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Mechanical Properties of Abandoned and Closed Roadways in the Kushiro Coal Mine, Japan

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ABSTRACT

The objective of this research is to clarify the mechanical properties and self-healing ability of Excavation Damaged Zone (EDZ) around rock caverns in clastic rock. Observations of nearly 100 closed roadways up to 50 years old, which can be regarded as very severe EDZs with no initial sealability and are up to 300 m deep in clastic rock, were made at Kushiro Coal Mine, Japan, to accomplish the objective. Most old roadways were closed, though a few remain open. Closure of old roadways was mainly due to roof deflection and/or floor heave. Large plastic deformations dominated; however, severe fractures were seldom observed in closed old roadways. Rayleigh wave velocity and hydraulic conductivity in the closed old roadways were in the range of 0.3 km/s to 1.2 km/s and 5×10^{-7} *m/s to* 1×10^{-7} *m/s, respectively, and*

those in EDZ and EdZ (Excavation disturbed Zone) around recently excavated roadways were 1.1 km/s to 1.8 km/s and 1 × 10^{-8} m/s to 5 × 10^{-8} m/s, respectively. The extent of EDZ around the present tailgate was in the range of 1 m to 5 m. Mechanical excavation and prevention from water are suggested as the key points for long-term maintenance of rock repositories. Pressurization from inside the cavern to decrease the permeability of EDZ is proposed for maintenance of rock repositories in medium-hard clastic rock masses at similar depths for long periods.

Keywords: EDZ; Permeability; Rayleigh wave velocity; Old roadways; Medium-hard clastic rocks.

1. Introduction

Region where irrecoverable damage or elastic deformation takes place appears around deep rock repositories for geological disposal. The former is called EDZs (Excavation Damaged Zones) and the latter EdZs (Excavation disturbed Zones) as described in Tsang et al. [1]. Generally speaking, permeability in EDZs is much higher than in intact rock masses, and the sealability of a rock cavern would be significantly compromised by high permeability. Mechanical properties for EDZ and EdZ of crystalline rock, rock salt, indurated clay and plastic clay can be found in Tsang et al. [1]. Mechanical properties of EDZ and EdZ for medium-hard clastic rocks, however, were not given in Tsang et al. [1].

Reasonable designs for geological disposal repositories could be established if sealability of EDZs recovered with time. Self-healing properties of rock salt and clays were also summarized in the above reference. There have been observations, unpublished as technical papers, in Japanese mines that loosened clastic-rock blocks, which can be regarded as a very severe EDZ, consolidated with time under pressure. This phenomenon is a type of self-healing of fractured clastic rocks.

The objective of this research is to clarify the mechanical properties and self-healing ability in EDZs around rock caverns in medium-hard clastic-rock masses. To accomplish the objective, comparisons will be introduced in this paper between Rayleigh wave velocities and permeabilities in abandoned and closed

roadways as old as 50 years, which can be regarded as very severe EDZs with zero initial sealability, and those in EDZs and EdZs around recently excavated roadways in clastic rocks as deep as 300 m.

The site, geology and the observed old roadways with surrounding mining activities are first described. Next, the observations at the old roadways are explained. Then the results of in-situ experiments are described. Mechanisms of old roadway closure are discussed based on the results of observations and experiments, along with results of some additional in-situ and laboratory experiments. Finally, findings are summarized aiming to give valuable information about mechanical and self-healing properties of EDZs around caverns in medium-hard clastic rocks.

2. Mine, Geology and Observed Sites

Coal mining in Kushiro, Japan began in 1857 at the Yamada Coal Mine. Mining continued at the Taiheiyo Coal Mine from 1920 to 2002 under the Pacific Ocean. The maximum depth was approximately 700 m below sea level, and the maximum annual production was approximately 2.6 Mt in 1977. The mine was closed because overseas coals became cheaper, and the Kushiro Coal Mine inherited the mining rights. Kushiro Coal Mine produces coal at a rate of 0.7 Mt/year by excavating coal seams which remained from excavation of Taiheiyo Coal Mine toward shallower levels. Usually, old roadways do not appear at mining faces or roadway sidewalls because mines toward deeper and used roadways are immediately back-filled and abandoned in coal mines. However, under the special circumstances stated above, roadways as old as 50 years appear at mining faces or sidewalls at the Kushiro Coal Mine. Almost 100 old roadways were observed and recorded as sketches and photographs. Rayleigh wave velocity measurements, permeability measurements and other in-situ tests were carried out at some of the closed roadways.

Taiheiyo Coal Mine workers excavated Eocene coal seams under the Pacific Ocean. The coal seams incline at approximately 5 degrees towards the sea. Coal seams named Upper, Main and Lower seams were excavated (Fig. 1). Rocks around the coal seams consist of shale, sandy shale, siliceous rock (altered

tuff) and clay. All rocks contain smectite and exhibit slaking behavior. Siliceous rock thickly dominates the area between the Main and Lower seams.

Old roadways were observed at 95 sites during the mining of the longwall panels, which are shown in Fig. 2 and are between 205 m and 308 m below sea level (Table 1). The old roadways were excavated between 40 and 50 years ago and later abandoned (Table 2). They appeared at the faces or sidewalls of the gate roadways of the mining panels. Old roadways on the mining faces were suitable for sketches and photographs but time-consuming experiments cannot be carried out because mining faces move. Old roadways on the sidewalls of gate roadways are not suitable for observation because there are steel arches and wood supports on the sidewalls. However, they are suitable for in-situ experiments because they are maintained until the face reaches the experiment sites.

Old roadways were back filled by (1) thickened waste water from coal processing, (2) a mixture of fly ash and water, (3) a mixture of fly ash, cement and water or (4) a mixture of rock powder, cement and water. The slurry for back filling was made thin for workability. For example, water comprised 50% of the volume for the mixture of fly ash and water. Back filling was carried out just after to 27 years after abandonment and 7 months to 34 years before observation (see Table 2 for detail) by any of the following two methods:

(1) Drill method

Drill holes were made from a roadway at a shallow level to old roadways by the "room method", which denotes coal recovery through branch-like roadway excavations made by continuous miners. Some parts were left unfilled because the number of the drill holes was limited.

(2) Mound method

A mound was made, and deeper parts were back filled. This procedure was iterated. Numbers of unfilled parts may be less than produced by the drill method. However, the density of the filling material in the upper part was lighter than the lower part because the filling slurry is thin.

The ground-water level deepened with increases in depth from further excavations after the old roadways were excavated by Taiheiyo Coal Mine. It was confirmed that the ground water level was deeper by 50 m or more than at the sites of observation. Seawater never invaded the underground workings, although the excavation was carried out under the Pacific Ocean.

3. Effect of water on the physical properties of sandstone sampled from the roof of the Main seam

Cylindrical specimens with a diameter 50 mm and length 35 mm were taken and dried in a desiccator for two weeks. The specimens were immersed into either distilled water, a brine of 3.3% by weight or a sulfuric acid solution of 0.025 mol/l. Specimens immersed in the brine did not collapse during the observation period of two weeks. Specimens immersed in distilled water or the sulfuric acid solution, however, started to collapse two days after the test began.

Uniaxial compression tests and Brazilian tests were carried out for sandstone specimens with a diameter of 30 mm and a length of 60 mm for uniaxial compression or 30 mm for Brazilian tests. Rocks were vacuum-packed immediately after sampling and were prepared with tap water. They were immediately tested or tested after drying at room temperature for several days. Strengths showed the strong negative correlations with water content (Fig. 3).

4. Case studies for old roadways

4.1 Jobu Hidari Lower Seam No. 1 SD

Old roadways in this mining panel were level roadways with a square or trapezoid cross section and were supported by 3-part wooden frame. They were excavated by continuous miners, used for approximately three years, and sealed when abandoned. Then the roadway was back filled by the mound method. The main seam was excavated in 2003 (Table 2). Most old roadways were completely closed by significant roof deflections (Figs. 4 and 5). Siliceous rock and clay exhibited large plastic deformations and filled the

space between the almost-unfractured roof and floor.

4.2 Jobu Hidari No. 6 SD

Old roadways in this mining panel were another level roadway. Sections, support, excavation methods and filling conditions were the same as stated above. The Main seam was excavated in 2002 (Table 2). Most old roadways were completely closed. Some were closed by significant floor heaving (Fig. 6), and some were closed by fragments of the roof and the filling-material mixture of fine coal powder produced during coal processing (Fig. 7).

