

Depth Variability of Compressive Strength Test Results of Toki Granite from Shobasama and Mizunami Construction Sites, Japan

Flavio Lanaro · Toshinori Sato · Shigeo Nakama

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Abstract This paper studies the depth variability of uniaxial compressive laboratory test results on intact Toki granite (i.e., sound rock without macroscopic fractures) from the Shobasama and Mizunami Construction Sites, Japan. Some of the depth variability observed in the laboratory results can be indirectly attributed to the high fracture frequency of the “upper highly fractured rock domain” from which some of the samples were taken. For samples taken from the “lower sparsely fractured rock domain,” however, the uniaxial compressive strength of the granite seems to be very strongly correlated to the level of in situ rock stress (i.e., maximum shear stress) determined by measurement results obtained from hydrofracturing tests. The correlation between the laboratory results and the level of in situ stress is explained by the damage due to the complex stress path that the cores undergo during drilling, besides the stress concentrations at the drill-bit/rock contact, which can also affect the microcracking of the samples. An attempt to adjust laboratory test results to estimate the in situ intact rock strength of Toki granite based on its correlation with in situ stresses was carried out.

F. Lanaro · T. Sato · S. Nakama
Japan Atomic Energy Agency, Mizunami, Japan

Present Address:

F. Lanaro (✉)
Grontmij AB, Stockholm, Sweden
e-mail: flavio.lanaro@grontmij.se

Present Address:

T. Sato
The Agency for Natural Resources and Energy (ANRE), METI, Tokyo, Japan

Present Address:

S. Nakama
Japan Atomic Energy Agency, Tokai, Japan

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1 Introduction

The Japan Atomic Energy Agency (JAEA) is currently performing extensive investigations on crystalline rocks at depth at the Mizunami Underground Research Laboratory (MIU) construction site (Gifu, Central Japan). The studies were preceded by similar investigations at the Shobasama site in the same municipality. The goal of the site investigations is to improve knowledge of deep geological environments and enhance reliability and confidence in the design of a final repository for high-level radioactive waste in crystalline rocks.

For the design and operation of a repository facility, the strength of the intact rock (i.e., sound rock without macroscopic fractures), especially in sparsely fractured bedrocks such as Toki granite in Mizunami, is one of the key parameters. Knowledge of rock mass heterogeneity and the effects of the sampling process on the intact rock strength measured in laboratory are important for predicting brittle failure and optimizing rock support.

Eberhardt et al. (1999) have shown that the uniaxial compressive strength of samples of the Lac du Bonnet granite (URL, Canada) decreases from about 240 to about 180 MPa and even 140 MPa for samples taken at 130, 240, and 420 m below the surface, respectively. At these depths, the difference between the major and minor principal stresses increases from about 5–10 MPa at 130 m, to 13 MPa at 240 m, and to about 41 MPa at 420 m depth. Although the major principal stress at the URL is generally higher than the stresses measured in Mizunami, the difference between the maximum and minimum in situ stresses for the two sites is comparable. Thus, potential damage of the cores of Toki granite is also expected to result in reduced uniaxial compressive strength of the core samples compared with the undisturbed in situ strength.

Core damage during drilling is mainly induced by tensional stresses appearing parallel to the core axis (see, e.g., Jaeger 1963; Haimson 1997). Such tensile stresses are partially induced by the geometry of the core stub and partially enhanced by the maximum in situ shear stress. The results reported by Lavrov et al. (2003) also confirm this fact: samples subjected to tensile stresses about 50–80% of the Brazilian tensile strength exhibited reduced compressive strength when tested in uniaxial compression. Core damage is also generated by stress concentrations at the contact between drill-bit and rock and by the effect of drilling fluids (Martin and Stimpson 1994).

In this paper, a short description of two geographically close sites investigated by JAEA for the location of an underground laboratory in crystalline rock is given. The results from laboratory testing of Toki granite are presented and related to various geological features such as fracture frequency, weathering, facies, and in situ rock stresses. Furthermore, a conceptual model for describing the in situ variation of the uniaxial compressive strength of the Toki granite with depth is proposed based on an adjustment of the results obtained in laboratory to account for sample damage. The difference between strength in laboratory and in situ is then explained by the

damage that cores might have suffered during drilling in highly stressed bedrock at depth.

2 Geology of the Sites

The Shobasama and the Mizunami construction sites are located in the Gifu Prefecture in Central Japan. The sites are just a few kilometers apart from each other and are characterized by very similar geological conditions. A Cretaceous granite basement about 68 Ma old (Toki granite) is covered by Miocene sedimentary rocks dating from 20 to 1 Ma ago (Itoigawa 1980; TODO 1999; Yusa et al. 1993). The Toki granite basement presents a surface characterized by paleo-channels. Weathering is found at the bottom of the paleo-channels but tends to decrease significantly along the slopes of the basement. Below the weathered layer, the Toki granite seems to be affected by rather heavy fracturing to a depth varying between 100 and 500 m. This bedrock volume is referred to as the Upper Highly Fractured Domain (UHFD; fracture frequency between 1 and 5 fractures/m). Below this domain, the fracture frequency drops in what is called the Lower Sparsely Fractured Domain (LSFD; fracture frequency less than 1 fracture/m). All the geological features described herein are common to the two sites.

