This is Chapter 5 “Thermo-chemo-mechanical shotcrete model” from my PhD thesis

Kluckner, A. 2023. *Tunnelling at greater depths: Study on the ground and system behaviour when passing a stiff rock block in a weak zone*. PhD thesis. Graz University of Technology, Graz, Austria.

The full thesis can be downloaded from the TU Graz repository: LINK

If you have any questions or remarks, you can contact me on

ResearchGate: LINK

or on

LinkedIn: LINK.

Enjoy reading.

Best regards,
Alexander Kluckner

Dipl.-Ing. Alexander Kluckner, BSc

Tunnelling at greater depths: Study on the ground and system behaviour when passing a stiff rock block in a weak zone

DOCTORAL THESIS

to achieve the university degree of

Doktor der technischen Wissenschaften

submitted to

Graz University of Technology

Reviewers

Em.Univ.-Prof. Dipl.-Ing. Dr.mont. Wulf Schubert

Faculty of Civil Engineering Sciences
Graz University of Technology, Graz, Austria

Univ.-Prof. Dr. Nobuharu Isago

Faculty of Urban Environmental Sciences
Tokyo Metropolitan University, Tokyo, Japan

Graz, January 2023

Contents

Chapter 5

Thermo-chemo-mechanical shotcrete model

At the *Semmering Base Tunnel* (SBT), which is under construction, geotechnical engineers use the software suite TUNNEL:Monitor ([142]) to analyse recorded displacements of the tunnel lining. Besides standard evaluation approaches (e.g., displacement vector analysis, state line diagrams) (for details, refer to [291, Chapter 5, p. 42ff]), the suite also allows to calculate strains, stresses, and utilisations within the lining from displacement data. The latter is possible because of developments by *Prof. Christian Hellmich* (Vienna University of Technology, Vienna, Austria) and his colleagues (cf., e.g., [154, 236]). The developments resulted in the so-called *hybrid method*. [302] details one of the latest versions of the method. Descriptions below are limited to the version implemented in TUNNEL:Monitor installed at the SBT and utilised for this thesis (cf. Chapter 8 on p. 169, Chapter 9 on p. 201, and Chapter 10 on p. 243). Note that this implementation does not make use of the hierarchical modelling technique described in [302, Section 2.3, p. 229f].

The hybrid method comprises two main operations (cf. [210, p. 1048]):

1. Reconstruction of the displacement field history from the displacements recorded at monitoring cross sections at the construction site and approximation of the strain field.

2. Application of thermal, chemical, and mechanical considerations to model the material behaviour of the shotcrete. The resulting concept constitutes the so-called *thermo-chemo-mechanical shotcrete model*.

The following sections give some information on the two operations. If not referenced, cited information bases on personal communications with the software engineers of TUNNEL:Monitor.

Once the strain field is available, applying the shotcrete model results in lining stresses and utilisations variable in both space and time (in incremental form). Six layers discretize the lining across its thickness. Stresses are calculated for each layer. The utilisation is the average across the lining thickness. The model considers only circumferential and longitudinal axial stresses. Because shotcrete linings usually are in a biaxial stress state (cf. Section 4.4 on p. 49), this simplification is reasonable (cf. [210, p. 1050]).

The implementation makes use of the Boltzmann superposition principle (cf. Footnote 6 on p. 206). According to [354], the application of this principle yields acceptable results for the viscoelastic system response of a given stress history as long as the load or imposed deformation, either causing compressive or tensile stresses, continuously increases. It does not in case the load or imposed deformation varies strongly in its direction (e.g., large temperature increase under a restrained condition with compressive stresses first, then decrease of temperature causing a significant reduction of compressive stresses or even switch to tensile stresses). This excludes the stress decrease due to relaxation, provided that the load or imposed deformation still increases or at least remains unchanged. If the implemented shotcrete model uses Boltzmann's superposition principle without distinguishing between loading and unloading, it can therefore be assumed that it still yields acceptable results for stress histories primarily with an increase of load or imposed deformation over time.

5.1 Displacement and strain field

In the direction of the tunnel drive, monitoring cross sections are several metres apart from each other, each comprising a few monitoring targets only being uniformly distributed along the lining circumference (cf. Fig. 5.1 below and Fig. 8.5 on p. 180). To get a continuous displacement field in-plane (i.e., in the circumferential direction between monitoring targets), out-of-plane (i.e., in the longitudinal direction between neighbouring monitoring cross sections), and between two subsequent recordings regarding time, spatial and temporal interpolations are required. [158, p. 2107ff]

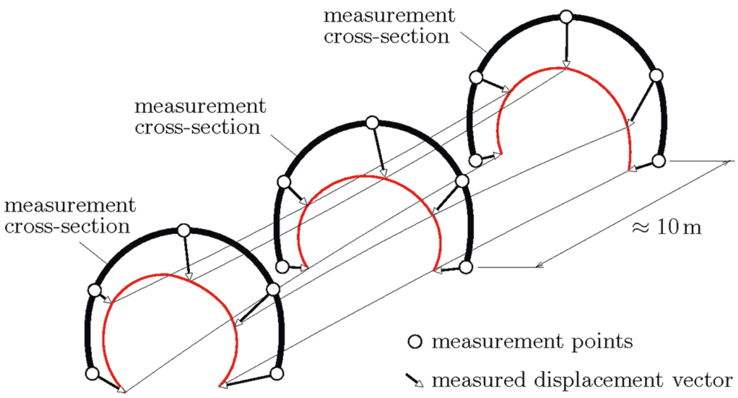

Figure 5.1: Conventional tunnel drives: Spatial interpolation of measured displacements in the circumferential direction between neighbouring measurement points (or targets), and in the longitudinal direction between neighbouring measurement (or monitoring) cross sections (from [302, Fig. 1, p. 228]).

First, interpolations are performed for each monitoring cross section using the in-plane displacement components. Spline functions allow for the temporal and spatial interpolations. The former depends on the number of measurement epochs available. Second, linear interpolations between two neighbouring monitoring cross sections result in the spatial displacement field. Longitudinal (or out-of-plane) displacements and out-of-plane bending remain unconsidered.

The approach works only in the scope of geometric linearity requiring deformations to be small compared to the dimensions of the engineering structure (cf. [242, p. 154]). If the hybrid method shall be able to simulate lining failure properly, it needs to consider geometric nonlinearity and surfaces of discontinuity. [154, p. 6]

Processing the changes in the displacement field (i.e., length of spline segments between calculation points, curvature at calculation points) yields the axial lining strain and the lining thickness. Plane cross sections being perpendicular to the circumferential lining axis before the deformation remain perpendicular during the deformation (fundamental assumption of the *Euler-Bernoulli* beam theory; cf., e.g., [334, Fig. D.9, p. 563]). This assumption is valid as long as the thickness is small.

5.2 Shotcrete model

The shotcrete model implemented in TUNNEL:Monitor at the SBT adopts the theory of thermodynamics of a chemically reactive porous continua by [86] considering the principle of mass conservation. Based on that theory, already in 1995, [401] developed a constitutive law for early age concrete. Here, the formation of the calcium silicate hydrate (C-S-H) phases on the microlevel is the main determinant of the description of the material behaviour (cf. [154, p. 6]). The approach decomposes the investigated continuum into representative elementary volumes (REV) and examines the energy state of each finite REV affected by chemo-physical transformations taking place inside (cf. [86] in [154, p. 8]). [399, 402] introduced chemoplasticity to consider for cracking. And [154] extended the concept towards shotcrete. Mechanical equilibrium and thermodynamics constitute the physics ([158, p. 2104]).

Shotcrete is a chemically reactive material with an evolving microstructure and each REV of the hardening shotcrete is the superposition of porous continua with **n** fluid phases and **1** skeleton phase (cf. Fig. 5.2). The latter comprises aggregates, unhydrated cement, and hydrates. Because hydrates already formed enclose unhydrated cement, free water (not yet combined with cement) needs to bypass those hydrates. The water has to diffuse through them. As the hydrates grow, it takes more time for the water to reach the unhydrated cement. This diffusion process determines the rate of hydration (cf. Section 4.1 on p. 47). [154, p. 6ff]

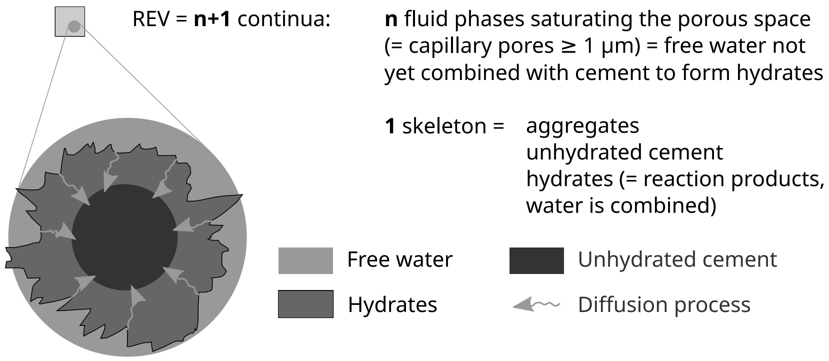

Figure 5.2: Diffusion of water through layers of hydrates (redrawn and modified from [401, Fig. 1, p. 787]).