4.3 Jobu Hidari No. 5 SD

Old roadways in this mining panel were roadways made by the room method (Section 2). Sections, supports and mining equipment were substantially the same as those above. The roadways were sealed several months after mining and abandoned. The roadway was filled by the drilling method. Most old roadways were completely closed by significant roof deflections and softened roof rocks (Figs. 8 and 9) or by significant floor heaving (Fig. 10).

4.4 Jobu Chuo No. 0 SD

Old roadways in this mining panel were roadways of the room method. Sections, supports, mining equipment and filling methods were substantially the same as those above. Some completely open old roadways were still observed (Fig. 11). Piles of thin slabs of roof shale were observed.

4.5 Jobu Chuo No. 1 SD

Old roadways in this mining panel were inclined main roadways with arch sections that were excavated by blasting and supported by steel arches. The roadways were used for 46 years and were back filled by the mound method 7 to 10 months before the observation. The rock masses above and below the

roadways were well observed, although the roadway itself seldom appeared on the face.

When the old roadway was below the face, significant roof deformations were observed (Fig. 12). Shear fractures in the sidewalls were also observed when the roadways were almost in the working coal seam (Fig. 13). Significant floor deformations were observed for old roadways located above the working coal seam, even though the distance between the coal seam and the roadway was 6 m (Fig. 14).

5. Case study for a longwall goaf

The Lower seam was first mined at Jobu Hidari No. 6 SD; the face moved to the Main seam because the Main seam near the starting point had already been mined 52 years ago. The 52-year-old longwall goaf in the Main seam was observed when the face switched from the Lower seam to the Main seam. The longwall goaf was completely closed, and there was no aperture between the sandy shale seam and the thin sandy shale seam that formed the immediate roof and the floor of the Main seam, respectively (Fig. 15).

Longwall goafs are generally filled by rock blocks of various sizes, an effect which was also confirmed in this mine. The excavation of the Lower seam was carried out several months to several years after the excavation of the Main seam in this mine. There were several experiences in other mining panels in which rock blocks from the longwall goaf of the Main seam fell into the face of the Lower seam. However, there was no such accident during mining of the Lower seam in Jobu Hidari No. 6 SD. The observed longwall goaf was considered to be consolidated for 52 years and was strong.

6. In-situ tests for physical properties in closed old roadways and virgin rock mass

Electrical devices basically cannot be used in Japanese coal mines. Efforts were made to reduce usage of those devices when planning the following tests, which is one of the reasons that some of the following

tests may appear out-dated. However, the authors believe that the results are significant even though the accuracy was limited. Electric devices using the least power were used by special permission.

6.1 Rayleigh wave velocity

Measurements were carried out at sidewalls of the tailgate for Jobu Chuo No. 0 SD. Holes 300 mm deep with diameters of 24 mm were drilled at the apices of two rectangles with side lengths between 1.5 m and 3 m on the sidewall or roof. Rock bolts 300 mm long were grouted by resin. One of the rectangles was drawn on the closed old roadway surface and the other rectangle on the surface of the virgin field next to the old roadway. The latter is called "virgin" in this paper to distinguish it from the closed old roadways (old and severe EDZ), although the latter would normally be considered a "fresh" EDZ.

One of the rock bolts was hit by the impulse hammer (RION, PH-61, 2 Hz to 10 kHz), and an elastic wave was received by accelerometers (TEAC, 706, 3 Hz to 14 kHz, 10 mV/m/s^2) fixed by magnet mounts (TEAC, MG-707) at the heads of the other rock bolts. Signals were amplified by a dry battery-operable preamplifier (TEAC, SA-610H, 0.2 Hz to 30 kHz) by 40 dB, and 100 pre- and 900 post-trigger data points at ±10 V and 14 bits were recorded for each accelerometer at 40 kHz by a dry battery-operable data logger (Keyence, NR-2000).

The response amplitudes and the dominant frequencies (Table 3) at the surface of the closed old roadway were much smaller than those at the surface of the virgin field. The obtained Rayleigh wave velocities for the surface of the virgin field seemed slightly small, which is likely due to the EDZ 1 m to 5 m around the tailgate, as shown in the next section. The Rayleigh wave velocity and the dominant frequency at the surface of the closed old roadway were 0.3 to 0.7 times and 0.2 to 0.5 times those at the surface of the virgin field, respectively.

6.2 Lugeon tests

Tests were carried out at the tailgate of Jobu Hidari No. 6 SD. Two horizontal boreholes with 55 mm

diameters were drilled at both the closed old roadway and the virgin field. Gas pipes with 20 mm diameters were inserted into the drill holes and grouted with a hard-formed resin, except for the deepest 1-m part for pressurizing. The deepest 1-m part was pressurized by air pressure and then water pressure while recording flow rate Q. Ordinary supplied compressed air and water from the ground surface were regulated and used for pressurization.

Permeability k_0 was calculated with the following equation.

$$k_0 = \frac{\mu_a Q}{2\pi L p} \ln\left(\frac{L}{R}\right) \tag{1}$$

where μ_a is viscosity of the pressure fluid, Q is the flow rate, L is the pressurized length, R is the borehole radius and p is pressure. Permeability was converted to hydraulic conductivity k by the following equation, even if air was used for pressure fluid, for the sake of easy comparison:

$$k = \frac{g\rho_W}{\mu_W} k_0 \tag{2}$$

where g is gravitational acceleration, ρ_W is the density and μ_W the viscosity of water. The hydraulic conductivity estimated here includes some ambiguity because Eq. (1) is only valid for a dry rock mass with air injection and a saturated rock mass with water injection, but the rock mass was considered to be partially saturated before the test as already stated in Section 2. Injecting air prior to the injection of water should decrease the saturation ratio.

The 2-m hole in the closed old roadway showed the least pressure at the largest flow rate in the air test series (Fig. 16). It was impossible to raise pressure beyond than the critical pressure. The 5-m hole in closed old roadway and the 2-m hole in the virgin rock mass exhibited critical pressures beyond which the slope of the flow rate-pressure curves decreased. The 5-m hole in the virgin rock mass did not reach critical pressure up to 0.28 MPa.

Table 4 summarizes the hydraulic conductivities, converted from permeabilities, that were calculated based on the smallest air-pressure data. The hydraulic conductivities for the 2-m holes were 3 to 4 times larger than those for the 5-m holes in both the closed old roadway and the virgin rock mass, which is due

to the EDZ around the tailgate. Comparing the old roadways and virgin rock mass, hydraulic conductivities for the former were 30 to 40 times those of latter. Due to a water leak (2-m hole) and an insufficient flow rate to monitor (5-m hole), the water-test series did not give results for the virgin rock mass but gave results for the closed old roadway, which were similar to the air test series (Table 4).

7. In-situ tests for closure of roadways and longwall goafs

7.1 Steel arch removal test at Jobu Hidari No. 5 SD (Fig. 2)

Steel arches at the tailgate just next to the longwall coal face were removed, and rock mass collapses were observed. A small roof fall occurred when three steel arches were removed (an unsupported span of 3.4 m). The tailgate was completely collapsed by fallen rock blocks up to 1 m in size due to a large roof fall that occurred when two more steel arches were removed (unsupported span of 5.1 m). Those rock blocks were obviously from EDZ around the tailgate under the abutment pressure of the longwall mining panel.

7.2 Steel arch removal test at a test roadway

The test roadway was located 239 m below sea level, away from mining areas (Narasaki et al. [2]). The test was carried out on May 24, 2006. There was no large roof fall, even after 15 steel arches were removed; the unsupported span reached 16 m without large roof falls, except for rather small falls of loosened rocks that were as large as tens of centimeters. The EDZ around the test roadway seemed to be smaller than that around the tailgate because the test roadway was far away from mining areas. A few months later, in August and September, humid summer air flowed into the site; dripping water was seen on the rock surface, and several large rock falls, as large as 2 m, occurred. It is estimated that the rock mass was weakened by the humid-air inflow and the large-scale roof falls were induced.

7.3 Test on stress recovery at longwall goaf

The test was carried out at the tailgate for Jobu Hidari No. 5 SD (Fig. 2). The floor was smoothed, and a pressure sensor was placed on the smoothed surface, covered by gravel. The pressure sensor was a 30 cm x 30 cm flat jack sandwiched by a pair of 1-mm thick steel plates. A spring-driven nonelectric data recorder was placed at a safe place, and a 100-m long stainless steel tube connected the pressure sensor and the recorder.

