwan, A.K.H. & Lee, P.K.K. 2000. GEO Report No. 102: A Study on the Effects of Blasting Vibration on Green Concrete, Geotechnical Engineering Office, Hong Kong Government.

Liu, H., Wang, F., Zhang, J., Meng, S. & Duan, Y. 2014. Fracturing with carbon dioxide: Application status and development trend. Petroleum Exploration and Development, 41(4): 513-519.

Lucca, F.J. 2003. Effective Blast Design and Optimization, Terra Dinamica L.L.C.

Lv, Q., Long, X.P., Kang, Y., Xiao, L.Z. & Wu, W. 2013. Numerical investigation on the expansion of supercritical carbon dioxide jet, IOP Conference Series: Materials Science and Engineering, 52: 072011.

Persson, P.A., Holmberg, R. & Lee, J. 1993. Rock Blasting and Explosives Engineering, CRC Press.

Roland, R. & Wagner, W. 1996. A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. Journal of Physical and Chemical Reference Data, 25(6): 1509-1596.

Wang, H., Li, G., He, Z., Shen, Z., Wang, M. & Wang, Y. 2017. Mechanism study on rock breaking with supercritical carbon dioxide jet. Atomization and Sprays, 27(5): 383-394.

Wang, H., Li, G., Shen, Z., Tian, S., Sun, B., He, Z. & Lu, P. 2015. Experiment on rock breaking with supercritical carbon dioxide jet, Journal of Petroleum Science and Engineering, 127: 305-310.

Zhang, Y., Deng, J., Ke, B., Deng, H. & Li, J. 2018. Experimental study on explosion pressure and rock breaking characteristics under liquid carbon dioxide blasting. Advances in Civil Engineering, 2018: Article 7840125.