On the macroscale, a single chemical reaction may represent the hydration process, having the reactant phase at the start and the product phase at the end. On the scale of the REV, because of the chemical reaction, the volume fractions of their constituents (i.e., fluid phases and skeleton) continuously change. Three laws help to describe the energy state[1] and its change within a REV:

- Mass conservation law: ". . . the total mass is constant during a chemical reaction . . . " ([16, p. F68]);
- First law of thermodynamics (= the conservation of energy principle): ". . . the conservation of energy in all of its forms." ([154, p. 8]); ". . . energy can be neither created nor destroyed during a process; it can only change forms." ([66, p. 70]); "The internal energy of an isolated system is constant." ([16, p. B10]);

[1] Energy exists in different forms ([119, p. 4-3]): gravitational energy, electrical energy, radiant energy, nuclear energy, kinetic energy, mass energy, heat energy, elastic energy, and chemical energy. The last three forms are treated by the approach described here.

- Second law of thermodynamics: "...the quality of energy, i.e. its transformability into efficient mechanical work, can only deteriorate." ([154, p. 9]); "The quantity of energy is always preserved during an actual process (the first law), but the quality is bound to decrease (the second law). This decrease in quality is always accompanied by an increase in entropy." ([66, p. 340]);[2] "A spontaneous change is accompanied by an increase in the total entropy of the system and its surroundings." ([16, p. B22]).

Note that the REV are assumed to be closed (i.e., sealed conditions). The external mass supply is zero. [154, p. 7ff]

In thermodynamics of continua, so-called state variables (e.g., temperature, or pressure) characterise the state of a system (here, it is the energy state of a REV). By observing those state variables, the REV's state can be determined. An important feature of a state variable is that it "depends only on the current state of the system", but it is independent of "the path or the means of attaining the state". Further, "any change in its value is independent of how the change in state was brought about." Here, the evolution of a state variable of a REV is independent of the variable's evolution rate and of the state of a neighbouring REV (local state postulate). The latter may be not true but is assumed. ([16, p. 273], [133, terms *property* and *state* on p. 58], [154, p. 9])

For each REV, the energy state is described in full by several state variables. Their evolution constitutes the evolution of the REV. The model by [154, p. 9f] considers following state variables:

- $\boldsymbol{\varepsilon}$: strain tensor;
- T: absolute temperature;
- m: mass of non-evaporable water per unit volume combined with cement to form hydrates;
- $\boldsymbol{\varepsilon}^p$: plastic strain tensor;
- $\boldsymbol{\chi}$: vector of strain hardening and softening variables;
- w: mass of water per unit volume engaged in the micro-diffusion process;
- $\boldsymbol{\varepsilon}^f$: flow strain tensor;
- γ: viscous slip.

$\boldsymbol{\varepsilon}$ and T are external state variables as they are directly measurable on the macroscale.[3] The others are internal (hidden) state variables. The latter directly link to physical and chemical dissipative phenomena taking place on the microscale. $\boldsymbol{\varepsilon}^p$ and $\boldsymbol{\chi}$ represent the irreversible skeleton deformation resulting from microcracking (cf. Section 4.6.5 on p. 60). The micro-diffusion process characterised by w results in (viscoelastic) short-term creep (cf. Section 4.6.4 on p. 57). $\boldsymbol{\varepsilon}^f$ and γ relate to the long-term creep (cf. Section 4.6.4 on p. 57) because of dislocation-like processes in the nanopores of the C-S-H phase (cf. Subsection 'Concept of the microprestress force' on p. 60). And m directly links with strength growth, because m is proportional to the increase in hydrate mass ([401, p. 788]) (cf. Section 4.2 on p. 47). [154, p. 10]

[2] Entropy is a thermodynamic quantity relating a change in the heat to the temperature. [243, p. 306]

[3] Normality is assumed for T and $\boldsymbol{\varepsilon}$ with respect to other state variables. "A particular state variable is said to be normal with respect to a set of state variables if evolutions of this state variable can occur independently from the evolutions of the state variables of the considered set" ([154, p. 11]).

By introducing the intrinsic dissipation[4] per unit volume of a closed system, a relation between the stress tensor, $\boldsymbol{\sigma}$, and the strain tensor, $\boldsymbol{\varepsilon}$, is established (cf. [155, p. 692]). It comprises the Helmholtz energy (or free energy), Ψ, depending on the internal energy, e,[5] the internal entropy, S,[6] and T (cf. [87, p. 12], [154, p. 9]). Note that Ψ refers to systems where the volume is maintained constant ([16, p. 40]). Now, [154] relates the microscopically phenomena taking place in shotcrete material represented by the internal state variables cited above to energetically conjugated thermodynamic forces using state equations ([212, p. 303]). Then, $\Psi = \Psi\left(\boldsymbol{\varepsilon}, T, m, \boldsymbol{\varepsilon}^p, \boldsymbol{\chi}, w, \boldsymbol{\varepsilon}^f, \gamma\right)$ ([154, p. 9]). Thermodynamic forces are ([154, p. 11ff]):

- $\boldsymbol{\sigma}$: stresses; driving force of plastic and flow strains;
- A_m: chemical affinity (cf. Section 4.1 on p. 47); driving force of the hydration process;
- A_w: driving force of short-term creep; it's associated with the rate of water diffusion in the capillary pores;
- $\boldsymbol{\zeta}$: hardening force; driving force of strain hardening and softening;
- Γ: microprestress force (cf. Subsection 'Concept of the microprestress force' on p. 60); driving force of viscous slip;
- grad$T$[7]: driving force of the entropy flow.

$\left\{\boldsymbol{\sigma}; \boldsymbol{\varepsilon}^p; \boldsymbol{\varepsilon}^f; \boldsymbol{\chi}; \gamma; \boldsymbol{\zeta}; \Gamma\right\}$ determine the intrinsic dissipation, φ_i; it is $\{A_m; m; A_w; w\}$ for the chemical dissipation, $\varphi_{\rightarrow}$, and it is $\{\text{grad}T; T\}$ for the thermal dissipation related to heat conduction, φ_T. The mechanical dissipation, $\varphi_M = \varphi_i + \varphi_{\rightarrow}$, describes "the rate of mechanical energy transformed irreversibly into heat". $A_m \dot{m}$[8], for example, is a heat source and refers to the energy and heat because of the diffusion of free water through the layers of hydrates (i.e., the latent dissipative heat due to the exothermic nature of the hydration reaction). [154, p. 11f, 17]

Now consider that the thermodynamic forces $\{\boldsymbol{\sigma}; A_m; A_w; \boldsymbol{\zeta}; \Gamma\}$ and the entropy, S, all link to (or are derived from) the free Helmholtz energy, Ψ. Thus, mutual dependencies must exist. They are described via mixed partial derivatives of Ψ. These relations (or dependencies) are termed *Maxwell symmetries* (cf., e.g., [66, p. 649f]) and, here, they constitute thermo-chemo-mechanical couplings in the shotcrete material. Knowing a minimum of material parameters (e.g., from calorimetric or creep tests), those couplings allow for characterising all other state variables (e.g., evolution of the plastic/hardening properties) ([402, p. 1131]). [154, p. 14]

The following subsections give some information on the couplings considered in the shotcrete model, on evolution rates of the microscopic dissipative phenomena (i.e., time derivatives of state variables) mathematically described with evolution equations[9], and on how some important input parameters can be determined.

5.2.1 Chemo-thermal coupling

When free water combines with cement during hydration (chemical reaction), latent heat is produced and the temperature changes. The coupling links the development of the latent heat to

[4] Intrinsic ... independent of field and boundary conditions (cf. [154, p. 6]).

[5] It is the total energy of a system. [16, p. B13]

[6] Cf. Footnote 2 on p. 72.

[7] *grad* is a mathematical operator that makes a vector from a scalar ([119, p. 14f]). The vector "is in the direction of steepest ascent" and "its magnitude is the rate of increase" "with distance in this direction" [243, p. 15].

[8] Dots on top of letters symbolise derivatives with respect to time.