Monitoring started when the face was 3.5 m behind the sensor. The face position was 5.4 m ahead of the sensor on Sept. 21, the day after the installation. The mining was finished on Sept. 28, when the face was 34 m ahead of the sensor, and monitoring was continued for 2 months longer. The resolutions of the recorders for both the pressure and time were not precise enough but the pressure recovered to approximately 0.3 MPa by Sept. 28 and kept an almost-constant value.

8. In-situ test on EDZ around present roadways

The extent of the EDZ around the present roadways are already partially shown; the virgin field rock around the present tailgate yielded at 2 m deep from the sidewall and did not yield at 5 m deep (Section 6) in Lugeon tests. More precise tests are described in this section. One is similar to a Lugeon test using air, but the pressurized part was divided with a double packer to obtain a permeability distribution along the borehole depth. The other measures Young's modulus distribution along boreholes using a Goodman jack.

8.1 Permeability distribution along the borehole depth

The instruments were almost the same, but a double packer was used to divide the pressurized part at 0.5 m. The test was carried out in a 15-m long and 15-degree upward borehole drilled in the sandstone seam at the tailgate of Jobu Hidari No. 5 SD (Fig. 2) before the abutment pressure appeared. Permeability was on the order of 10^{-11} m^2 less than 4 m deep and on the order of 10^{-12} m^2 or less for depths more than 4 m (Fig. 17). It is estimated that the rock mass within 4 m from the sidewall was an EDZ. It was impossible

to carry out the test due to borehole collapse when the face reached 5 m to the borehole.

8.2 Distribution of Young's modulus along boreholes

Young's modulus of rock mass was measured with a Goodman jack. Tests were carried out at the tailgate of Jobu Hidari No. 5 SD (Fig. 2). The first test was carried out for a horizontal borehole drilled from the sidewall into the virgin field of siliceous rock. The UCS and the Young's modulus of the intact saturated specimen were 52 MPa and 12 GPa, respectively. Loading was carried out in three directions: vertical and 120 degrees and 240 degrees from vertical. A significant anisotropy was not observed in this plane (Fig. 18). Young's modulus for rock mass within 1 m from the sidewall was much smaller than that for rock mass deeper than 1.5 m. The EDZ boundary was estimated to be between 1 m and 1.5 m from the sidewall.

The second test was carried out in the sandstone borehole for a Lugeon test by air for measuring a permeability distribution, as stated in the previous section, when the face approached 5 m to the borehole. Loading was carried out only in the EDZ. Small values of Young's moduli were obtained showing yielding of rock mass around the tailgate.

9. Laboratory test on hydraulic conductivity of a fractured rock specimen

A permeability test for a sandstone core sampled from Jobu Hidari No. 6 SD roof was carried out to obtain basic knowledge on hydraulic conductivity of fractured rock. The sample was vacuum-packed at the site, and a 60-mm long, 30-mm diameter cylindrical rock core was taken immediately after unpacking. The core was vacuum-saturated in pure water. End pieces were installed into it, and the core and end pieces were jacketed by heat-shrink tubing.

The jacketed specimen was inserted into an ultra-compact triaxial vessel (Fujii & Kondo [3]). This ultra-compact pressure vessel is basically a stainless steel cylinder with grooves for O-rings. Triaxial

compression tests under confining pressures up to 30 MPa can be easily carried out using the ultra-compact triaxial vessel, a pair of end pieces made of stainless steel, heat-shrink tubing, a heat gun and hydraulic pumps, aside from the usual apparatus for a uniaxial compression test. Although strain was not measured in this experiment, strain gages can be glued to the specimen sides and cables, which should be as thin as 0.3 mm and can be trained between the specimen and the heat-shrink tubing to the atmospheric pressure so that special outlets that connect the inside and outside of the vessel are not required for strain measurement. A pair of attachments was used to supply pore water.

The specimen was consolidated for 10 hours under a hydrostatic pressure of 5 MPa and pore pressures of 2 MPa (upstream) and 1 MPa (downstream). The platen was stopped for 1 week after the specimen was compressed axially to show peak stress and residual state under the drained condition. Slight stress relaxation was observed during the week. The confining pressure was increased to 11 MPa for a week and then decreased to 5 MPa for a week.

Hydraulic conductivity increased with specimen failure (Fig. 19); however, it gradually decreased with time in the residual state and reached almost the same level as that for the intact rock specimen. Hydraulic conductivity decreased with the increase in confining pressure and then increased with its decrease. The variation of hydraulic conductivity with confining pressure looked reversible and associated with elastic deformation of the rupture plane. Similar results on Kimachi sandstone can be seen in Takada & Fujii [4].

The specimen was immersed into blue resin, and a thin section was made after the resin hardened. Fracture closures and poorly connected tortuous fractures were observed in the thin section (Fig. 20). These were likely the causes of the decrease in hydraulic conductivity with time in the residual state. The mechanism of the fracture closure should be considered further. The authors, however, think that the fracture closure occurred mainly by crushing of the mineral particles and visco-elastic deformation around the rupture plane and not by the pressure solution because the duration and temperature were much shorter and lower than those deep underground where the pressure solution dominates.

10. Discussion

10.1 Mechanisms of roadway closure

The UCS of dry coal from the sites is approximately 20 MPa. Assuming the unit weight of rock mass is 25 kN/m^3, vertical stresses for the 205-m to 380-m deep old roadways would be 5.1 MPa to 9.5 MPa. The competence factor was calculated as 3.9 to 2.1, or 2.2 to 1.2 when correcting for excavated area. A small EDZ could develop under the competence factor of these levels.

An EDZ would likely have developed under the influence of the abutment pressure and roadside pressure of mining activity around the old roadways. In particular, the roadway observed in Jobu Chuo No. 1 SD was significantly damaged by the surrounding mining activity. The roadway was enlarged many times when damaged, and the total excavated volume reached several times the roadway volume.

However, the complete closure of the old roadways cannot be explained only by the above stress because the deformations seen in the closed old roadway, namely significantly deflected roofs and severe floor heaves, were completely different from the loosened rock blocks in the EDZ under abutment pressure seen in the artificial roof fall test in Section 7.1.

The key factor to the closure of the old roadways was likely water. In fact, the rocks in this coal mine are significantly weakened by water, as shown in Section 3. Humidity of inflow air also significantly affected roadway stability, as shown in Section 7.2. The unclosed old roadways were sealed, and air inflow was shut down. This procedure prevented the inflow of the humid air, thereby maintaining the stability of old roadways. Slurry back filling also supplied enough water for closure. Slurry should have reached everywhere when the mound method was used for back filling and all old roadways back filled by the mound method were closed. Slurry was not observed in the unclosed old roadways at the Jobu Chuo No. 0 tailgate.

The large deflection of roof and floor were likely due to decreases in Young's modulus due to water

supply. Numerically calculated deformations around a circular tunnel also show inward displacements that are larger at the centers of roofs or floors than at the sidewalls.

On the other hand, stress seems to have dominated for the longwall goaf because of its tabular geometry, although the measured stress recovery in Section 7.3 was just 0.3 MPa. Stress recovery was likely larger in the middle of longwall goafs, as shown in the results from a deeper level in the same mine (Sato et al. [5]). Stress recovery phenomenon could explain why the 52-year-old longwall goaf in Section 5 was strong enough and showed no roof fall.

10.2 Proposal for design and construction of rock repositories for long-term use

Some old roadways were open for 50 years supported only with wooden props in approximately 300-m deep medium-hard clastic-rock mass, which means that rock repositories in the similar medium-hard clastic-rock mass and at a similar depth can be maintained for 10 to 100 years if excavation damage and contact with water are prevented. Mechanical excavation with limited water usage and shotcrete are examples of such a solution. There would be high-permeability EDZs around the opening even if the rock repository itself was maintained by the above efforts. It would be useful to pressurize the EDZ from inside the rock cavern to decrease the permeability of the EDZ, as shown in Section 9, just as in Opalinus clay (Buehler et al. [6]). This outcome could be achieved with a bentonite-sand mixture as the filling material for the rock cavern and would be one more advantage in addition to those known for bentonite-sand mixture used as filling material, namely, its low permeability and expansion, which prevent apertures between inside surfaces of the opening and the filling materials.

