# POLYURETHANE GEOCOMPOSITES. MECHANICAL PROPERTIES AND DEFORMATION

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**ABSTRACT**

*The results of the laboratory study on grouting of polyurethane resins are described. Polyurethane geocomposites are generated during injection process of resin into loosened soils and rocks or disrupted rock beds. In relation to the rock samples, they have specific textures (continuous, massive or bubble-like), very variable cohesion on contacts between rock fragments and resin and complicated course of deformation curves (stress - strain diagram), too. Typical data for polyurethane grouts and geocomposites with different type and granularity of rock fragments are given in the paper.*

## INTRODUCTION

Significant increase of chemical grouting application in mining and civil and underground engineering requires better knowledge of grouting procedures and resulting engineering properties of the final products, i. e. injected rocks and soils. Geocomposites are materials which are formed by cementing together resin, mineral particles, rock fragments or broken blocks of rock. These materials are used either as sealing materials, e. g. in the form of sealing walls, or they are the product of consolidating and reinforcing grouting in porous soils and rocks or cavernous rocks using polyurethane capable of being foamed. Laboratory investigations represent one of the methods how to obtain information on the properties of material so formed.

## MEASURING OF PHYSICAL AND MECHANICAL PROPERTIES OF CURED GROUTS

According the laboratory results the properties of geocomposites are determined mainly by the properties of the resin, by the degree of its foaming and by its adhesion to the surface of rock. Thence we tested in the first stage properties of pure cured grouts.

Specimens for compressive strength tests are prepared by pouring tested grout into cylindrical forms. Cured specimens after treatment of frontal planes are tested in uniaxial or triaxial press. In case of tensile tests grout is poured into board forms and then after curing beam specimens are cut. We have good experience in using water jet cutting for preparation of the beam specimens.

Special technology is used for preparation of specimens from foaming grouts, which represent majority of applied chemical grouting materials. Producers introduce polyurethane grouts with high factor of foaming mainly between 5 and 15 (and more). In fact the value answers foaming in free space, but during grouting in porous or crushed rock real foaming factor is lower than 3. To test the influence of foaming factor on properties of cured grout, we use closed pressure forms for preparation of specimens. Volume of grout poured into the closed form determines foaming factor of the specimen. The factor of foaming is expressed as the ratio of the specific weight of unfoamed pure grout to the specific weight of tested foamed grout. The tested specimens are cylinders of diameter 53 mm with width-thickness ratio 2:1.

From many obtained results of relations between the factor of foaming and physical properties of cured grout we demonstrate here the results of uniaxial strength tests. Compressive strength, modulus of elasticity and the whole characteristics of stress - strain curve were evaluated. Also the velocity of ultrasonic waves was measured.

Three two-component polyurethane grouts were tested: Bevedan-Bevedol WF, WFA a S. We describe the results of the grout Bevedan - Bevedol WF, but we can say, that the behaviour and values of the other tested grouts are very similar.

From the stress-strain diagrams (Figure 1) it is possible to establish unambiguously compressive strength only for unfoamed grouts or grouts with low foaming factor ($k_{nap}$ = 1,0 - 1,5), which have deformation characteristics of fragile material (with high axial deformation) and facilitate reading of the maximal force or loading capacity of sample (mostly in the range to 5 mm of axial deformation); in the next phase of diagram it is obvious, that tested materials reach high residual strength with plastic deformation and non-linear strengthening.

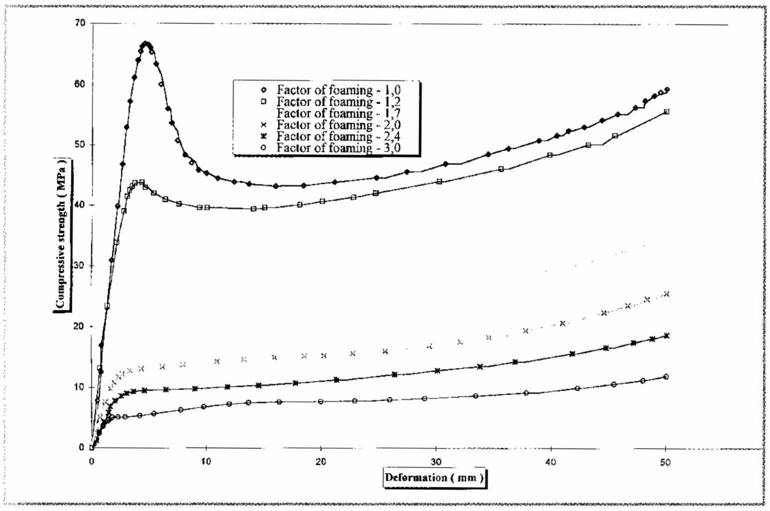


Figure 1. Stress - strain curves for different factor of foaming chemical ggrouts Bevedan - Bevedol WF.