[9] Evolution equations are used linking the rates of the internal state variables to the corresponding thermodynamic forces ([212, p. 303]). Here also the Maxwell symmetries and resulting couplings are essential (cf. [154, p. 18, 30]).

the energy state and yields the temporal and spatial distribution of the temperature, $T = T(t, x)$, and the hydration degree, $\xi = \xi(t, x)$. The model assumes following heat sources to be negligible and, thus, neglects them: heat due to microcracking and dislocation-like sliding within the hydrates (cf. [399]) and heat due to diffusion of absorbed water leading to short-term creep. Both are dissipative heat effects associated with friction (cf. [87, p. 86]) and mechanical work on the molecular- or microscale because of fluid flow and viscoelastic or plastic deformations. The model also assumes that no significant volume heat sources exist in shotcrete tunnel linings. [154, p. 17f], [158, p. 2104], [402, p. 1125]

The chemical affinity, A_m, depends on the state variables $\{\boldsymbol{\varepsilon}; T; \boldsymbol{\chi}; m; w; \gamma\}$. However, as a first approximation, it gets decoupled from $\{\boldsymbol{\varepsilon}; T; \boldsymbol{\chi}; w; \gamma\}$ (cf. [401]).[10] Thus, the driving force of the hydration, A_m, depends only on the hydration itself: $A_m \approx A_m(m)$. In this way, the influence of microcracking on strength growth, for example, is neglected.[11] [154, p. 24]

Since hydration is thermally activated, the evolution law by [401] used in this model considers the Arrhenius equation. Introducing the hydration degree, $\xi = m/m_\infty$, (cf. Section 4.1 on p. 47) with m_∞ being the asymptotic hydration mass, and with $m_\infty = m_\infty(A_0)$ (cf. [402, p. 1127]), where A_0 is the initial chemical affinity (starting the chemical reaction; [155, p. 694]), a relation between $\dot{\xi}$ and $\tilde{A}$ can be established. $\tilde{A} = A_m/(m_\infty \eta_m)$ is the normalised chemical affinity (cf. [402]). η_m is the viscosity describing the hydration rate. [154, p. 24f]

Knowing the normalised chemical affinity from a laboratory test (cf. Subsection 'Ageing' on p. 75), a two-dimensional, central-symmetric Finite Element simulation then yields the time-dependent temperature and hydration degree field across the lining thickness by solving the heat transfer problem.

For an example of thermo-mechanical simulations considering the same coupling approach, refer to [150].

5.2.2 Thermo-mechanical coupling

This coupling simply yields the strain resulting because of changes in the temperature (i.e., thermal strain). For the concrete material, isotropy of the thermal dilatation is assumed (cf. also Section 4.6.2 on p. 52). [154, p. 15]

5.2.3 Chemo-mechanical coupling

With this coupling, the development of the macroscopic, intrinsic material properties with the hydration degree, ξ, (from the chemo-thermo coupling; cf. first subsection above) is described. It's the Young's modulus, E, the uniaxial peak compressive strength, f_c, the chemical dilatation (i.e., autogenous shrinkage, ε^{shr}), the asymptotic long-term creep compliance, J^f_∞, and the characteristic time for the short-term (viscoelastic) creep, τ_w. The model assumes that they all depend on the mass of hydrates formed only (for some of them, weak links to other state variables exist but are neglected; cf. [44, 63, 399, 401] in [154, p. 15f]). The couplings establish the relation between the microscopic phenomena of chemical or mechanical origin and the strains they provoke (cf. [370, p. 285]). For more information on the material properties, refer to Section 4.2 (p. 47) and related subsections in Section 4.6 (p. 51).

[10] According to [402, p. 1127] (referring to [401]), the relations between the chemical affinity and the loading history and temperature changes induced by external heat supply are weak. However, in case temperature changes and loading (here in terms of mean stress) are high in magnitude, their influence may be significant.

[11] Note that the development of strength depends only on m. But the compressive strength at a particular moment depends also on the state of microcracking, χ, (cf. Subsection 'Microcracking—multisurface chemoplasticity' on p. 77).

The model only considers basic creep (in terms of short- and long-term creep; cf. subsections below). It neglects drying creep (cf. Section 4.6.4 on p. 57) on the basis that drying is negligible considering the humid conditions usually present in tunnels ([154, p. 27]). The creep model follows the solidification theory after [32, 31].

The primary model only considers autogenous shrinkage. It neglects drying shrinkage. The software engineers of TUNNEL:Monitor substituted the original formulation with equations suggested by [20] accounting for both autogenous and drying shrinkage. For general information on shrinkage, refer to Section 4.6.3 (p. 54). The information given in the first subsection below refers to the implementation in the primary model.

The following subsections give some information on the microscopic phenomena mentioned above.

Ageing

Predicting ξ requires the knowledge of $\tilde{A}$. In adiabatic[12] or semi-adiabatic calorimetric experiments (at a constant temperature, T;[13] semi-adiabatic: experimental device allows for a certain heat diffusion, cf. [154, p. 39]), the accumulated heat is measured that develops during the hardening of a cement paste sample. As the heat release is proportional to $\tilde{A}$, such an experiment yields the development of $\tilde{A}$ with time. Solving the transient heat transfer problem mentioned in Section 5.2.1 results in the development of ξ with time. Fig. 5.3d plots $\tilde{A}$ over ξ. [123, 320] in [172, p. 49], [304, p. 3, 11f]

ξ now can be linked to the consequences of the hardening on the macroscale, the material properties. The evolution of shotcrete strength as a function of ξ and the linearity of the chemical hardening (cf. Fig. 5.3c and Fig. 5.5b) is verified experimentally by, e.g., [44, 63, 263]. ξ_0 in Fig. 5.3c is the so-called percolation threshold (cf. [6]). Below this threshold, the ground-lining system behaves like there would be no lining at all ([156, p. 706]). Beyond the threshold, the material can support a stress deviator and starts to carry load ([370, p. 288]). Here the threshold is 5%. In [154, p. 44], [158, Fig. 2, p. 2106], and [212, Fig. 16, p. 303], it is 1%. However, the threshold can be also higher (cf. [303]). It is assumed that hydration is practically completed after 28 days ([154, p. 50]; cf. also [347, Tab. 1, p. 5]). With a compression test on a shotcrete sample at an age of 28 days, $f_c = f_c(\xi)$ can be described (cf. Fig. 5.5b). [154, p. 30ff]

In a similar way, the Young's modulus, E, and the autogenous shrinkage strains, ε^{shr}, are linked with ξ (cf. Fig. 5.4, and Fig. 5.5a). The model assumes isotropic elasticity, isotropy for the chemical dilatation (i.e., autogenous shrinkage), and a constant Poisson's ratio, ν, (for ν, refer to Section 4.9.1 on p. 67). The slope of the straight line in Fig. 5.4d is characterised by the chemical dilatation coefficient. When evaluating Fig. 5.4, relating graph (a) with (c) and (b) with (d), consider that the relation between ξ and t is nonlinear (cf. [402, p. 1128]). [154, p. 32ff]

Models on basis of the degree of hydration are usually formulated via direct coupling between the release of heat of hydration and strength growth. This works particularly well if the binder does not contain any latent hydraulic components. Now the problem is, in case the concrete mix comprises slag cement or fly ash[14], the coupling between hydration heat and strength growth gets weak. This is because those additives set hydraulically featuring a latent nature ([393] in [353, p. 10]). That means that hydration of these additives proceeds—and contributes to strength growth—even if the temperature and the hydration degree do not change ([355]).

[12] In an adiabatic system or process, no heat energy is transferred to or from the surrounding. However, energy in terms of work may be transferred. [16, p. 268, 309], [243, p. 311]

[13] The temperature, T, influences the kinetics of the hydration. The reaction is faster if T is higher. [401, p. 782]

[14] Additives like fly ash and granulated slag are used to improve the properties of the sprayed concrete (e.g., workability, rebound). [289, p. 12]

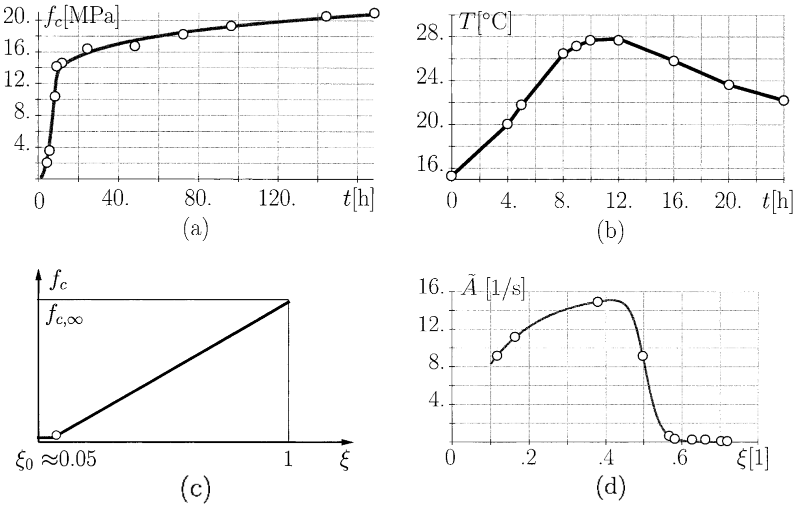

Figure 5.3: Hydration related parameter developments for a shotcrete material (from [155, Fig. 1–3, p. 694f]): (a) uniaxial peak compressive strength, $f_c = f_c(t)$; (b) temperature, T, during hydration; (c) linear chemical hardening, $f_c = f_c(\xi)$; (d) normalised chemical affinity, $\tilde{A} = \tilde{A}(\xi)$. Test data for (a), (b), and (d) from [173]. Note the different scaling of the axis of abscissas in (a) and (b).