11. Concluding remarks

Almost 100 old roadways, some as old as 50 years, were observed at Kushiro Coal Mine in Japan. Most of the old roadways were closed, while a few unclosed old roadways remain. Closure of old roadways was mainly due to roof deflection and/or floor heave. Large plastic deformations dominated; however,

severe fractures in closed old roadways were seldom observed. Longwall goafs from 52 years ago had enough strength to retain face stability.

The main findings on the mechanical properties of the closed old roadways are as follows.

(1) Rayleigh wave velocities at the surfaces of the closed old roadways and virgin fields (EDZs around the present roadways, see Section 6.1) were in the range of 0.3 km/s to 1.2 km/s and 1.1 km/s to 1.8 km/s, respectively.

(2) Dominant frequencies at the surfaces of the closed old roadways and virgin fields were in the range of 0.3 kHz to 0.6 kHz and 0.8 kHz to 3.1 kHz, respectively.

(3) Hydraulic conductivities in the closed old roadways and the virgin fields were in the range of 5×10^{-7} m/s to 1×10^{-5} m/s and 1×10^{-8} m/s to 5×10^{-8} m/s, respectively.

The main findings from the various in-situ tests are as follows.

(1) The tailgate under the abutment pressure was completely collapsed by fallen rock blocks of various sizes, up to 1 m, when the unsupported span reached 5.1 m.

(2) Test roadways away from the mining areas did not show large roof falls, even though the unsupported spans reached 16 m. Severe rock falls as large as 2 m occurred after humid summer air flowed into the site.

(3) Stress recovery in the longwall goaf was confirmed at the tailgate.

(4) Extents of EDZs around the present tailgate were in the range of 1 m to 5 m.

The mechanisms for the deformation of old roadways considered the results of the in-situ tests, laboratory tests and numerical analyses. It was realized that mechanical excavation and prevention from water are the key points for long-term maintenance of rock repositories. Proposals for maintaining rock repositories in medium-hard clastic-rock masses at similar depths for a long time were made, based on the above discussion. The proposals mention not only the use of mechanical excavation and prevention of water but also pressurization from inside the cavern to decrease permeability of the EDZ, based on the laboratory result from the permeability tests under triaxial compression.

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Table 1 Sites of old roadway observation

Sites	Depth		Coal seam	Old roadway position		
	SL (m)	Sea depth (m)		In working seam	Roof	Floor
Jobu Hidari Lower Seam No. 1 SD	340-355	23-25	Lower Seam	10	0	0
Jobu Hidari No. 6 SD	310-205	20-5	Lower and Main Seam	24	4	4
Jobu Hidari No. 5 SD	205-335	5	Main Seam	23	0	0
Jobu Chuo No. 0 SD Tailgate	318-323	20-25	Main Seam	5	0	0
Jobu Chuo No. 1 SD	380-307	28-20	Main Seam	3	14	8

Table 2 Type and mining history of observed sites

Sites	Type	History of old roadway*	Mining history of the site	Mining history around the site
Jobu Hidari Lower Seam No. 1 SD	Level roadways	E 1960 A 1963 F 1970 O 2004	Left as a safety pillar. Main seam was mined in 2003.	North/south of the site was mined by longwall method between 1959 and 1960/1960 and 1964.
Jobu Hidari No. 6 SD	Level roadways	E 1953 A 1956 F 1983 O 2006	Main Seam along tailgate/maingate was mined in 1954-1958 by steel prop and roof bar method.	Main seam around the setup entry was mined in 2002 by longwall method.
Jobu Hidari No. 5 SD	Gobs by room method	E 1959 A 1959 F 1983 O 2005	Unmined.	West of the start part was mined by longwall method in 1982.
Jobu Chuo No. 0 SD Tailgate	Gobs by room method	E 1961 A 1961 F 1970 O 2004	Unmined.	North of the site was mined by room method in 1959 and then by longwall method in 1977.
Jobu Chuo No. 1 SD	Main roadways	E 1959 A 2005 F 2005 O 2006	Left as a safety pillar.	Main and Lower Seam in the west of gateway was mined in 1962 by slicing method. East of tailgate was mined in 1995 by longwall method.

*E: excavated, A: abandoned, F; filled and O: observed

Table 3 Mean values of Rayleigh wave velocity and dominant frequency measured at thee different sites.

	Rayleigh wave velocity (km/s)			Dominant frequency（Hz）		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Virgin field	1.78	1.57	1.13	3080	1192	775
Old roadway	1.16	0.76	0.34	686	604	306

Table 4 Hydraulic conductivity and critical pressure measured by Lugeon test

Used fluid / Hole No.*	Air		Water	
	Hydraulic conductivity (m/s)	Critical pressure* （MPa）	Hydraulic conductivity (m/s)	Critical pressure* (MPa)
No.1 (virgin, 2 m)	5.29×10^{-8}	0.11		
No.2 (virgin, 5 m)	1.36×10^{-8}	0.28**		
No.3 (old roadway, 2 m)	1.83×10^{-6}	0.04**	1.0×10^{-5}	0.20
No.4 (old roadway, 5 m)	5.07×10^{-7}	0.11	6.0×10^{-7}	0.59

* see Fig. 16

** indicates the applied maximum pressure under which the critical pressure was not observed.

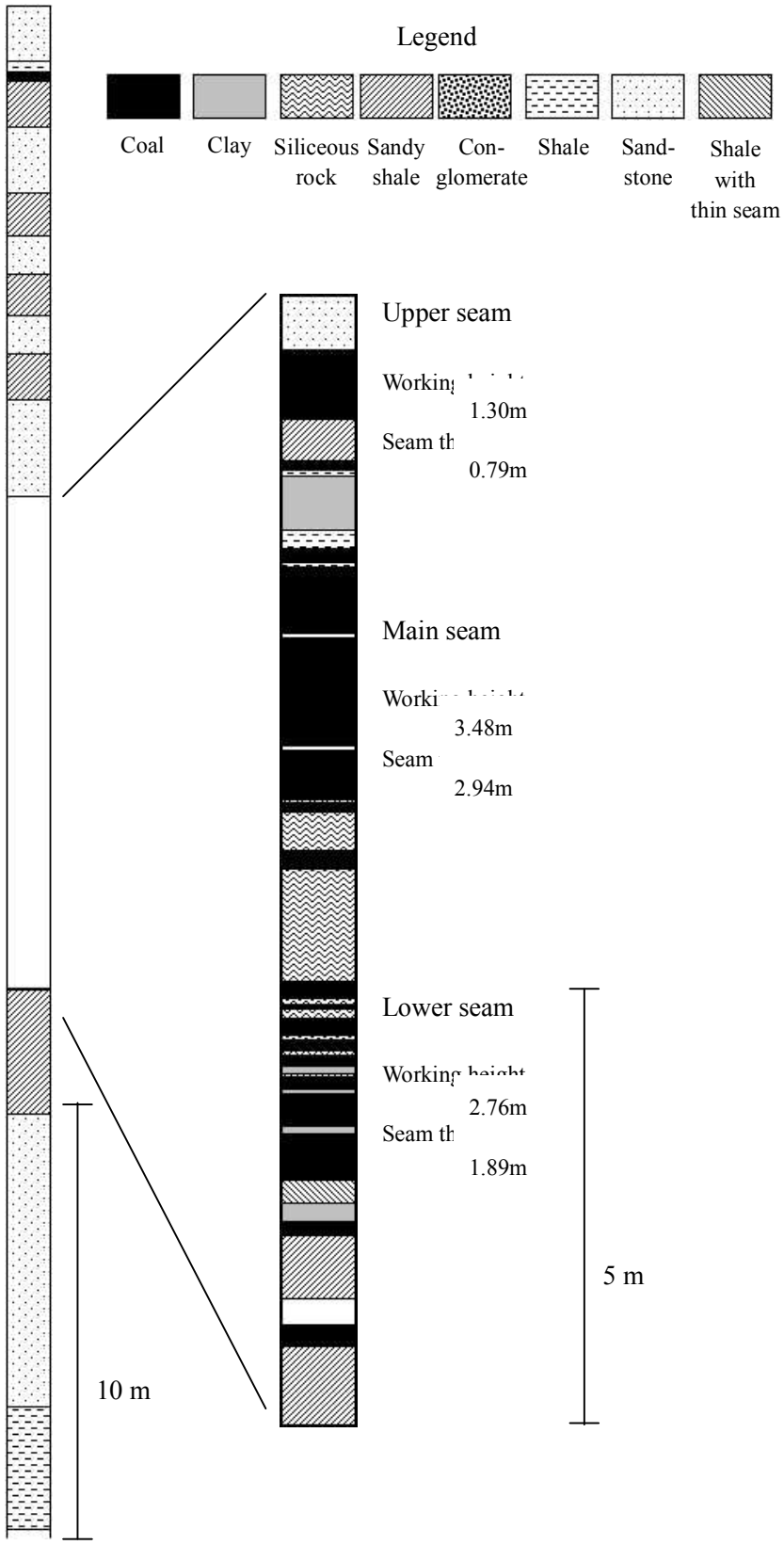


Fig. 1 Geological columnar section.