2.1 Shobasama Site

The Shobasama site lies along a creak basin in the territory of Mizunami City (Fig. 1, left). Several boreholes were drilled at this site to depths between 400 and 1,000 m. However, only boreholes MIU-1 to 4 and AN-1 were sampled for rock mechanics testing. On the northern edge, the site is intersected by the Tsukiyoshi

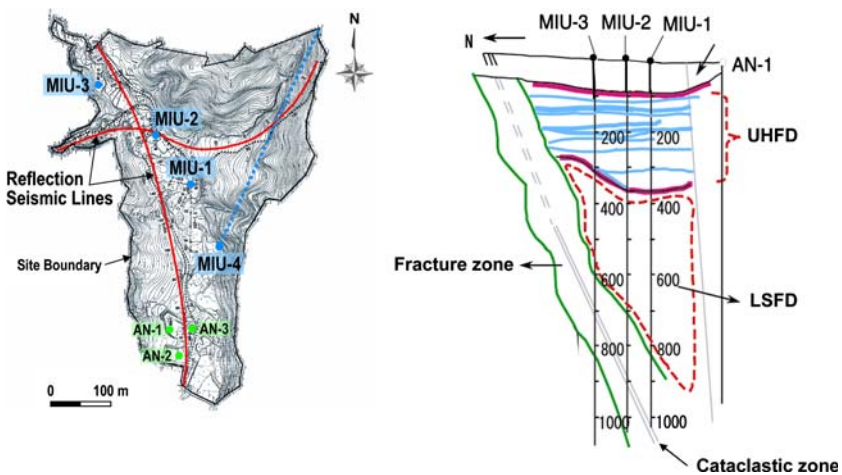


Fig. 1 Map of the Shobasama site (*left*) and vertical cross section of the geological conceptual model of the site along a NNW–SSE line (*right*) (Tsuruta et al. 2004)

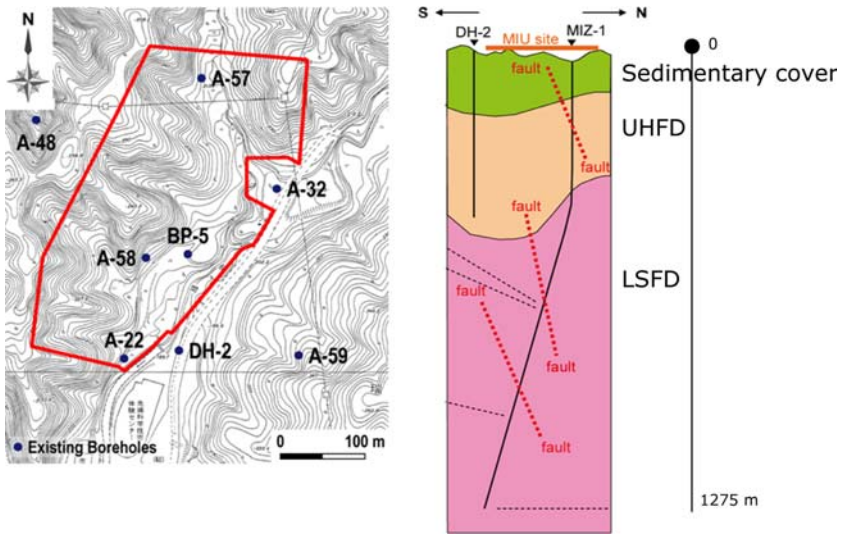


Fig. 2 Map of the Mizunami site (*left*) and vertical cross section of the geological conceptual model of the site along a NNE–SSW line (*right*) (Tsuruta et al. 2004)

Fault, a large fault zone that trends E–W and dips about 60–70° towards S (Fig. 1, right). The site, originally chosen as the location for the Mizunami Underground Laboratory, was abandoned in favor of the nearby Mizunami construction site.

2.2 MIU Construction Site

The MIU construction site at Mizunami is located on the flank of a hill and limited on the SE edge by a river (Fig. 2). The geological model of the site encompasses the UHFD and LSFD domains as defined above. Furthermore, the Tsukiyoshi Fault bounds the northern edge of the site. As of September 2008, the excavation of the main and ventilation shaft has been carried out to a depth of 300 and 255 m, respectively, from the surface (see http://www.jaea.go.jp/04/tono/miu_e/ for the latest update).

3 Laboratory Test Results

Laboratory tests were carried out on the Toki granite for determination of the physical properties (effective porosity, elastic wave velocity, and density) and mechanical properties [uniaxial compressive strength (UCS), triaxial compressive strength, and Brazilian tests]. Samples were collected at rather uniform spacing along boreholes MIU-1 to 4 and AN-1 at Shobasama, MIZ-1 at the MIU construction site, and the adjacent borehole DH-2 (Tables 1, 2). Figure 3 shows the variation of UCS along the boreholes at the two sites.

Table 1 Borehole information and number of effective porosity, uniaxial compressive tests on borehole cores and hydrofracturing stress measurements in the Toki granite

| Borehole | Total length (m) | Inclination | No. of effective porosity measurements | No. of UCS tests | No. of HF stress measurements |
|----------|------------------|---|--|------------------|-------------------------------|
| MIU-1 | 1,011.80 | Vertical | 180 | 90 | – |
| MIU-2 | 1,012.00 | Vertical | 110 | 30 | 13 |
| MIU-3 | 1,014.00 | Vertical | 40 | 10 | 7 |
| MIU-4 | 790.10 | 30° from vertical | 60 | 30 | – |
| AN-1 | 1,010.20 | Vertical | 20 | 20 | 16 |
| MIZ-1 | 1,300.00 | Vertical to ~380 m, then inclined up to 14° from vertical | 192 | 45 | 12 |
| DH-2 | 501.00 | Vertical | 60 | 30 | – |

Table 2 Average physical and mechanics properties of Toki granite obtained in various investigation campaigns (Nakama et al. 2003; Yamada et al. 2007)

| Borehole | Density (kg/m ³) | Effective porosity (%) | Young's modulus (GPa) | Poisson's ratio (–) | P-wave velocity (m/s) | UCS (MPa) | Brazilian tensile strength (MPa) | Cohesion (MPa) | Friction angle (°) |
|---------------------|------------------------------|------------------------|-----------------------|---------------------|-----------------------|-----------|----------------------------------|----------------|--------------------|
| MIU-1 to 4 and AN-1 | 2,620 | 1.31 | 51 | 0.34 | 5,270 | 168 | 8.0 | 34 | 55 |
| DH-2 | 2,610 | 0.83 | 58 | 0.33 | 4,800 | 117 | 7.8 | 37 | 53 |
| MIZ-1 | 2,630 | 1.15 | 54 | 0.26 | 5,450 | 171 | 6.4 | 39 | 52 |

4 Rock Stress Measurements

Extensive campaigns of rock stress measurements were carried out at the sites. Hydrofracturing methods were applied to estimate the in situ stresses in four of the seven boreholes analyzed in this study. The results are reported in Fig. 4 in terms of maximum and minimum horizontal stress and vertical stress, respectively. The location of the encountered fault zones is also presented. Their position clearly affects the stress distribution by reducing the measured stresses inside or in the immediate vicinity of the fault zones.