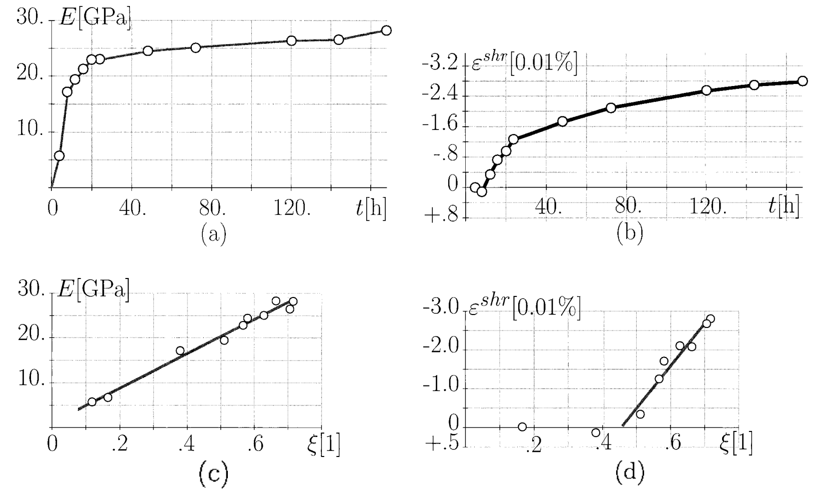

Figure 5.4: Hydration related parameter developments for a shotcrete material (from [155, Fig. 4–5, p. 695]): (a) Young's modulus, $E = E(t)$; (b) autogenous shrinkage strains, $\varepsilon^{shr} = \varepsilon^{shr}(t)$; (c) chemo-mechanical coupling of the Young's modulus, $E = E(\xi)$; (d) chemo-mechanical coupling of the autogenous shrinkage strains, $\varepsilon^{shr} = \varepsilon^{shr}(\xi)$. Test data from [173].

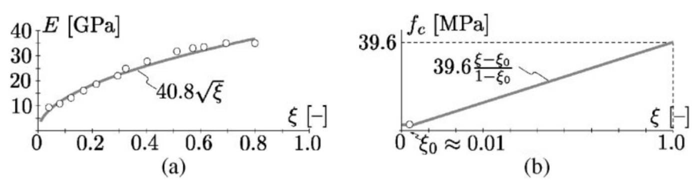

Figure 5.5: Hydration related evolutions of the shotcrete material implemented in the thermo-chemo-mechanical shotcrete model (modified from [211, p. 2363, Fig. 2b–c]): (a) Young's modulus, $E = E(\xi)$; (b) uniaxial peak compressive strength, $f_c = f_c(\xi)$.

Microcracking—multisurface chemoplasticity

The hardening force, ζ, depends on the state variables $\{\boldsymbol{\chi}; m; w; \gamma\}$. ζ relates to the material's strength and, according to experiments, depends only on $\{\boldsymbol{\chi}; m\}$. Thus, the model neglects w and γ (partial decoupling), and chemical hardening (i.e., strength growth) and plastic hardening and softening determine ζ. [154, p. 18]

The model is a two-surface chemoplasticity model comprising a Drucker-Prager[15] loading surface and a tension cut-off (Rankine criterion) (cf. Fig. 5.6; [155, p. 692]). It uses standard multisurface plasticity approaches to determine plastically admissible stress states and for the definition of the flow rule and the hardening rule. Associative hardening plasticity is assumed. [154, p. 19]

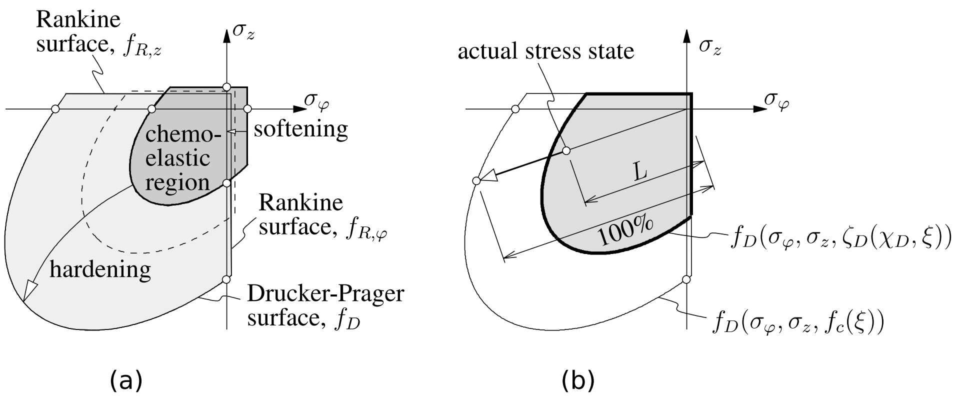

Figure 5.6: Shotcrete model: Yield surfaces in the σ_φ-σ_z stress space (from [210, Fig. 7 on p. 1054, Fig. 22 on p. 1065]): (a) description of the stress space and the yield surfaces; (b) illustration of the level of loading. z is the coordinate in the direction of the tunnel drive. φ is the angular coordinate in the circumferential direction.

The yield functions both on the compression and tension side depend on hardening parameters, namely χ_1 and χ_2. They make up the vector of strain hardening and softening variables, $\boldsymbol{\chi}$, and are linked to plastic volume dilation, ε_v^p. [154, p. 34f]

All input parameters to calibrate the loading surfaces can be determined from standard laboratory tests ([154, p. 36]):

- uniaxial peak compressive strength, f_c;
- uniaxial compressive yield strength, f_{cy};
- biaxial compressive strength, f_b;
- uniaxial peak tensile strength, f_t;
- uniaxial compressive strain at f_c (complete hydration assumed), $\varepsilon^u_{c,\infty} = 0.0022$ m/m (cf. [158, caption of Fig. 1, p. 2105]).

The model assumes isotropy of the chemical hardening: f_b/f_c = constant, f_{cy}/f_c = constant, and f_t/f_c = constant (cf. Section 4.8 on p. 64). On the compression side, the plastic hardening between $\{f_y; \chi = 0\}$ and $\{f_c; \chi = \chi_u\}$ is described with a quadratic plastic hardening law (cf. Fig. 5.7). R in the graph is the uniaxial chemoplastic compressive threshold. f_{cy} and f_c depend

[15]The Drucker-Prager model is acceptable for predominantly biaxial stress states (which is assumed here; cf. Section 4.4 on p. 49) but is insufficient in case of significant triaxial compressive stress states ([260, p. 3135]). In any case, in consequence of the isotropy of chemical and plastic hardening, the model cannot account for a dependence of the friction angle on the hydration degree or on the stresses ([402, p. 1130]).

on ξ. However, the development of strength is still linear and so is the coupling of ξ with $\boldsymbol{\chi}$. Note from Fig. 5.7 that the value of the hardening parameter at f_c, χ_u, is independent from ξ. Note also that plastic hardening is considered being isotropic ([402, p. 1130]). [154, p. 36ff]

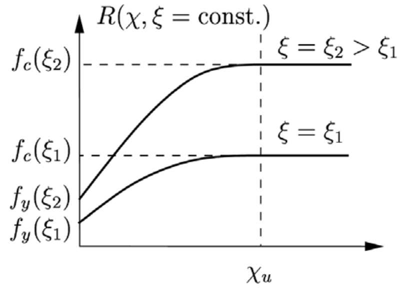

Figure 5.7: Shotcrete model: Quadratic hardening law for two different degrees of hydration, ξ_1 and ξ_2, (from [158, Fig. 1b, p. 2105]). Note that f_y in the graph is f_{cy} in the text.