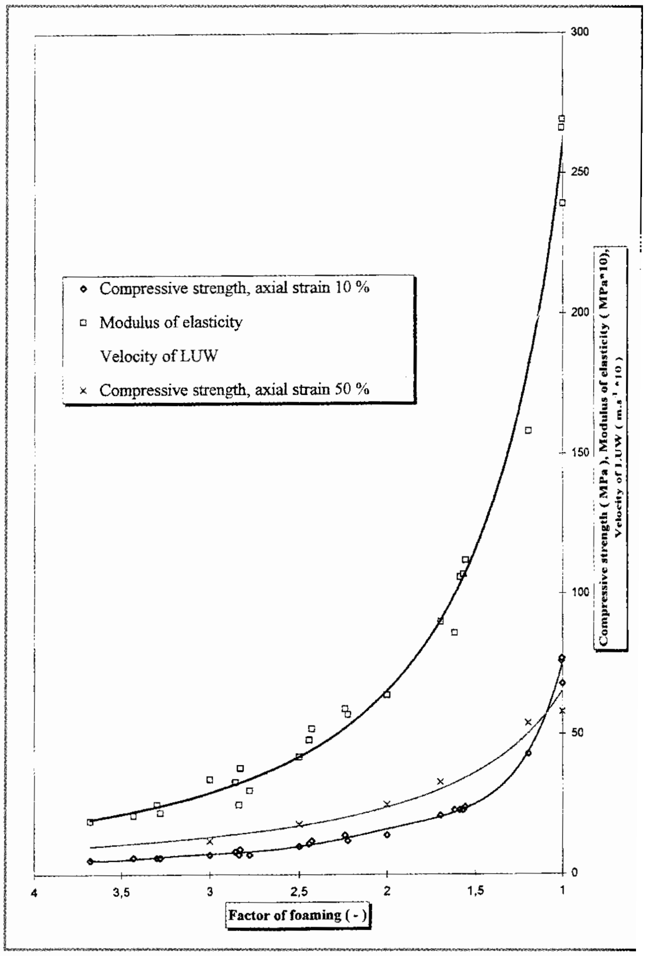


Figure 2. Compressive strength, modulus of elasticity and velocity of longitudional ultrasonic waves vs. factor of foaming.

Deformation curves of grouts with higher factor of foaming ($k_{nap}$ = 1,5 - 3) have characteristic of elastic - plastic material with non-linear strengthening; the strengthening decreases with increasing factor of foaming. The maximal force from deformation curves for calculation of the compressive strength was established at axial deformation 10 % and 50 %, i. e. extreme deformation (Widmann 1994).

Module of elasticity (deformation) were specified from the head linear part of deformation curves in the range of the axial deformation to 3 mm. The results of described tests are shown on the Figure 2. Resulting form of specimens even after axial deformation 50 % was barrel-shaped without fragile breaking (fissures, cracks) (Figure 3).

It is evident from the results, that the most expressive decrease of mechanical properties of samples comes in the range of foaming factor to 1,5 or 2. Further raising of the factor causes relatively smaller decrease of measured values. Behaviour of cured grout at big deformations is relatively less influenced by factor of foaming.