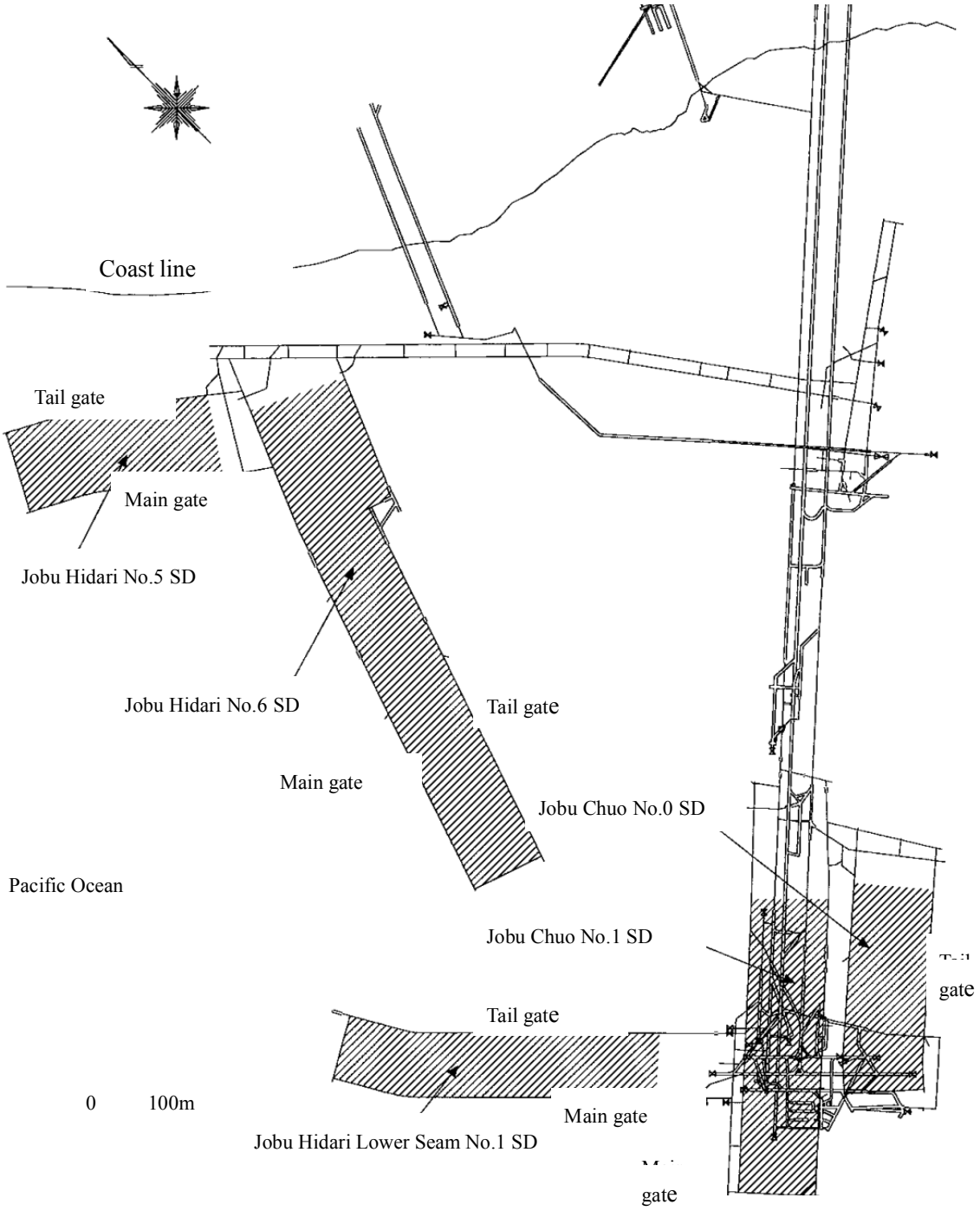
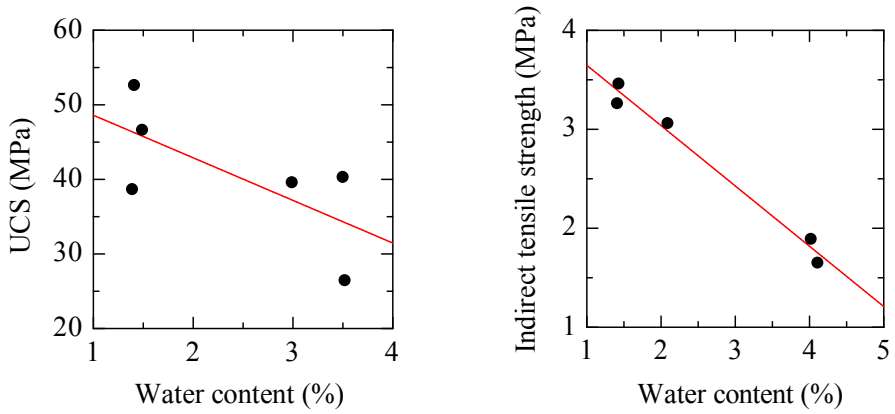


Fig. 2 Longwall mining panels in which old roadways were observed



(a) Uniaxial compressive strength (b) Indirect tensile strength

Fig. 3 Relationship between strengths and water content for sandstone specimen.

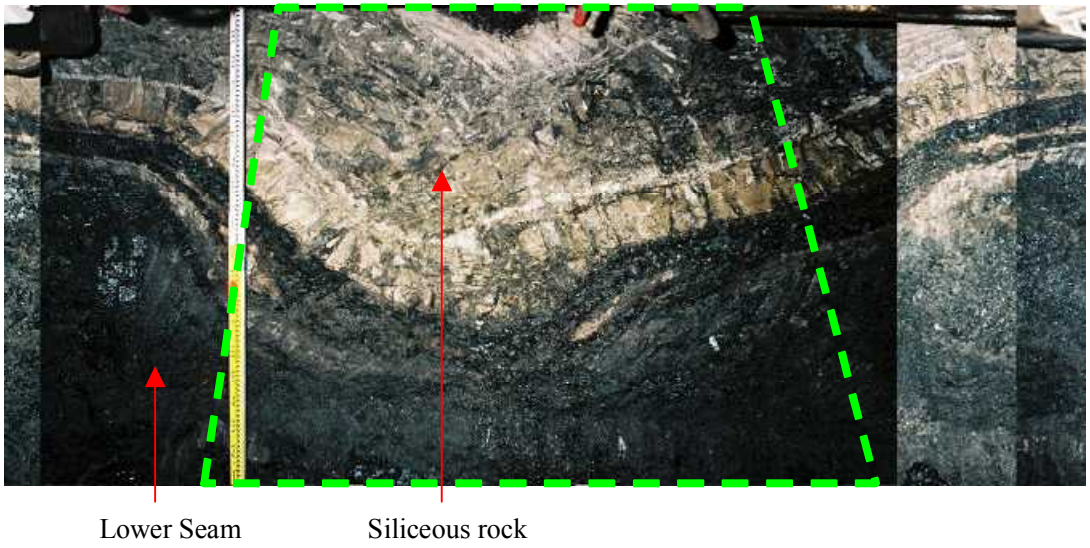


Fig. 4 Old roadway observed in Jobu Hidari Lower Seam No. 1 SD. Roadway which is denoted by the broken line is closed by the deflected and sagged roof. Heights of all photos of old roadways in Figs. 4 to 14 are approx. 2.5 m.