On the tension side, the model neglects plastic softening. Thus, in contrast to the compression side, the hardening force, ζ, is determined by ξ only and is independent from $\boldsymbol{\chi}$ (i.e., purely chemical hardening assumed). [154, p. 38]

Dislocation-like sliding in hydrates—long-term creep

The microprestress force, Γ, depends on the state variables $\{\boldsymbol{\chi}; m; w; \gamma\}$. However, based on experimental results, it gets decoupled from $\boldsymbol{\chi}$ and w. The model further neglects the influence of the evolution rate of m on $\dot{\Gamma}$. [154, p. 20f, 49]

Long-term creep starts with reaching the percolation threshold, ξ_0, (cf. p. 75). The material then can bear a deviatoric stress state. [370, p. 288]

The flow strains, $\dot{\boldsymbol{\varepsilon}}^f$, and the viscous slip, $\dot{\gamma}$, are activated thermally (cf. [27]). Thus, both the evolution law for $\dot{\boldsymbol{\varepsilon}}^f$ and the evolution law for $\dot{\gamma}$ consider the Arrhenius equation (cf. [16, p. 640]). [154, p. 21f]

Standard creep tests on concrete (or shotcrete) samples can be used to determine the required material parameters, but

- the conditions should be isothermal;
- the applied constant stress should be below $0.3 f_c$ (i.e., below the limit of proportionality; cf. Section 4.9 on p. 66);
- the applied stress should not vary during the loading phase of the test but remain constant;
- shrinkage tests (without loading) should be carried out simultaneously under the same conditions to get the shrinkage strains;
- several creep tests should be carried out varying the age of loading and the age of unloading (for the reversible part); this allows to determine the effect of ageing on creep.

With the constant compressive loading, σ, and the measured strain changing with time, ε, the compliance, $J = \varepsilon/\sigma$, can be calculated (cf. Fig. 5.8a). The latter "is the strain in the direction of the load application per unit of (uniaxial) stress." It's a characteristic material property ([153, p. 9]). Note that for the determination of the creep parameters, shrinkage strains and thermal strains must be subtracted out of ε. [154, p. 23, 46ff]

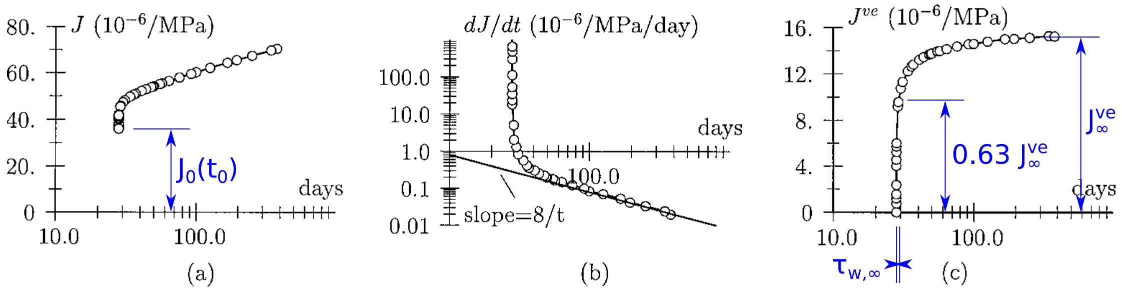

Figure 5.8: Exemplary compliance for a shotcrete using data from a creep test by [173] (modified from [370, Fig. 2a–c, p. 288]; modifications in blue). Development of the total mechanical compliance, J, (a), the rate of J (b), and the short-term creep compliance, J^{ve}, (c) with time. Note the logarithmic scaling of the axis of ordinates in all graphs, and of the axis of abscissas in graph (b). Note that J^{ve} in graph (c) is J^{v} in the text.

This compliance, or the stress-strain relation from a creep test in general, covers three components (modified after [154, Eq. 3.46, p. 49]):

$$\int dJ = \int_{t_0}^{t} \frac{dJ}{dt} dt = J(t, t_0) = J^v(t, t_0) + J^f(t, t_0) + J_0(t_0). \tag{5.1}$$

The constant of integration, $J_0(t_0) = 1/E(\xi(t_0))$, is the instantaneous (or elastic) compliance at the moment of load application, t_0. $J^v(t, t_0)$ is the short-term creep compliance. And $J^f(t, t_0)$ is the long-term creep compliance. Because Eq. 5.1 lacks of components relating to (stress-free) shrinkage or thermal strains, it is termed total mechanical compliance. Fig 5.8b graphs the rate of total compliance, dJ/dt. Note here that the curve tends towards a straight line. According to experiments by [214] (cf. Fig. 1b in [370, p. 287]) and [400], all dJ/dt curves from tests on shotcrete samples different in their ages at the moment of loading, t_0, tend towards such a straight line.[16] [154, p. 49f], [370, p. 288f]

Diffusion of absorbed water—short-term creep

The thermodynamic force determining short-term creep, A_w, depends on the state variables $\{\boldsymbol{\varepsilon}; T; \boldsymbol{\chi}; m; w; \gamma\}$. The model assumes the influence of $\{T; \boldsymbol{\chi}; \gamma\}$ insignificant and neglects it. Next to the stiffness, the stress, and a function of m, the evolution law for the viscoelastic creep strain, $\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{v}}$, depends on τ_w. It's the characteristic time[17] of the micro-diffusion process that results in short-term creep. $\tau_w = \tau_w(m)$ and, thus, it depends on the shotcrete age. This accords with statements by [358]. [154, p. 22f], [370, p. 285]

Similar as for the long-term creep (cf. previous subsection), the compliance is introduced. It simplifies the evolution law assuming that the asymptotic short-term (viscoelastic) creep compliance, J^v_∞, is independent from m (cf. [370]). [154, p. 23]

Now, subtracting the elastic compliance, $J_0(t_0)$, and the long-term compliance, $J^f(t, t_0)$, from the total mechanical compliance, $J(t, t_0)$, the short-term compliance, $J^v(t, t_0)$, results (cf. Eq. 5.1). Fig 5.8c gives an example. Here, J^v_∞ results to 15×10^{-6} MPa. [370] introduces the linear relation $\tau_w = \xi \cdot \tau_{w,\infty}$ and assumes $\tau_{w,28} \approx \tau_{w,\infty} \approx$ constant. So, ageing has no influence on the short-term creep characteristics the moment the shotcrete is 28 days in age or older.

[16] However, the asymptotic value of J depends on t_0 and on the temperature, T. The earlier the concrete is loaded and the higher T, the higher is J. (cf. [370, p. 288f] and Section 4.6.4 on p. 57)

[17] This time parameter is also termed retardation time and is a characteristic material property. Its general form is $\tau = \eta/E$. It describes the time required for a process to reach a quasi-static state. After that (i.e., $(t - t_0) > \tau$), $\dot{J} \approx 0$. [138] in [153, p. 29]

The non-ageing compliance for the short-term creep is ([370, Eq. 33, p. 288])

$$J^v = J^v_\infty \left[1 - \exp\left(-\frac{t - t_0}{\tau_w}\right)\right]. \tag{5.2}$$

With $t - t_0 = \tau_w = \tau_{w,\infty}$, Eq. 5.2 yields the share of the short-term creep compliance at the moment after which ageing effects are assumed to be insignificant:

$$J^v = J^v_\infty \left[1 - \exp\left(-1\right)\right] = 0.63 J^v_\infty. \tag{5.3}$$

Evaluating $0.63 J^v_\infty$ in Fig 5.8c allows to determine $\tau_{w,\infty}$ from the same graph. Here, $\tau_{w,\infty} \approx 1$ day. [154, p. 49f], [370, p. 289]

By performing several creep tests, one can approximate the development of J^v_∞ and $\tau_{w,\infty}$ with ξ. For the former, [304], for example, consider a negative linear correlation: $J^v_\infty(\xi) = J^{v,ini}_\infty (1 - \xi)$.

Bibliography

[1] Abler, P. *Einflüsse auf das Verformungsverhalten von jungem Spritzbeton im Tunnelbau.* Diploma thesis, University of Innsbruck, Innsbruck, Austria, 1992.

[2] ACI. ACI Manual of Concrete Practice. Technical report, American Concrete Institute (ACI), 1978.

[3] ACI Committee 209. 209R-92. Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures. Technical report, American Concrete Institute (ACI), March 1992. Reapproved 1997.

[4] ACI Committee 209. 209.1R-05. Report on Factors Affecting Shrinkage and Creep of Hardened Concrete. Technical report, American Concrete Institute (ACI), July 2005.

[5] ACI Committee 209. 209.2R-08. Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete. Technical report, American Concrete Institute (ACI), May 2008.

[6] Acker, P. *Comportement mécanique du béton: Apports de l'approche physico-chimique (Mechanical behavior of concrete: A physico-chemical approach).* PhD thesis, Ecole Nationale des Ponts et Chaussées, Paris, France, 1988.