The rock mechanics model of the Shobasama site identified three stress domains depending on the depth and the position with respect to the Tsukiyoshi Fault. In other words, two different sets of in situ stresses were identified for the hanging wall and footwall of the fault (Sato et al. 2004). Maximum and minimum horizontal stresses at 1,000 m were found to be about 40–60 and 20–30 MPa, respectively. Core discing, which is an indicator of high stresses relative to the intact rock strength, was observed in some of the boreholes at the Shobasama site (MIU-1 and MIU-3).

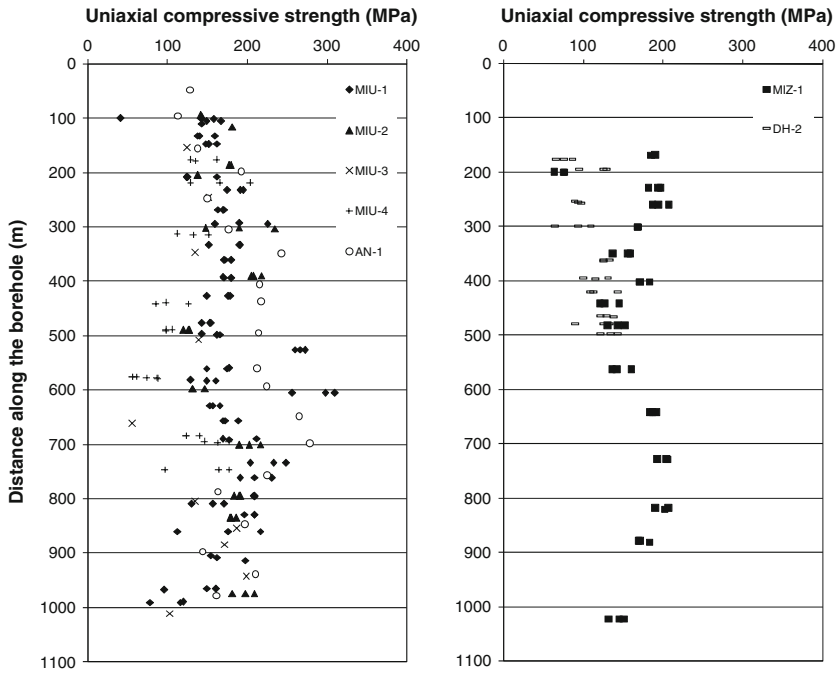


Fig. 3 Plot of the uniaxial compressive strength of Toki granite for samples taken from boreholes at the Shobasama site (*left*) and at the Mizunami construction site and surroundings (*right*). Note that boreholes MIU-4 and MIZ-1 are not vertical

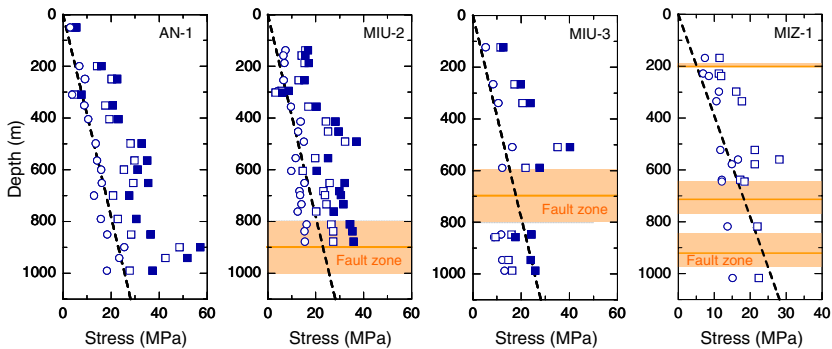


Fig. 4 Summary plots of the results of hydrofracturing measurements of the in situ stresses. *Filled squares* show the maximum total horizontal stress, *empty squares* show the maximum effective horizontal stress, and *empty circles* show the total minimum horizontal stress. The *dotted lines* show the estimated total vertical stress calculated as the weight of the overburden. The major fault zones identified along the boreholes are also indicated

Also at the MIU construction site, two stress domains were recognized above and below a fault encountered at the depth of 500 m. Approximately the same horizontal stresses were measured at depths of 500 and 1,000 m (maximum horizontal stress of 21 and 22 MPa, minimum horizontal stress of 12 and 15 MPa at about 500 and

1,000 m, respectively), whereas the estimated vertical stress doubles between the two depths (13 and 26 MPa at about 500 and 1,000 m, respectively) (Nakama et al. 2005).

5 Depth Variability of the Unconfined Compressive Strength of Intact Rock

By observing the depth distribution of the uniaxial compressive strength obtained according to the suggested methods by ISRM (1999) along boreholes MIU-1 to 4, AN-1, DH-2 and MIZ-1, very well defined oscillations of the values can be observed (Fig. 3). This can be interpreted as variability with depth of the mechanical property that might depend on:

- Different rock types and facies
- Effect of alteration and weathering
- Fracture intensity
- Vicinity to fault zones
- Damage of the core samples due to release of the in situ rock stresses

In the following sections, each of these causes is discussed to determine its importance for the laboratory results.

5.1 Facies of the Toki Granite

According to earlier studies, Toki granite has rather heterogeneous material properties (Sato et al. 2004). Toki granite presents three facies identified at the MIU construction site (Tsuruta et al. 2004):

- Muscovite-bearing biotite granite, medium to coarse grained
- Hornblende-bearing biotite granite, coarse grained
- Leucocratic biotite granite, medium grained

However, Fig. 5 shows that there seems not to be a clear relation between the facies and the uniaxial compressive strength. In fact, the strength appears to follow a pattern independent of the facies occurring at different depths.