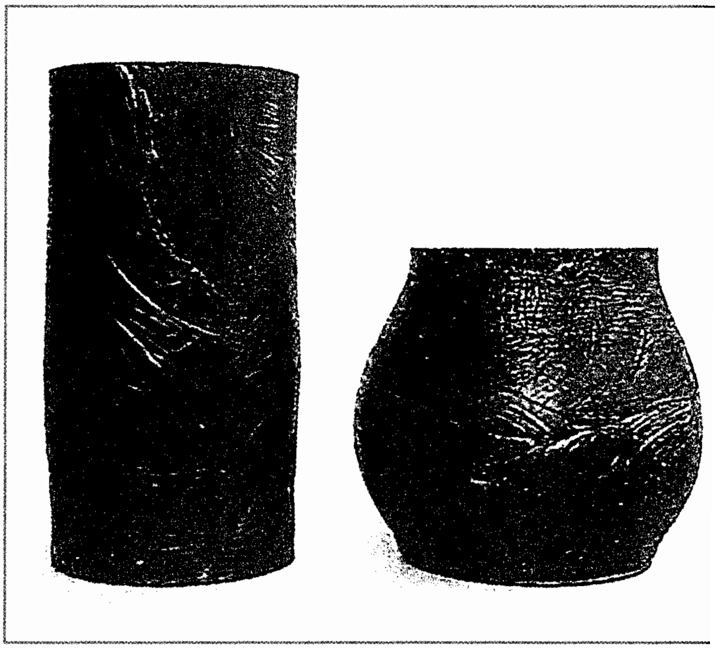

Figure 3. Specimens of grout Bevedan - Bevedol WF after axial deformation 10 % and 50 (factor of foaming - 1,0).

## LABORATORY TESTING OF GROUTING PROCESS AND PROPERTIES OF GEOCOMPOSITES

Laboratory research of grouting involves two groups of tests. Tests in pressure vessels fulfilled with rock material are executed in case of soils and crushed rocks. In hard rocks grouting tests of particular fissures (mostly artificially prepared) are used. Samples of grouted rocks and soils are tested after curing and physical and mechanical properties of geocomposites are measured.

The research of cracks grouting can be demonstrated on the tests of polyurethane gel Resicast, which was then successfully applied for sealing of concrete pressure walls of underground gas storage. Grouting tests were executed on cylindrical specimens from drill cores of carboniferous sandstone and siltstone with diameter 85 and 100 mm and height 200 mm. In the longitudinal axis of specimen the grouting hole was drilled into the depth of 2/3 of the sample height. Artificial crack perpendicular to the longitudinal axis was then executed by breaking of the sample. Polyurethane gel Resicast in composition GH 96D : GH 90 like 6 : 4 (mixed with water 1 : 9) was grouted into specimens which were pressed in hydraulic press. Al foil was used in the part of fissure plane to specify of the separation of the crack. The scheme of the test is shown in Figure 4.

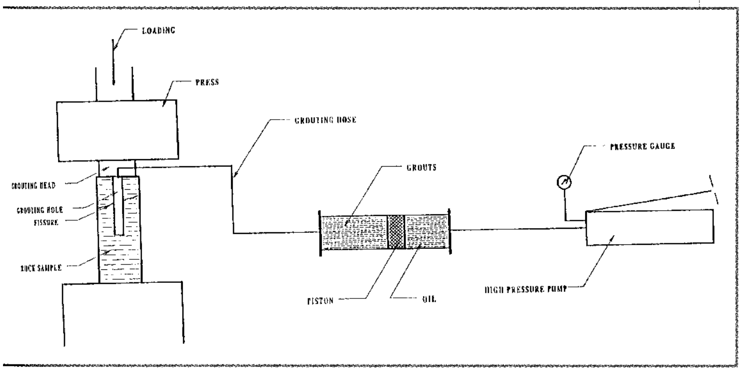


Figure 4. Scheme of fissure grouting test.

The velocity of grout spreading from central hole to periphery in relation to grouting pressure was measured. After curing of the gel the grouting hole was unblocked and the following group of tests was executed. Water was grouted into the specimens under the same conditions with measuring of pressure, to estimate sealing properties of the polyurethane gel. The results showed, that the tested grout can be effectively injected into fissures with minimum separation 0,02 mm with pressure app. 10 MPa. Sealing capacity of the gel can be proved by comparison of pressure values during grouting with pressure values during successive water test in the same specimens:

- sandstone - fissure 0,1 mm: grouting pressure 3,5 MPa, resistance against water 10 MPa
- siltstone - fissure 0,02 mm: grouting pressure 12 MPa, resistance against water 34 MPa.

In the majority cases the failure during water tests did not occur in grouted fissures.