[7] Acker, P. Micromechanical Analysis of Creep and Shrinkage Mechanisms. In Ulm, F.-J., Bažant, Z. P., and Wittmann, F. H., editors, *Creep, Shrinkage and Durability Mechanics of Concrete and other Quasi-brittle Materials. Proceedings of the 6th International Conference CONCREEP@MIT*, pages 15–26, Cambridge, USA, August 2001. Elsevier: Amsterdam.

[8] Adhikary, D. P. Shortcomings in the standard continuum based implicit joint model of layered rocks. *Journal of Geology and Mining Research*, 2(2):23–28, May 2010.

[9] Alber, M. and Kahraman, S. Predicting the uniaxial compressive strength and elastic modulus of a fault breccia from texture coefficient. *Rock Mechanics and Rock Engineering*, 42(1):117–127, January 2009.

[10] Aldrian, W. *Beitrag zum Materialverhalten von früh belastetem Spritzbeton.* PhD thesis, Montanuniversität Leoben, Leoben, Austria, May 1991.

[11] Allaby, M., editor. *A Dictionary of Geology and Earth Sciences.* Oxford University Press, 4th edition, January 2013.

[12] Allmendinger, R. W. Stereonet, September 2020. URL `https://www.rickallmendinger.net/stereonet`. Last access: 26.09.2020.

[13] Allmendinger, R. W., Cardozo, N., and Fisher, D. M. *Structural Geology Algorithms: Vectors and Tensors.* Cambridge University Press, December 2011.

[14] ASTM. D5607-02. Standard Test Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force. Standard, 2002.

[15] ASTM. D7012-10. Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures. Standard, 2010.

[16] Atkins, P., Jones, L., and Laverman, L. *Chemical principles*. W. H. Freeman and Company, 6th edition, 2013.

[17] Atzl, G., Brandtner, M., Selan, V., and Moritz, B. Numerical analyses of deep tunnels driven through massive faults. In Schubert, W. and Kluckner, A., editors, *Proceedings of the ISRM Regional Symposium EUROCK 2015 & 64th Geomechanics Colloquium–Future Development of Rock Mechanics*, pages 877–882, Salzburg, Austria, October 2015. Austrian Society for Geomechanics.

[18] Austin, S. A. and Robins, P. J., editors. *Sprayed Concrete: Properties, Design and Application*. Whittles Publishing, 1995.

[19] Austrian Standards Institute. ÖNORM EN 14487-1-1:2006. Spritzbeton: Teil 1: Begriffe, Festlegungen und Konformität. Standard, May 2006.

[20] Austrian Standards Institute. ÖNORM EN 1992-1-1:2015. Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau (konsolidierte Fassung). Standard, February 2015.

[21] Aydan, O., Sezaki, M., and Kawamoto, T. Mechanical and numerical modelling of shotcrete. In Pande, G. N. and Pietruszczak, S., editors, *Proceedings of the Fourth International Symposium on Numerical Models in Geomechanics (NUMOG IV)*, pages 757–764, Swansea, Wales, August 1992. Taylor & Francis, London.

[22] Bandis, S. C., Lumsden, A. C., and Barton, N. R. Fundamentals of rock joint deformation. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 20(6):249–268, December 1983.

[23] Barbero, M., Bonini, M., and Borri-Brunetto, M. Numerical modelling of the mechanical behaviour of bimrock. In Ribeiro e Sousa, L., Olalla, C., and Grossmann, N., editors, *Proceedings of the 11th Congress of the International Society for Rock Mechanics–The Second Half Century of Rock Mechanics*, volume 1 & 2, pages 377–380, Lisbon, Portugal, July 2007. Taylor & Francis Group, London.

[24] Barbero, M., Bonini, M., and Borri-Brunetto, M. Three-Dimensional Finite Element Simulations of Compression Tests on Bimrock. In *Proceedings of the 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG)*, pages 631–637, Goa, India, October 2008.

[25] Bažant, Z. P., editor. *Mathematical Modelling of Creep and Shrinkage in Concrete*. Wiley & Sons Ltd, New York, 1988.

[26] Bažant, Z. P. Creep and thermal effects in concrete structures: a conceptus of some new developments. In Mang, H. A., Bicanic, N., and de Borst, R., editors, *Proceedings of the Int. Conf. EURO-C "Computational Modelling of Concrete Structures"*, pages 461–480, Swansea, Wales, 1994. Pineridge Press.

[27] Bažant, Z. P. *Materials Science of Concrete IV*, chapter Creep and Damage in Concrete, pages 335–389. American Ceramic Society, Westerville, USA, 1995.

[28] Bažant, Z. P. and Panula, L. Practical prediction of time-dependent deformations of concrete. *Matériaux et Constructions*, 11(5):317–328, September 1978.

[29] Bažant, Z. P. and Prasannan, S. Solidification Theory for Concrete Creep. I: Formulation. *Journal of Engineering Mechanics*, 115(8):1691–1703, 1989.

[30] Bažant, Z. P. and Wittmann, F. H., editors. *Creep and Shrinkage in Concrete Structures*. John Wiley & Sons Ltd, Chichester, 1982.

[31] Bažant, Z. P., Hauggaard, A. B., and Baweja, S. Microprestress solidification theory for concrete creep. II: Algorithm and verification. *Journal of Engineering Mechanics*, 123(11): 1195–1201, November 1997.

[32] Bažant, Z. P., Hauggaard, A. B., Baweja, S., and Ulm, F.-J. Microprestress solidification theory for concrete creep. I: Aging and drying effects. *Journal of Engineering Mechanics*, 123(11):1188–1194, 1997.

[33] Bell, F. G. *Engineering Properties of Soils and Rocks*. Butterworth-Heinemann Ltd: Oxford, 3rd edition, 1992.

[34] Benz, T., Vermeer, P. A., and Schwab, R. A small-strain overlay model. *International Journal for Numerical and Analytical Methods in Geomechanics*, 33(1):25–44, January 2009.

[35] Benz, T. *Small-strain stiffness of soils and its numerical consequences*. PhD thesis, University of Stuttgart, 2007.

[36] Bergmair, M., Harer, G., Riedmüller, G., and Stadlmann, T. Die Baugeologie des Galgenbergtunnels. *Felsbau*, 14(1):15–21, 1996.

[37] Biscoping, M. and Kampen, R. Zusammensetzung von Normalbeton – Mischungsberechnung, February 2017. URL https://mitglieder.vdz-online.de/fileadmin/gruppen/vdz/3LiteraturRecherche/Zementmerkblaetter/ZM_B20_2017_2.pdf. Zement-Merkblatt Betontechnik B 20; last access: December 16th, 2022.

[38] Bjureland, W., Johansson, F., Sjölander, A., Spross, J., and Larsson, S. Probability distributions of shotcrete parameters for reliability-based analyses of rock tunnel support. *Tunnelling and Underground Space Technology*, 87:15–26, May 2019.

[39] Bjurström, S. Shear strength of hard rock joints reinforced by grouted untensioned bolts. In *Proceedings of the 3rd Congress of the International Society for Rock Mechanics (ISRM)*, pages 1194–1199, Denver, Colorado, USA, September 1974.

[40] Blair, T. C. and McPherson, J. G. Grain-size and textural classification of coarse sedimentary particles. *Journal of Sedimentary Research*, 69(1):6–19, January 1999.

[41] Blümel, M. Personal communication, November 2020.

[42] Boos, P. and Dietermann, M. Wet Shotcrete Performance—Laboratory Test Methods and influencing Factors in Practice. *Tunnel*, 29(6):31–41, 2010.

[43] Bossart, P., Meier, P. M., Moeri, A., Trick, T., and Mayor, J.-C. Geological and hydraulic characterisation of the excavation disturbed zone in the Opalinus Clay of the Mont Terri Rock Laboratory. *Engineering Geology*, 66(1–2):19–38, October 2002.

[44] Boumiz, A., Vernet, C., and Tenoudji, F. C. Mechanical properties of cement pastes and mortars at early ages. *Advanced Cement Based Materials*, 3(3-4):94–106, April 1996.

[45] Brady, B. H. G. and Brown, E. T. *Rock Mechanics for underground mining*. Springer Netherlands, 3rd edition, 2004.

[46] Brandtner, M. Numerical Analysis of Fault Zones—Coming Closer to a Solution. In Schubert, W., Kluckner, A., and Pilgerstorfer, T., editors, *Proceedings of the Workshop "Characterization of Fault Zones" as part of the 62nd Geomechanics Colloquium*, pages 60–63, Salzburg, Austria, October 2013. Austrian Society for Geomechanics.

[47] Brandtner, M. Personal communication, June 2020.

[48] Brandtner, M. Personal communication, April 2022.

[49] Brandtner, M. Personal communication, May 2022.

[50] Brandtner, M. and Lenz, G. Checking the system behaviour using a numerical model. *Geomechanics and Tunnelling*, 10(4):353–365, August 2017.