5.2 Alteration and Weathering

At the surface of the granite basement, weathering is often observed for a thickness between 0 and 30 m (Table 3). However, most of the samples of Toki granite tested in laboratory were taken below the weathered zone and should therefore be free from the effects of strong weathering.

5.3 Fracture Frequency and Fault Zones

As presented in Sects. 2.1 and 2.2, the rock mechanics conceptual models of the sites incorporate the definition of fracture domains based on the fracture frequency. Although fracture frequency accounts for macrofractures at borehole scale, microfracturing or other geological processes related to macrofractures might have

Fig. 5 Variation of the uniaxial compressive strength of Toki granite along borehole MIZ-1. The three facies (medium to coarse grained, medium grained, and coarse grained) are marked with different symbols

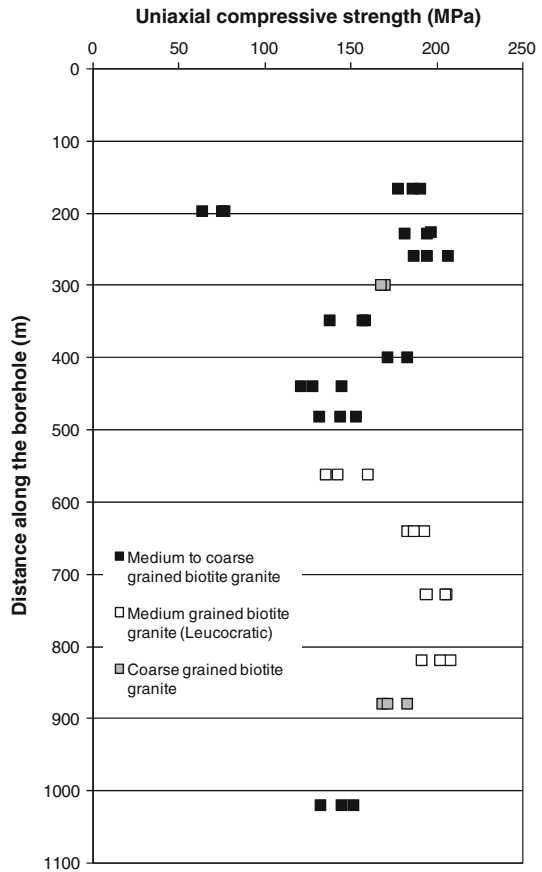


Table 3 Depth of Toki granite basement, of the weathered zone, and of the boundary between the upper highly and lower sparsely fractured domains, from the top of the boreholes

| Borehole | Depth of the Toki granite basement (m) | Depth of the weathered zone (m) | Thickness of the weathered zone (m) | Boundary between UHFD and LSFD (m) | Thickness of UHFD (m) |
|----------|--|---------------------------------|-------------------------------------|------------------------------------|-----------------------|
| MIU-1 | 88.8 | 103.0 | 14.2 | 350.0 | 261.2 |
| MIU-2 | 88.6 | 99.0 | 10.4 | 370.0 | 281.4 |
| MIU-3 | 87.9 | 97.9 | 10.0 | 317.0 | 229.1 |
| MIU-4 | 80.5 | 113.3 | 32.7 ^a | 268.5 | 187.9 ^a |
| AN-1 | 16.8 | 38.0 | 21.2 | 208.0 | 191.2 |
| MIZ-1 | 109.1 | – | 0.0 | 311.0 | 201.9 |
| DH-2 | 167.9 | 169.0 | 1.1 | 501.0 ^b | 333.1 ^b |

^a Corrected for borehole inclination

^b To the bottom of the borehole

affected the mechanical properties of the intact rock. In fact, the distribution of the uniaxial compressive strength with depth shows different patterns above and below the boundary between the UHFD and the LSFD.

5.3.1 Upper Highly Fractured Domain

When the samples collected in the UHFD are analyzed, the values of the uniaxial compressive strength of the Toki granite appear to increase with depth with a rather linear trend. Since the thickness of the UHFD varies from borehole to borehole, the distance along the borehole from the weathered boundary of the Toki granite was normalized with respect to the total thickness of the UHFD outside the weathered zone. This treatment allows two groups of boreholes to be distinguished: MIU-1 to 4 and MIZ-1 on one side, and AN-1 and DH-2 on the other side (Fig. 6). Linear fitting of the test results for the two groups yields the following trends:

$$\begin{aligned}
 UCS_{MI} &= 146 \text{ MPa} + 52 \text{ MPa} \times d, \quad \text{for } d < 1 \quad (R^2 = 0.305) \\
 UCS_{AD} &= 88 \text{ MPa} + 55 \text{ MPa} \times d, \quad \text{for } d < 2 \quad (R^2 = 0.716),
 \end{aligned}$$

where d is the normalized distance from the weathered boundary, and MI indicates the first group of boreholes and AD the second group, respectively.

The linear equation for the first group of boreholes, irrespective of site, has an intercept 66% larger than that of the second group. On the other hand, the slopes appear to be very consistent for the two groups since the difference is only 6%. When the maximum d is assumed, the same value of the uniaxial compressive strength of about 200 MPa is obtained from both equations.

5.3.2 Lower Sparsely Fractured Domain

In the LSFD, the uniaxial compressive strength of the tested samples shows well-defined oscillations when plotted against depth (Fig. 3). Although there is some

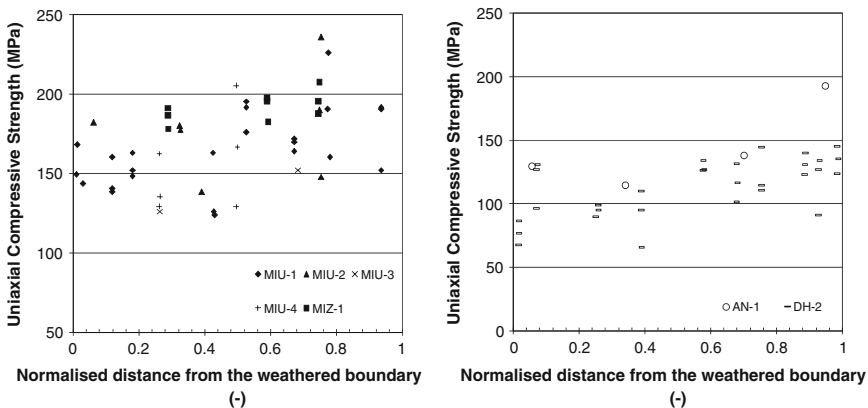


Fig. 6 Variation of the uniaxial compressive strength of the Toki granite in the UHFD as a function of normalized distance from the weathered boundary