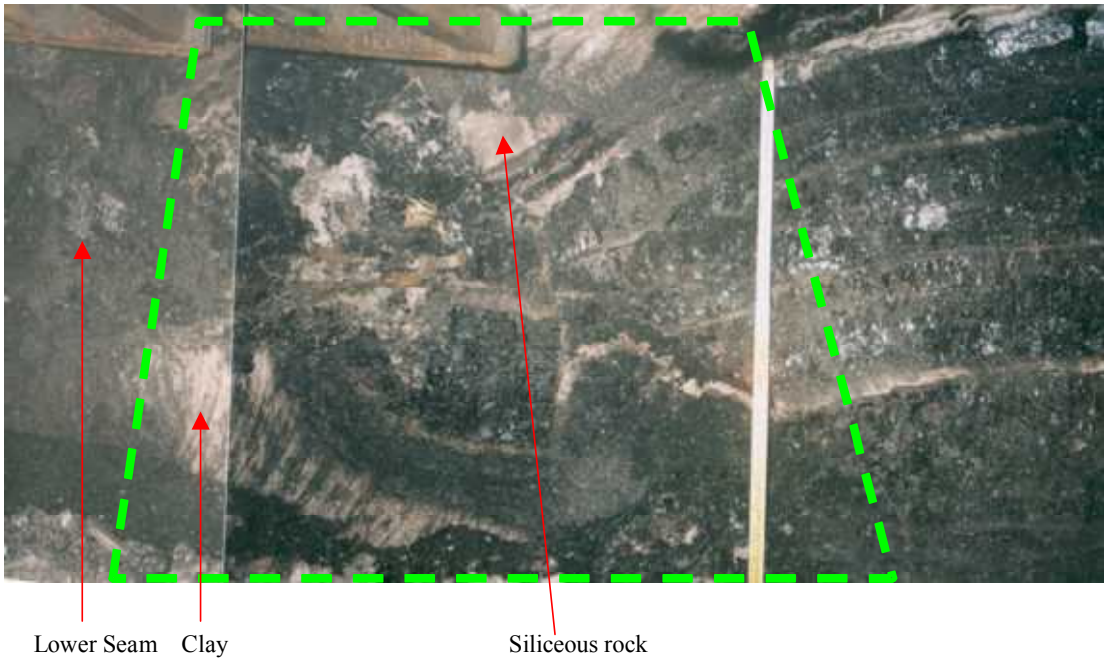


Fig. 5 Old roadway observed in Jobu Hidari Lower Seam No. 1 SD. Right part of the roof kept deflected shape. Left part was crushed by compression.

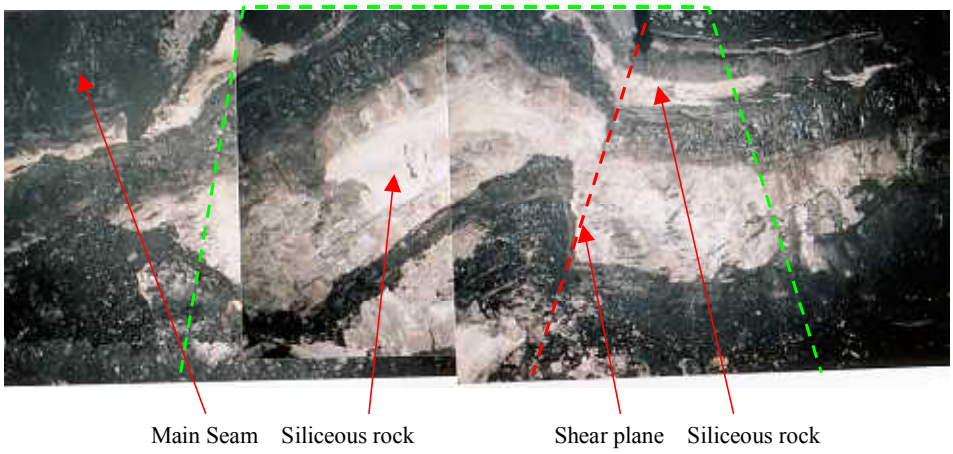


Fig. 6 Old roadway observed in Jobu Hidari No. 6 SD. The deflected floor was sheared. Variation in width of siliceous rock can be seen.

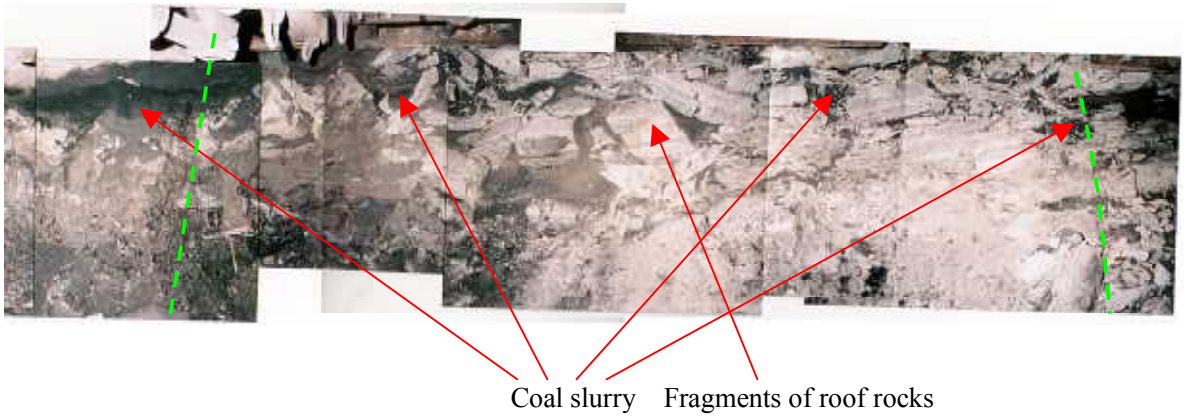


Fig. 7 Old roadway observed in Jobu Hidari No. 6 SD. Fragments of roof rock distributed in coal slurry (gray part seen around the top of the old roadway), the mixture of water and fine coal powder produced in coal processing.

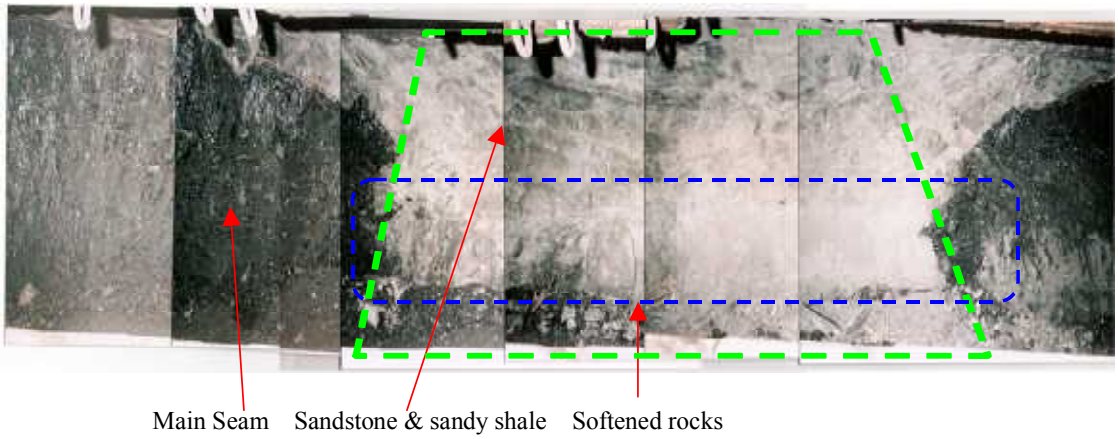


Fig. 8 Old roadway observed in Jobu Hidari No. 5 SD. Old roadway was closed by the deflected and sagged roof. Rocks below the deflected roof were softened.



Fig. 9 Old roadway observed in Jobu Hidari No. 5 SD. Old roadway was closed by the deflected and sagged roof. Rocks below the deflected roof were softened.