Adhesion to surface of discontinuities and mechanical properties of grouted fissures under different loading are tested in case of reinforcing grouts. Here we mention tensile tests. Three kinds of tensile tests (one direct and two indirect methods) were executed :

- tensile strength test (direct method)
- transverse tensile strength test (brasilian test)
- sleeve fracturing test

Artificial fissure is cut in rock sample and filled with grout. After curing the specimens are tested in press. In the direct tensile test the cylindrical sample is pulled in longitudinal axis, perpendicular to the injected fissure. Specimen is clasped in mechanical jaws.

In the transverse tensile test the discontinuity is situated in longitudinal axis. Specimen is loaded with almost linear force along the fissure edge. The kind of loading causes tensile strain of the fissure (with the exception of the fissure edge immediate surrounding).

In the sleeve fracturing test specimens have shape of disk with circular central hole, corresponding to the diameter of co-axial bolts. The fissure passes through the central hole (Figure 5). The central hole is filled with plastic material and tensile strain is made out by pressure of co-axial bolts. The tensile strain is calculated on the base of the theory of thick-walled cylindrical vessels. Typical record of sleeve fracturing test is shown on Figure 6.

The results of tests are represented in Table 1, which contains the comparison of results from different testing methods on the same materials.

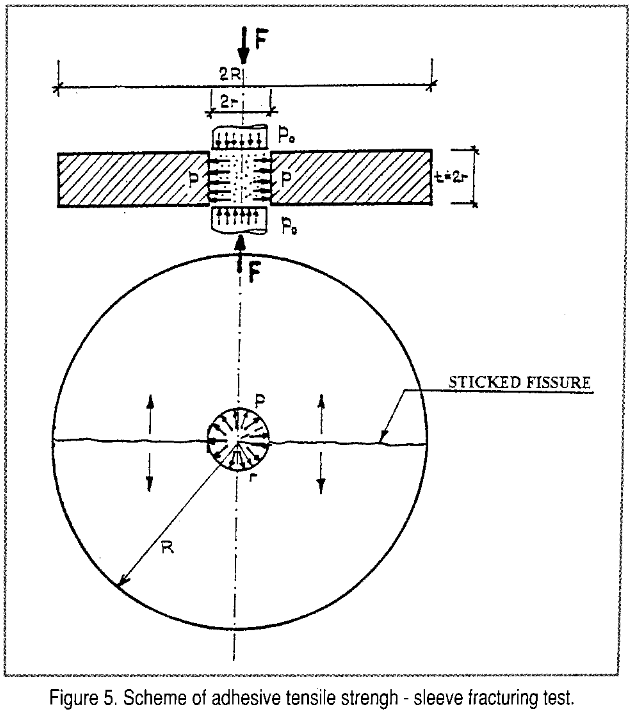


Figure 5. Scheme of adhesive tensile strengh - sleeve fracturing test.

| TEST NUMBER | ADHESIVE TENSILE STRENGTH | | |
|---|---|---|---|
| | Direct tensile test | Brazilian test | Sleeve fracturing test |
| | (MPa) | (MPa) | (Mpa) |
| 1 | 1,85* | 9,42* | 3,9*2 |
| 2 | 3,31* | 12,79*1 | 3,1*2 |
| 3 | 3,98* | 7,22*1 | 3,5*2 |
| 4 | 5,46* | 10,50*1 | 4,1*2 |
| 5 | 5,92* | 10,20*1 | 3,6*2 |
| 6 | — | - | 3,6*2 |
| 7 | — | - | 4,0*2 |
| 8 | — | - | 3,8*2 |
| **Average value** | **4,10** | **10,03** | **3,7** |
| **Standard deviation** | 1,47 | 1,80 | 0,3 |

*..... tensile failure out of stuck fissure
*1... combined tensile failure in rock sample and stuck fissure
( app. 15 - 20 % in rock sample, 80 % in contact of rock and grout)
*2... tensile failure only in contact of rock and grout

Table 1. Resulting values of adhesive tensile strength
(coarse - grained sandstone and grout Bevedan - Bevedol WF).