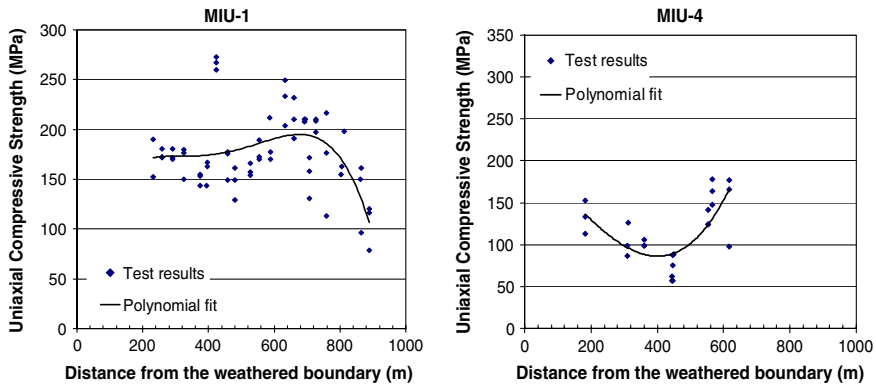


Fig. 7 Variation of the uniaxial compressive strength of the samples with distance from the weathered boundary for two boreholes at the Shobasama site. *Polynomial curves* are fitted to the test results to show the dominant trends with depth

spread in the data, the variation of the uniaxial compressive strength appears to be quite smooth and almost never abrupt in all boreholes. For this reason, polynomial interpolations were carried out (Fig. 7). The smooth variation could be explained in three ways:

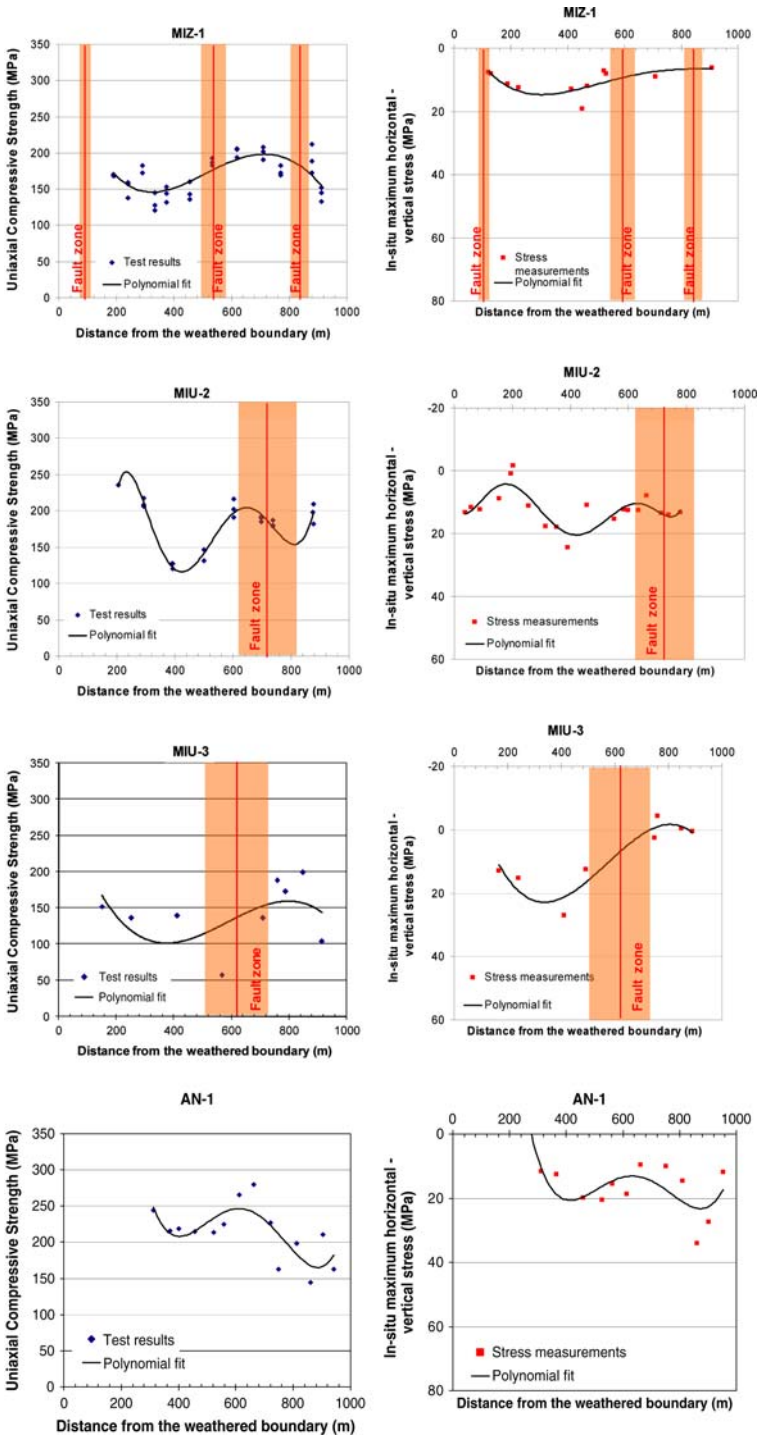
1. By the presence of fault zones and related geological processes that could reduce the intact rock strength (e.g., Laws et al. 2003).
2. By the effect of release of the in situ rock stresses in the samples prior to testing that would damage them by, for example, microcracking (e.g., Eberhardt et al. 1999; Holt et al. 2000).
3. By the effect of the drilling parameters: fluid pressure, weight on bit, torque, etc. (see, e.g., Martin and Stimpson 1994).