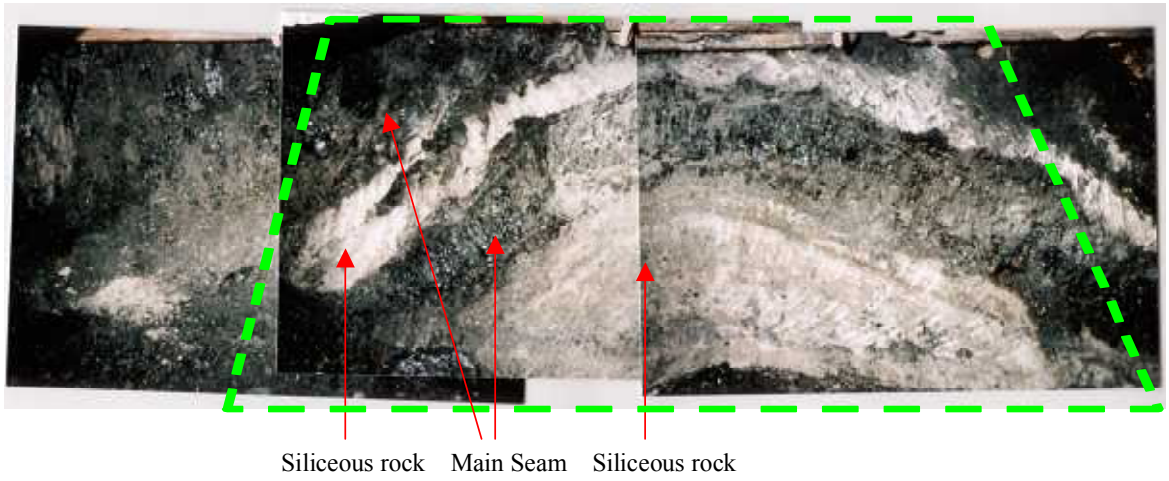


Fig. 10 Old roadway observed in Jobu Hidari No. 5 SD. Roadway was closed by deflected and heaved floor.



Fig. 11 Old roadway observed in Jobu Chuo No. 0 SD tailgate. Fallen rock slabs piled up on the heaved floor.

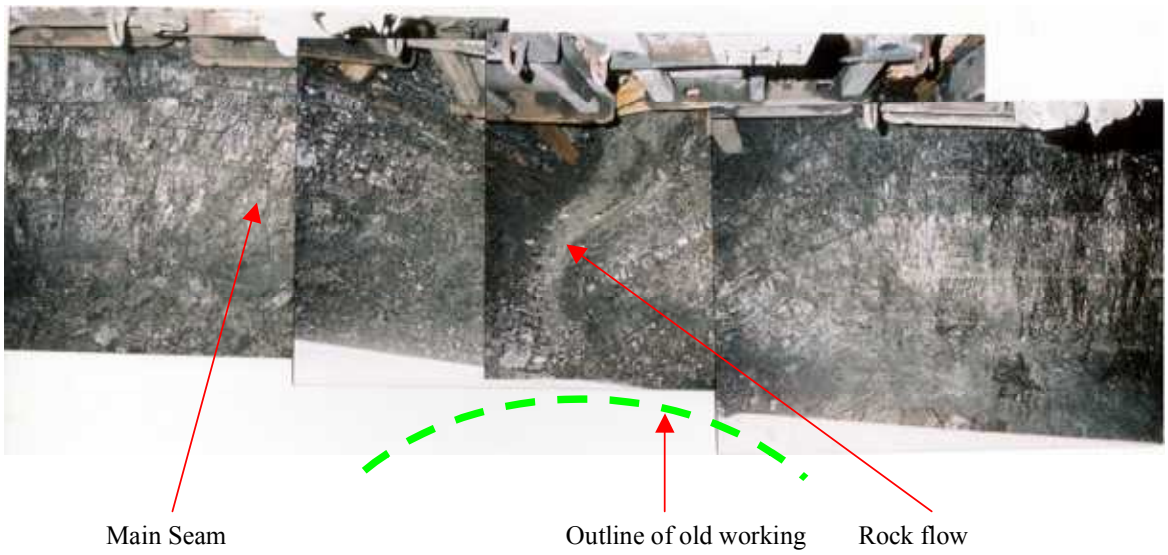


Fig. 12 Roof just above an old roadway observed in Jobu Chuo No. 1 SD. Crushed roof rocks flowed into the gape of the deflected coal seam.

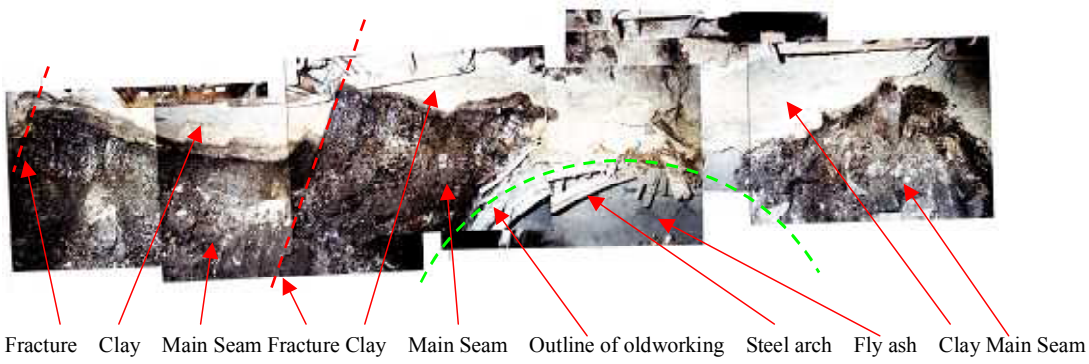


Fig. 13 Old roadway observed in Jobu Chuo No. 1 SD. Shear fractures and variation of clay thickness can be seen.

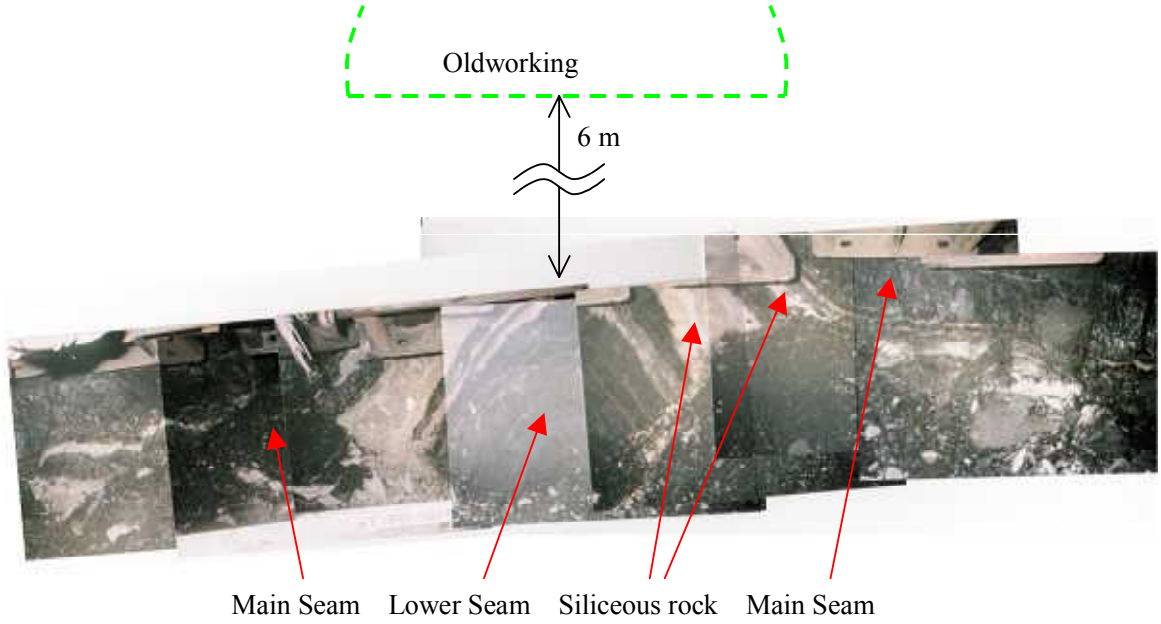


Fig. 14 Observation at 6 m below the old roadway in Jobu Chuo No. 1 SD. Severe floor heave can be seen.



Fig. 15 A goaf of the Main seam mined in 1954, appeared at the working face of Jobu Hidari No.6 SD. The white broken line indicates the boundary between the roof and the floor of the excavated Main seam.