[51] Bray, J. W. Unpublished note. 1977.

[52] BRITE-EURAM. BRE-CT92-0231. new Materials, Design and Construction Techniques for Underground Structures in Soft Rock and Clay Media. Technical report, Mott MacDonald Ltd (project coordinator), 1998. Research project funded by EU (programme: FP3-BRITE/EURAM 2).

[53] Brodie, K., Fettes, D., Harte, B., and Schmid, R. Towards a unified nomenclature of metamorphic petrology: 5. structural terms including fault rock terms. PDF, November 2004. URL https://www.ugr.es/~agcasco/personal/IUGS/pdf-IUGS/scmr_struc2_structuraltermsincludingfaultrockterms.pdf. Recommendations by the IUGS Subcommission on the Systematics of Metamorphic Rocks. Last access: 07.01.2023.

[54] Brosch, F.-J. and Pischinger, G. Small- to meso-scale brittle rock structures and the estimation of "paleostress" axes—A case study from the Koralm region (Styria/Carinthia). *Austrian Journal of Earth Sciences*, 107(2):37–59, 2014.

[55] Brown, E. T. and Gonano, L. P. Improved compression test technique for soft rock. *Journal of the Geotechnical Engineering Division*, 100(2):196–199, 1974.

[56] Brugg Kabel AG. Datasheet: BRUsens strain V3 (LLK-BSST V3 7.2 mm). Version: 2012/09/12 Rev. 02 TH. Technical report, Brugg, Switzerland, 2012.

[57] Bryne, L. E. *Time Dependent Material Properties of Shotcrete for Hard Rock Tunnelling*. PhD thesis, KTH Royal Institute of Technology, Stockholm, Sweden, May 2014.

[58] Buchmayer, F., Monsberger, C. M., and Lienhart, W. Advantages of tunnel monitoring using distributed fibre optic sensing. *Journal of Applied Geodesy*, 15(1):1–12, December 2020.

[59] Budil, A. *Längsverschiebungen beim Tunnelvortrieb.* PhD thesis, Graz University of Technology, Graz, Austria, May 1996.

[60] Bürgi, C. *Cataclastic fault rocks in underground excavations - A geological characterisation.* Phd thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, 1999.

[61] Burgstaller, M., Goricki, A., and Vanek, R. Semmering Base Tunnel new—Tender documents: Report on the geotechnical ground characterisation. Project document (in german), Austrian Federal Railways, April 2014.

[62] Button, E. A. *A Contribution to the Characterization of Phyllitic and Schistose Rock Masses for Tunnelling.* PhD thesis, Graz University of Technology, Graz, Austria, 2004.

[63] Byfors, J. Plain concrete at early ages. Technical report, Swedish Cement and Concrete Research Institute, Stockholm, Sweden, 1980.

[64] Candappa, D. C., Sanjayan, J. G., and Setunge, S. Complete Triaxial Stress-Strain Curves of High-Strength Concrete. *Journal of Materials in Civil Engineering*, 13(3):209–215, June 2001.

[65] Cardozo, N. and Allmendinger, R. W. Spherical projections with OSXStereonet. *Computers & Geosciences*, 51:193–205, February 2013.

[66] Çengel, Y. A., Boles, M. A., and Kanoğlu, M. *Thermodynamics: an engineering approach.* McGraw-Hill Education, New York, USA, 9th edition, 2019.

[67] CEB. International System of Unified Standard Codes of Practice for Structures—Volume 2: CEB-FIP Model Code for Concrete Structures. In *CEB Bulletins d'information*, number 124. Comité Euro-International du Béton (CEB), 1978.

[68] CEB. CEB-FIP Model Code 90: Design Code. Technical report, Comité Euro-International du Béton (CEB), 1993.

[69] Cervera, M., Oliver, J., and Prato, T. Thermo-Chemo-Mechanical Model for Concrete. I: Hydration and Aging. *Journal of Engineering Mechanics*, 125(9):1018–1027, September 1999.

[70] Cervera, M., Oliver, J., and Prato, T. Thermo-Chemo-Mechanical Model for Concrete. II: Damage and Creep. *Journal of Engineering Mechanics*, 125(9):1028–1039, September 1999.

[71] Chang, Y. *Tunnel support with shotcrete in weak rock—a rock mechanics study.* PhD thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 1994.

[72] Chen, A. C. T. and Chen, W.-F. Constitutive Relations for Concrete. *Journal of the Engineering Mechanics Division*, 101(4):465–481, August 1975.

[73] Chen, G., Kemeny, J. M., and Harpalani, S. Fracture propagation and coalescence in marble plates with pre-cut notches under compression. In Myer, L. R., Cook, N. G. W., Goodman, R. E., and Tsang, S. F., editors, *Proceedings of the International Symposium on Fractured and Jointed Rock Masses*, pages 443–448, Lake Tahoe, California, USA, June 1992. A.A. Balkema.

[74] Chen, W.-F. *Plasticity in Reinforced Concrete.* McGraw-Hill, New York, 1982.

[75] Cheng, C. Influence of discontinuities on post-peak behavior of rock in uniaxial compressive test by numerical study. In Farag, A. A., editor, *Proceedings of the 2nd International Conference on Multimedia Technology (ICMT 2011)*, pages 6406–6409, Hangzhou, China, July 2011. Institute of Electrical and Electronics Engineers.

[76] Cheng, Z. and Detournay, C. Plastic hardening model I: Implementation in FLAC3D. In Gómez, P., Detournay, C., Hart, R., and Nelson, M., editors, *Proceedings of the 4th Itasca Symposium on Applied Numerical Modeling*, pages 267–276, Lima, Perú, March 2016. Itasca International Inc., Minneapolis.

[77] Cheng, Z. and Lucarelli, A. Plastic hardening model II: Calibration and validation. In Gómez, P., Detournay, C., Hart, R., and Nelson, M., editors, *Proceedings of the 4th Itasca Symposium on Applied Numerical Modeling*, pages 393–402, Lima, Perú, March 2016. Itasca International Inc., Minneapolis.

[78] Codegone, G., Festa, A., and Dilek, Y. Formation of Taconic mélanges and broken formations in the Hamburg Klippe, Central Appalachian Orogenic Belt, Eastern Pennsylvania. *Tectonophysics*, 568-569:215–229, September 2012.

[79] Coli, N., Berry, P., and Boldini, D. Analysis of the block-size distribution in the Shale-Limestone Chaotic Complex (Tuscany, Italy). In Wilson, S., Ewy, R., and Tutuncu, A., editors, *Proceedings of the 42nd US Rock Mechanics Symposium and 2nd U.S.-Canada Rock Mechanics Symposium*, pages 1–7, San Francisco, California, 29 June–2 July, 2008. American Rock Mechanics Association (ARMA): Alexandria. ARMA 08-233.

[80] Coli, N., Boldini, D., and Bandini, A. Modeling of complex geological rock mixtures under triaxial testing conditions. In *Proceedings of the 2012 Regional Symposium of the International Society for Rock Mechanics (EUROCK 2012)—Rock Engineering and Technology for Sustainable Underground Construction*, pages 1–12, Stockholm, Sweden, May 2012.

[81] Cook, N. G. W. The application of seismic techniques to problems in rock mechanics. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 1(2):169–179, March 1964.

[82] Cook, N. G. W. An experiment proving that dilatancy is a pervasive volumetric property of brittle rock loaded to failure. *Rock Mechanics*, 2(4):181–188, December 1970.

[83] Cook, N. G. W., Hoek, E., Pretorius, J. P. G., Ortlepp, W. D., and Salamon, M. D. G. Rock mechanics applied to the study of rockbursts. *Journal of the South African Institute of Mining and Metallurgy*, 66:436–528, 1966.

[84] Cordes, T., Weifner, T., Unteregger, D., and Bergmeister, K. Interaction between deep tunnel drives and an existing tunnel in fault zones–Modelling against reality. *Geomechanics and Tunnelling*, 12(6):641–650, December 2019.

[85] Cornejo-Malm, G. Schwinden von Spritzbeton. Research report, ETH Zurich, 1995.

[86] Coussy, O. *Mechanics of Porous Continua.* Wiley: Chichester, United Kingdom, 1995.

[87] Coussy, O. *Mechanics and physics of porous solids.* John Wiley & Sons, Ltd: Chichester, United Kingdom, 1st edition, 2010.

[88] Cowan, D. S. Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America. *GSA Bulletin*, 96(4):451–462, April 1985.

[89] Cudny, M. and Truty, A. Refinement of the Hardening Soil model within the small strain range. *Acta Geotechnica*, 15(8):2031–2051, March 2020.