6 Correlation between Strength and In Situ Rock Stresses

The following considerations can be applied when trying to answer question (1) to (3) in Sect. 5.3.2:

1. Contrary to what was expected, the uniaxial compressive strength of the samples seems to increase when approaching the fault zones (Fig. 8). This indicates that the position of the faults is somehow correlated to the position of the peaks of the diagrams of strength versus depth.

Fig. 8 On the *left*, variation of the uniaxial compressive strength of the samples with distance from the weathered boundary along the boreholes at the Shobasama and Mizunami sites. On the *right*, variation of the difference between the maximum horizontal in situ stress, measured by hydrofracturing, and the vertical stress, calculated as the weight of the overburden, as a function of the distance from weathered boundary. The *polynomial curves* are fits to the available data to show the dominant trends with depth. Note that the *y*-axes of the stress diagrams are reversed



2. The positive correlation between the strength and the position of the fault zones suggests the hypothesis that the release of the in situ stresses might have affected the integrity of the intact rock samples and thus their strength. In fact, the presence of the faults often produces a local decrease of the in situ stresses, and this, in turn, would guarantee less damaged or undamaged samples. This is also supported by the plots of the polynomial fits of the difference between the in situ maximum horizontal stress measured and the vertical stress calculated as the weight of the overburden for boreholes MIU-2, MIU-3, AN-1, and MIZ-1 (Fig. 8). The polynomial fits of the stress component mirror very well the shape of the polynomial fits of the uniaxial compressive strength. Note that the plots of the in situ stresses have reversed y-axes.
3. The very good correlation between the troughs of the strength and the peaks of the in situ stresses might exclude the hypothesis of purely drilling-induced damage. However, damage due to release of in situ stresses is always associated with drilling, which produce a local increase of stresses around the borehole.

No clear correlation between the in situ stresses and the uniaxial compressive strength could be observed for the core samples taken from the UHFD.

7 Discussion

This study shows that the uniaxial compressive strength of Toki granite varies significantly along the investigated boreholes. Attention was therefore focused on these variations and potential explanations. One of the factors playing a role in the variation of the intact rock strength seems to be the vicinity to the surface of the granite basement. Besides the weathered layer, a rather linear increase of the uniaxial compressive strength with depth was observed in the superficial UHFD. This linearity seems to continue through the entire thickness of the UHFD. In some boreholes (e.g., AN-1), the linearity even extends beyond the lower limit of the UHFD into the LSFD.

Typically, in the LSFD, the strength of the intact rock oscillates with depth. It was observed that the oscillation of the values follows the variation of the measured in situ stresses very well: peaks of strength are associated with troughs of the difference between maximum horizontal in situ stress and vertical stress, and vice versa.

In fault zones, the rock mass quality is lower than for the adjacent rock mass due to higher fracture intensity, higher fluid flow, and alteration processes. However, samples for uniaxial compressive testing of Toki granite were chosen in core sections of sound rock, i.e., in rock blocks not affected by fracturing and alteration within the faults. Moreover, in situ stresses might decrease when approaching the fault zones due to the relief of high stresses through slip along the fault and due to the weaker mechanical properties of the faults compared with the surrounding competent rock mass. Therefore, at the sites, it is often observed that the uniaxial compressive strength of Toki granite measured in laboratory increases within or around fault zones. As this is likely to be an effect of release of in situ stresses, it

only seems to be a contradiction of the assumption that the faults are expressions of damage of the rock mass, and thus the mechanical properties of the intact rock (i.e., blocks between the fractures) close to them should decrease or stay unchanged.

The uniaxial compressive strength of the intact rock at different depths can be inferred by means of the polynomial fits in Fig. 8 (left). In the same way, the difference between maximum in situ horizontal stress and vertical stress at the same depths can be calculated by using the polynomial fits in Fig. 8 (right). The estimated values of the strength can then be plotted as functions of the in situ stress component for each depth along the boreholes. Such correlations are shown in Fig. 9, in which all the boreholes show almost the same behavior irrespective of location (i.e., Shobasama or Mizunami) or level of stress. Certainly, some of the patterns observed in Fig. 9 might depend on the approximation by the best polynomial fits and on the scarcity of data for some of the boreholes (e.g., MIU-3).

An explanation for the slight change in correlation from borehole to borehole could also be that the stress field is not the same in all the boreholes and some of the borehole locations have generally higher average stresses. Furthermore, depending on the angle between the borehole axis and the principal stress directions, the effect of stress release on the compressive strength of intact rock core samples might vary significantly.

The ranges of variation of the uniaxial compressive strength seem not to coincide for all the boreholes, indicating that the strength might also vary spatially from

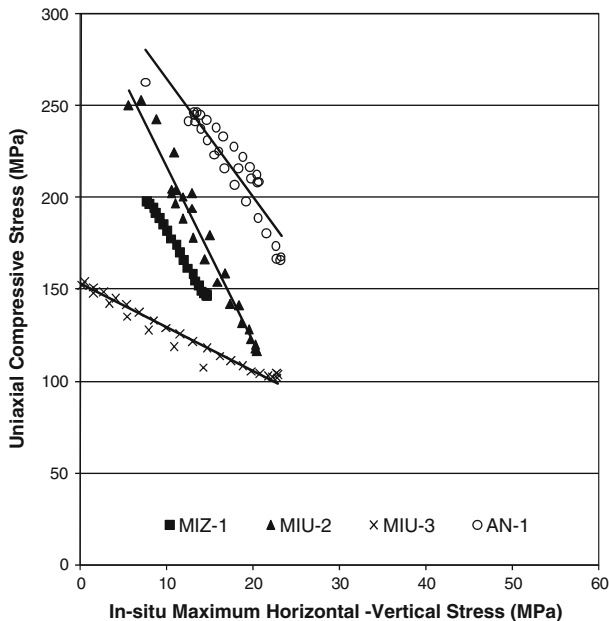


Fig. 9 Correlation between maximum in situ horizontal stress (estimated by using the polynomial fits with depth in Fig. 8, left) minus the vertical stress, and uniaxial compressive strength of Toki granite (estimated by using the polynomial fits with depth in Fig. 8, right) for the boreholes analyzed in this study. Strong negative correlation can be observed between strength and the in situ stress component in all boreholes

borehole to borehole due to reasons other than stress-release-related damage. Such variations should be explained by other geological and structural features.