| TEST NUMBER | ADHESIVE TENSILE STRENGTH (MPa) | | |
|---|---|---|---|
| | Bevedan - Bevedol | Bevedan - Bevedol | Bevedan - Bevedol |
| | WF | WFA | S |
| 1 | 3,0* | 3,4 | 2,3 |
| 2 | 3,4 | 3,0 | 2,3 |
| 3 | 2,9 | 3,3 | 2,4 |
| 4 | 2,9 | 3,2 | 3,2 |
| 5 | 3,9 | 2,2 | 2,5 |
| 6 | 3,0 | 3,4 | 3,2 |
| 7 | 4,1 | 3,8 | 2,7 |
| 8 | 3,4 | 3,2 | 2,4 |
| **Average value** | **3,3** | **3,2** | **2,6** |
| **Standard deviation** | 0,43 | 0,43 | 0,35 |

Table 2. Resulting values of adhesive tensile strength of coarse-grained sandstone with three grouts Bevedan - Bevedol WF, Bevedan - Bevedol WFA and Bevedan - Bevedol S - sleeve fracturing test.

| TEST NUMBER | ADHESIVE TENSILE STRENGTH ( MPa ) | |
|---|---|---|
| | Bevedan - Bevedol WF + siltstone | Bevedan - Bevedol WF + coarse-grained sandstone |
| 1 | 4,4 | 3,0 |
| 2 | 4,7 | 3,4 |
| 3 | 3,5 | 2,9 |
| 4 | 3,6 | 2,9 |
| 5 | 3,6 | 3,9 |
| 6 | – | 3,0 |
| 7 | – | 4,1 |
| 8 | – | 3,4 |
| **Average value** | **4,0** | **3,3** |
| **Standard deviation** | 0,49 | 0,43 |

Table 3. Resulting values of adhesive tensile strength of coarse-grained sandstone and siltstone with grout Bevedan - Bevedol WF - sleeve fracturing test.

In all tests from the Tables 2 and 3 failures occurred in the contact of grout and rock in tested fissures.

The demonstrated results can be summarised :

- nominally comparable results can be obtained from the same kind of tests,
- the direct method, .i.e. simple tensile strength test is limited by rock strength, especially by stress in clasped jaws,
- sleeve fracturing tests provide good level results; the test is acceptable for comparative tests of grouts.

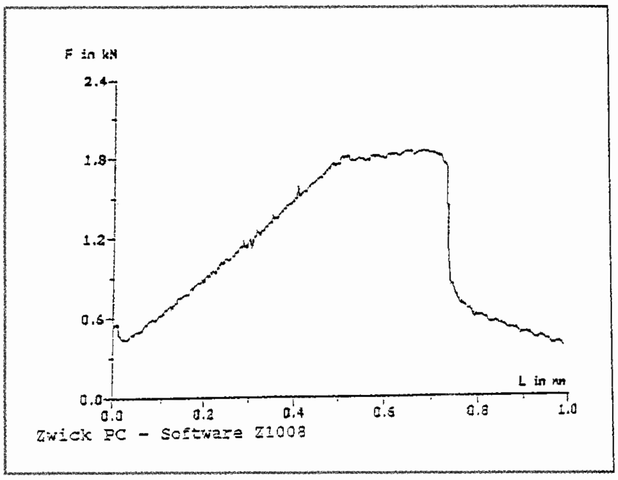


Figure 6. Record of sleeve fracturing.

The research of grouting process in porous soils and crushed rocks in pressure vessels includes measurements of grouting pressure in the pump and inside the vessel, volume of grout and its spreading in soil. Pressure tanks for the tests have different shape and dimension. Thick-wall tube with inner 145 mm diameter and 2 m length with regularly situated pressure gauges is used for the measurement of grout flow.

Pressure vessels used for tests can be dismantled into pieces, so all injected body can be removed and used for tests of physical and mechanical properties of created geocomposites.

Uniaxial compressive tests of geocomposites demonstrated, that the characteristics of deformation curves enables to divide tested materials into several groups according to the kind of deformation which is connected with the type of rock, grout and texture of injected sample. All groups with different values of compressive strength are characterised by high deformation over ultimate strength and high values of residual strength. Figure 7, 8 and 9 show characteristic deformation curves from uniaxial compressive tests of different geocomposites. Figure 7 represents high plastic material consists of fragmented shales, grouted with polyurethane resin Bevedan - Bevedol WF with foaming factor. Figure 8 shows much stronger but more fragile geocomposite, arisen from fragmented coal injected by grout Bevedan - Bevedol S almost without foaming (foaming factor 1). Figure 9 demonstrates geocomposite from gravel grouted with highly foamed resin Bevedan - Bevedol (foaming factor 3,1).