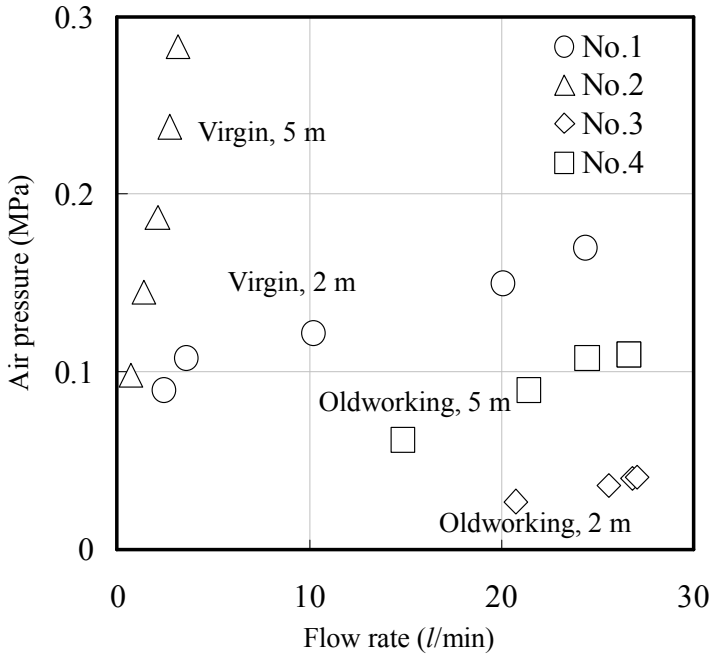


Fig. 16 Injection pressure vs. flow rate obtained by Lugeon test when the compressed air was used as fluid.

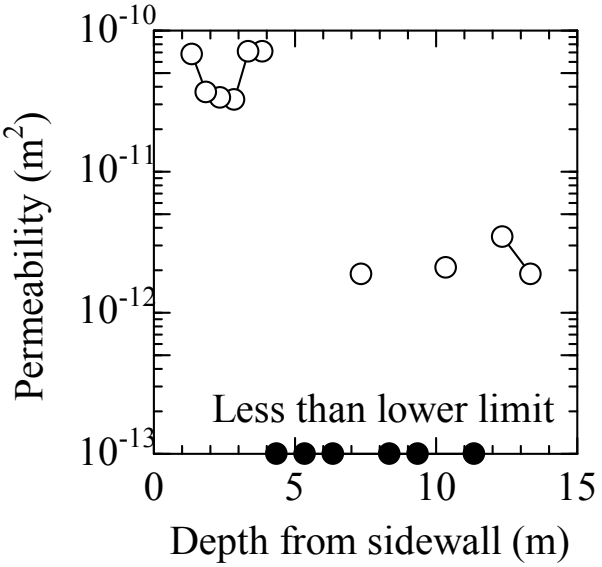


Fig. 17 Permeability distribution along a borehole.

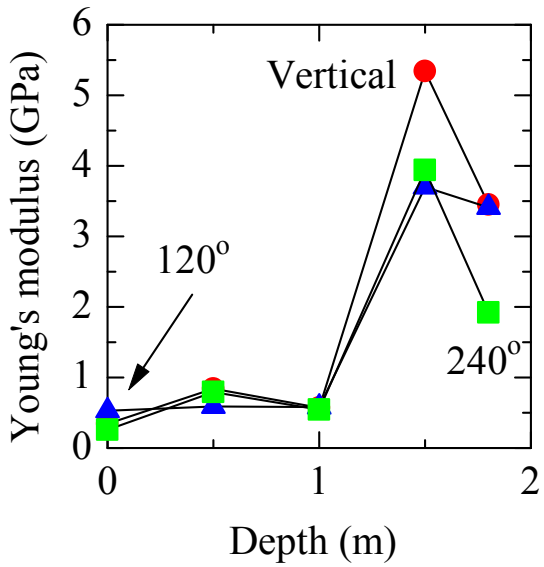


Fig. 18 Distribution of Young's modulus along the borehole in siliceous rock.

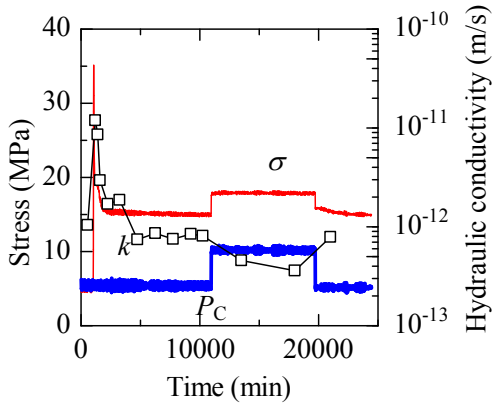


Fig. 19 Axial stress (σ), confining pressure (P_C) and hydraulic conductivity (k) versus time obtained under the triaxial compression test using sandstone.

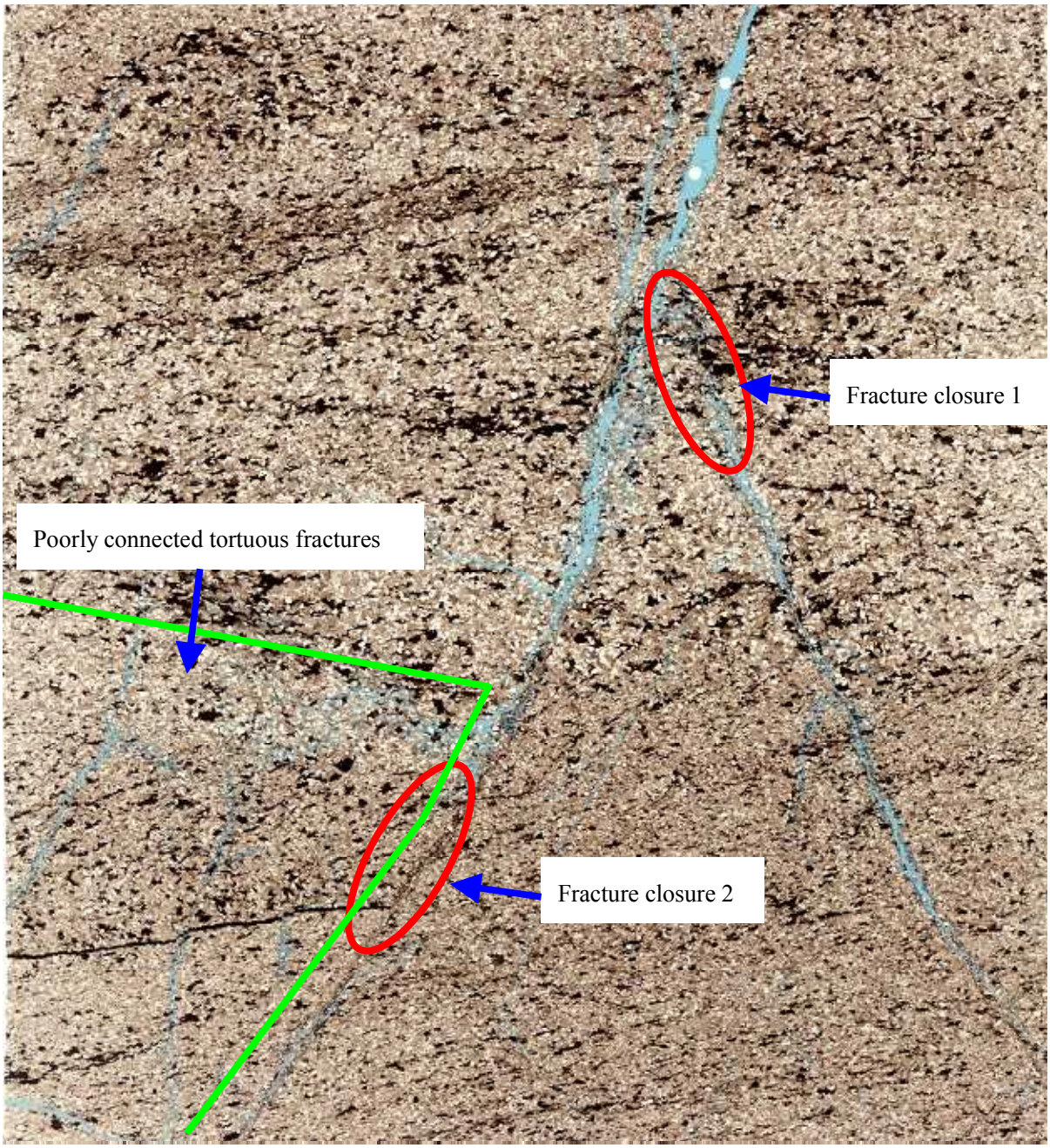


Fig. 20 Micrograph of the thin section prepared from the rock specimen used for the triaxial test shown in Fig. 19. The photo corresponds to the thin section of 23 mm wide. Vertical direction of the photo coincides with the loading axis. Test piece was impregnated with blue resin before preparation of the thin section.