It can be concluded that there seems to be strong negative correlation between the uniaxial compressive strength of the Toki granite and in situ stresses: the higher the stresses, the lower the strength of the samples. The in situ stress component that correlates with the strength is the difference between the maximum horizontal stress and the vertical stress. This is twice the maximum in situ shear stress in a vertical plane, if the vertical and horizontal directions are assumed to be principal directions.

The drilling of the borehole locally changes the stress conditions in the rock mass, inducing much higher stresses that might affect the integrity of the cores. In fact, the stress path experienced by the core during drilling can induce damage when approaching the failure envelope of the intact rock in triaxial conditions. Typical damage induced by the drilling stress path is microfracturing of the core and in extreme cases core discing (see, e.g., Matsuki et al. 2004).

Microfracturing is often associated with increase of porosity of core samples. For the samples from borehole MIZ-1, in fact, a decrease of strength is systematically associated with an increase of effective porosity (ISRM 1979) as shown in Fig. 10 (left). Thus, both strength and porosity of intact rock appear to be affected by in situ stresses (Fig. 10, right), resulting in the apparent drilling-induced heterogeneity of Toki granite observed at the Shobasama and MIU construction sites.

As another proof of this, the microcracking induced by stress release during drilling seems to have caused the estimation of the principal stresses from core deformation to fail. For measuring the stresses, the acoustic emission/deformation rate analysis (AE/DRA) method was also applied but the initiation of acoustic emission was recorded at an unexpectedly early stage during loading, which prevented the stress determination (Yamada et al. 2007).

It is worth mentioning here that drilling parameters were not considered in this study and could certainly contribute to some extent to the variations of the uniaxial compressive strength observed for the Toki granite.

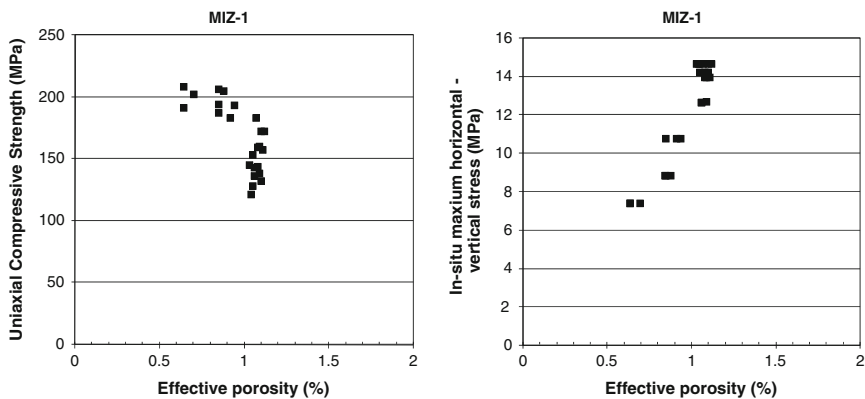


Fig. 10 Correlation between the effective porosity of the samples and the uniaxial compressive strength (left) and the difference between the maximum horizontal and vertical in situ stress (right). Stresses are obtained at the position of the samples by means of the polynomial fits in Fig. 8 (right)

The results of this study for the UHFD and LSFD can be combined to build a conceptual model that explains the variability of the laboratory results of uniaxial compressive tests carried out on samples of Toki granite.

8 Conceptual Model for In Situ Uniaxial Compressive Strength of Toki Granite

Based on the observations in the former sections, a conceptual model explaining the variation of the uniaxial compressive strength of intact Toki granite (i.e., sound rock without macroscopic fractures) at the Shobasama and Mizunami construction sites can be developed (Fig. 11). In this model, the in situ uniaxial compressive strength of the intact rock is assumed to:

1. Increase linearly with depth in the UHFD (below the superficial weathered zone) towards the values obtained in the LSFD according to a relation similar to those reported in Sect. 5.3.1
2. Have a rather constant average value in the LSFD

The linear increase of the intact rock strength in the UHFD is merely an observation of the available data. No specific explanation was attempted in this study.

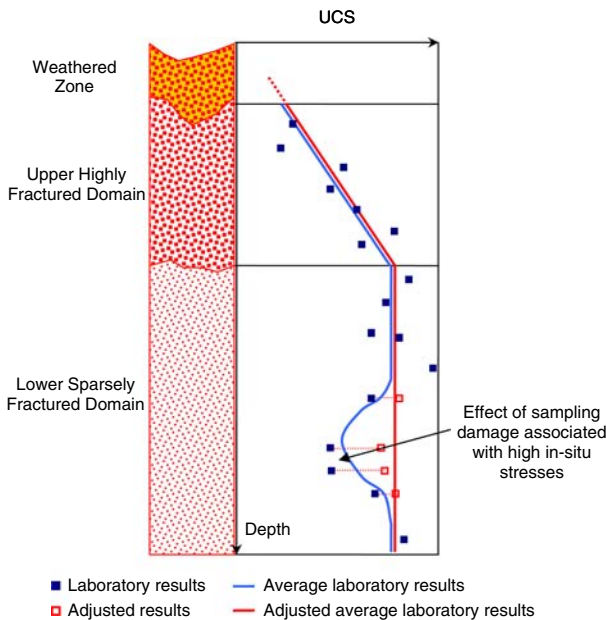


Fig. 11 Conceptual model of the variation with depth of the in situ uniaxial compressive strength of Toki granite at the Shobasama and Mizunami construction sites

In the LSF_D, some of the large scale-variations of the laboratory uniaxial strength could be explained and correlated to damage induced by the release of in situ stress during drilling (Sect. 6). Based on this knowledge, it is possible to adjust the laboratory results to account for sampling damage by means of the correlation between the strength of intact granite and in situ stresses in the borehole. The correlation varies slightly from borehole to borehole, probably due to different angles between the borehole axis and the principal stress directions, the drilling parameters, and/or the ratio between the magnitudes of the in situ principal stress components. However, Fig. 9 shows that such correlation is highly consistent for all boreholes and its linearity allows for a rather simple adjustment of the laboratory results to take into account possible underestimation of intact rock strength due to the effects of in situ stresses on the core. This adjustment can only be applied to the results from boreholes where the variation of the in situ rock stresses is known.