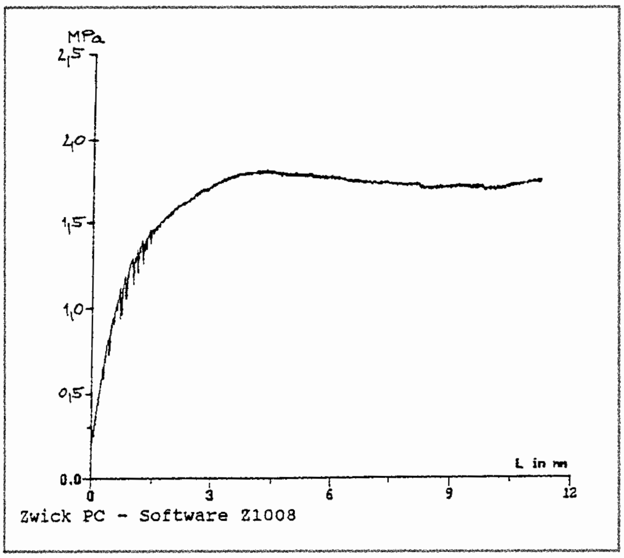


Figure 7. Record of unaxial compressive strength test.

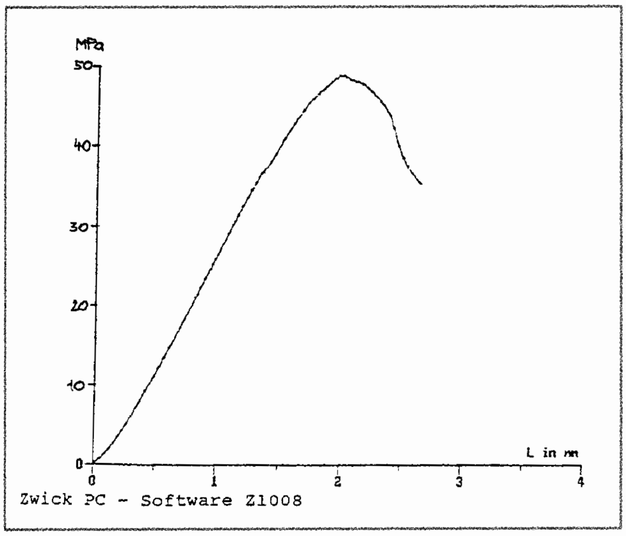


Figure 8. Record of unaxial compressive strength test.

## CONCLUSIONS

Laboratory tests show high effectivity of polyurethane grouts in both targets - sealing and reinforcing of rock.

An important feature of injected porous rock is that it has large deformability, especially beyond the compressive strength limit. This property is quite different from original quality of rock and thus may be of great importance for stability of grouted rock mass.

The real foaming factor of grout influences mechanical properties of the geocomposite i.e. compressive strength, modulus of elasticity and deformability significantly.

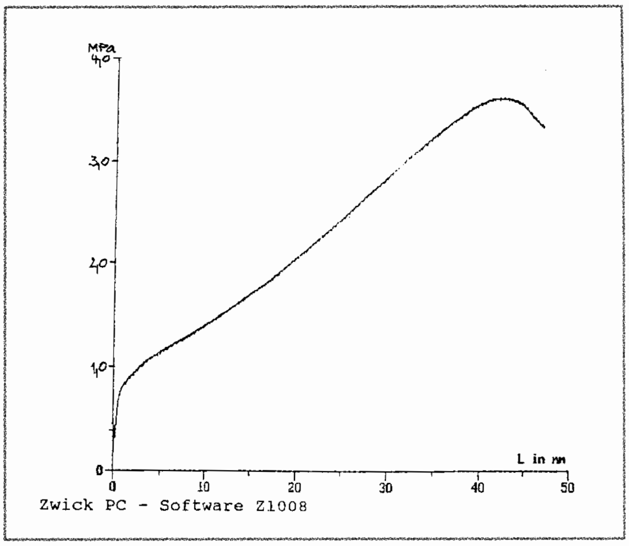


Figure 9. Record of unaxial compressive strength test.

The laboratory research of chemical grouts and geocomposites has recently developed and often requires approaches different from standard laboratory tests in rock mechanics and building materials.

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