To apply the adjustment, the value of uniaxial compressive strength of the samples unaffected by stress-release damage (i.e., from sections of borehole with low in situ stresses) has to be estimated. Based on this value, a reference stress level (i.e., difference between the maximum horizontal and vertical in situ stress) under which the sample should not be affected by stress-release-related damage can be obtained. Based on the difference between the actual stress level in the position of core sampling and the reference stress level, an estimation of the loss of strength can be attempted by using the linear relation in Fig. 9.

This adjustment for sample damage was applied to the laboratory results from boreholes MIZ-1, MIU-2, MIU-3, and AN-1. Figure 12 shows the data set of laboratory results before (left) and after (right) the suggested adjustment. It is clear that, for most of the boreholes, the adjusted data set appears to be more consistent than the non-adjusted laboratory result data set. The span of variation of the uniaxial compressive strength diminishes (the standard deviation reduces by between 8% and 65%) and most of the laboratory results cluster around a higher average value of about 200 MPa (the average value increases by between 13% and 31%), except for

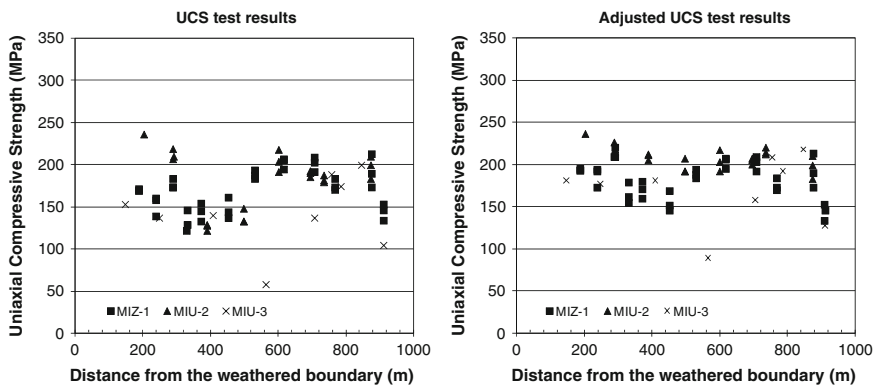


Fig. 12 Uniaxial compressive strength of Toki granite samples from the LSF_D at Shobasama and Mizunami construction sites before (left) and after (right) adjustment to account for the effect of in situ-stress release due to drilling and related core damage

Table 4 Mean value and standard deviation of the uniaxial compressive strength of intact Toki granite in the LSFD before and after the correction suggested in Sect. 8

| Borehole (no. of samples from LSFD) | UCS, mean (MPa) | UCS, standard deviation (MPa) | Corrected UCS, mean (MPa) | Corrected UCS, standard deviation (MPa) | Difference of the means after correction (%) | Difference of the standard deviations after correction (%) |
|-------------------------------------|-----------------|-------------------------------|---------------------------|---|--|--|
| MIZ-1 (33 ^a) | 168 | 25 | 194 | 23 | +16 | -8 |
| MIU-1 (63 ^b) | 181 | 45 | No correction | - | - | - |
| MIU-2 (22 ^c) | 180 | 34 | 207 | 12 | +13 | -65 |
| MIU-3 (9 ^d) | 143 | 43 | 187 | 40 | +31 | -7 |
| MIU-4 (24 ^e) | 115 | 37 | No correction | - | - | - |
| AN-1 (14 ^f) | 213 | 38 | 244 | 27 | +15 | -29 |

^a Samples below 299 m were considered

^b Samples below 361 m were considered

^c Samples below 303 m were considered

^d Samples below 248 m were considered

^e Samples below 314 m were considered

^f Samples below 312 m were considered

the values from AN-1, which are generally higher (Table 4). These changes are larger for boreholes where the measured differential in situ stresses were larger. The adjusted average values also strongly resemble the maximum strength estimated for the UHFD in Sect. 5.3.1.

9 Conclusions

This study focused on heterogeneities observed in some of the physical properties of Toki granite at the Shobasama and MIU construction sites. The influence of sampling depth, fracture intensity, and in situ stresses on the uniaxial compressive strength of intact rock was evaluated. A positive linear correlation between strength and sampling depth was found in the UHFD in all analyzed boreholes. In the LSFD, the correlation with depth was lost and effective porosity and strength of the intact rock seem to become negatively correlated to the magnitude of in situ stresses (e.g., the difference between the maximum horizontal and vertical in situ stresses).

The findings in this paper, although they do not consider drilling parameters, might be of importance in predicting the in situ intact rock strength. In fact, if the samples tested in laboratory have been damaged, the in situ intact rock strength is likely to be higher than that obtained in laboratory. Some corrections should then be applied to the laboratory results to make them representative of in situ conditions at the sites.

Based on the polynomial interpolation of the variation with depth of the uniaxial compressive strength and of the difference between the maximum horizontal and vertical in situ stresses, an adjustment of the laboratory values of the intact rock

strength to account for sample damage is shown herein. This correction shows that the strength of undamaged samples of intact Toki granite would be much less heterogeneous than shown by the laboratory results. Based on corrected values, a conceptual model of the variation of the uniaxial compressive strength of Toki granite at the Shobasama and MIU construction sites was developed, which takes into account the presence of the highly fractured and sparsely fractured rock domains, the magnitude of the maximum horizontal in situ stress measured by hydrofracturing method in the borehole, and the vertical in situ stress estimated from the weight of the overburden.

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