[90] Daller, J., Atzl, G., and Blümel, M. *Festschrift zum 60. Geburtstag von Wulf Schubert*, chapter Bestimmung von Gesteinskennwerten an Störungsmaterial, pages 50–58. Institute of Rock Mechanics and Tunnelling, Graz University of Technology, Graz, Austria, 2010.

[91] Dassault Systèmes Simulia Corp. *Abaqus/CAE 2017 documentation*.

[92] Davila Mendez, J. M. *Displacements Analysis in Layered Rock Masses*. PhD thesis, Graz University of Technology, Graz, Austria, January 2016.

[93] Deere, D. U. *Rock Mechanics in Engineering Practice*, chapter Geological considerations, pages 1–20. Wiley, New York, 1968. Chapter 1.

[94] Deere, D. U. and Miller, R. P. Engineering classification and index properties for intact rock. Technical report AFWL-TR-65-116, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, USA, December 1966.

[95] Deutsche Gesellschaft für Geotechnik e.V. (DGGT). *Empfehlungen des Arbeitskreises "Numerik in der Geotechnik"–EANG*. Wilhelm Ernst & Sohn, Verlag für Architektur und technische Wissenschaften GmbH & Co. KG, Berlin, Germany, February 2014.

[96] Dickmann, T. Personal communication, July 2021.

[97] Diederichs, M. S., Carvalho, J. L., and Carter, T. G. A Modified Approach For Prediction of Strength And Post Yield Behaviour For High GSI Rockmasses In Strong, Brittle Ground. In Eberhardt, E., Stead, D., and Morrison, T., editors, *Proceedings of the 1st Canada-US Rock Mechanics Symposium: Rock Mechanics: Meeting Society's Challenges and Demands*, pages 249–257, Vancouver, Canada, April 2007. ARMA-07-031.

[98] Ding, Y. *Technologische Eigenschaften von jungem Stahlfaserbeton und Stahlfaserspritzbeton*. PhD thesis, University of Innsbruck, Innsbruck, Austria, 1998.

[99] Dorfmann, E. M. *Zugkriechen von Beton in Abhängigkeit der Spannungsgeschichte*. Master's thesis, Graz University of Technology, Graz, Austria, June 2017.

[100] Eberhardt, E. Numerical modelling of three-dimension stress rotation ahead of an advancing tunnel face. *International Journal of Rock Mechanics and Mining Sciences*, 38(4):499–518, June 2001.

[101] Eberly, D. Approximating an Ellipse by Circular Arcs, April 2016. URL `https://www.geometrictools.com/Documentation/ApproximateEllipse.pdf`. Last access: 26.09.2020.

[102] Egger, P. *Einfluss des Post-Failure Verhaltens von Fels auf den Tunnelausbau unter besonderer Berücksichtigung des Ankerausbaus*. PhD thesis, Universität Karlsruhe, Karlsruhe, Germany, 1973.

[103] Ekici, Z. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz—Tender documents: Calculation values. Project document (in german), Austrian Federal Railways, 2014.

[104] Engels, S., Wieselthaler, F., Pischinger, G., and Holzer, R. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz, track 1—Engineering geological documentation. Project document (in german), Austrian Federal Railways, 2016.

[105] Engels, S., Wieselthaler, F., and Holzer, R. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz, track 1—Geotechnical horizontal and longitudinal section. Project document (in german), Austrian Federal Railways, 2017.

[106] Engl, D. A., Fellin, W., and Zangerl, C. Scherfestigkeiten von Scherzonengesteinen—Ein Beitrag zur geotechnischen Bewertung von tektonischen Störungszonen und Gleitzonen von Massenbewegungen. *Bulletin für Angewandte Geologie*, 13(2):63–81, 2008.

[107] England, G. L. and Illston, J. M. Methods of computing stress in concrete from a history of measured strain. *Civil Engineering and Public Works Review*, 60(1–3):513–517, 692–694, 846–847, April, May, June 1965.

[108] Entfellner, M. *Prediction of Displacements and Shotcrete Lining Utilization—Decision strategy for a timely application of ductile support systems in conventional tunnelling*. Master's thesis, Graz University of Technology, Graz, Austria, August 2017.

[109] Entfellner, M., Schubert, W., and Moritz, B. A. Early warning of overbreaks in tunnels. In *Proceedings of the 2022 Regional Symposium of the International Society for Rock Mechanics (EUROCK 2022)–Rock and Fracture Mechanics in Rock Engineering and Mining*, pages 1–8, Espoo, Finland, September 2022.

[110] European Committee for Standardization. EN 1992-1-1:2004. Eurocode 2: Design of concrete structures - Part 1-1 : General rules and rules for buildings. Standard, December 2004.

[111] Fairhurst, C. E. and Hudson, J. Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 36:279–289, 1999.

[112] Farmer, I. W. Stress distribution along a resin grouted rock anchor. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 12(11):347–351, November 1975.

[113] Farmer, I. W. *Engineering Behaviour of Rocks*. Springer Netherlands, 1st edition, 1983.

[114] Fasching, F. and Vanek, R. Engineering geological characterisation of fault rocks and fault zones. *Geomechanics and Tunnelling*, 4(3):181–194, June 2011.

[115] Faulkner, D. R., Lewis, A. C., and Rutter, E. H. On the internal structure and mechanics of large strike-slip fault zones: field observations of the Carboneras fault in southeastern Spain. *Tectonophysics*, 367(3-4):235–251, June 2003.

[116] Faulkner, D. R., Jackson, C. A. L., Lunn, R. J., Schlische, R. W., Shipton, Z. K., Wibberley, C. A. J., and Withjack, M. O. A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. *Journal of Structural Geology*, 32(11): 1557–1575, November 2010.

[117] Feder, G. and Arwanitakis, M. Zur Gebirgsmechanik ausbruchsnaher Bereiche tiefliegender Hohlraumbauten (unter zentralsymmetrischer Belastung). *Berg- und Hüttenmännische Monatshefte*, 121(4):103–117, 1976.

[118] Feenstra, P. H. and de Borst, R. Aspects of Robust Computational Models for Plain and Reinforced Concrete. *HERON*, 38(4):1–76, 1993.

[119] Feynman, R. P., Leighton, R. B., and Sands, M. *The Feynman Lectures on Physics*, volume I: Mainly Mechanics, Radiation, and Heat. Basic Books, 2010.

[120] fib. Structural Concrete: Textbook on Behaviour, Design and Performance: Updated knowledge of the CEB/FIP Model Code 1990. Technical report, fédération internationale du béton (fib), Lausanne, Switzerland, July 2000.

[121] fib. CEB-FIP Model Code for Concrete Structures 2010. Technical report, fédération internationale du béton (fib), 2013.

[122] Fischnaller, G. *Untersuchungen zum Verformungsverhalten von jungem Spritzbeton im Tunnelbau—Grundlagen und Versuche*. Master's thesis, University of Innsbruck, Innsbruck, Austria, 1992.

[123] Fjellström, P. *Measurement and Modelling of Young Concrete Properties*. Licentiate thesis, Luleå University of Technology, Luleå, Sweden, 2013.

[124] Forth, J. P. Predicting the tensile creep of concrete. *Cement and Concrete Composites*, 55: 70–80, January 2015.

[125] Fossen, H. *Structural Geology*. Cambridge University Press, 2nd edition, 2016.

[126] GEOKON. Instruction Manual: Model 4200 Series, Vibrating Wire Strain Gauges. Version: 11/08/2019 (revision DD). Technical report, Lebanon, New Hampshire, USA, 2019.

[127] Glawe, U. and Upreti, B. N. Better Understanding the Strengths of Serpentinite Bimrock and Homogeneous Serpentinite. *Felsbau*, 22(5):53–60, 2004.

[128] Golser, J., Schubert, P., and Rabensteiner, K. A new concept for evaluation of loading in shotcrete linings. In *Proceedings of the International Congress on Progress and Innovation in Tunnelling*, volume I, pages 79–85, Toronto, Canada, September 1989.

[129] Golser, J., Rabensteiner, K., Sigl, O., Aldrian, W., Wedenig, H., Brandl, J., and Maier, C. Materialgesetz für Spritzbeton. Technical report, Bundesministerium für wirtschaftliche Angelegenheiten: Straßenforschung, 1990.

[130] Goodman, R. E. *Introduction to Rock Mechanics*. John Wiley & Sons, 2nd edition, 1989.

[131] Goodman, R. E. *Engineering geology : rock in engineering construction*. John Wiley & Sons, Inc., 1993.

[132] Goricki, A. and Pimentel, E. Triaxial Tests on Cataclasites. *Rock Mechanics and Rock Engineering*, 48(5):2167–2171, November 2014.

[133] Granet, I., Alvarado, J. L., and Bluestein, M. *Thermodynamics and Heat Power*. CRC Press, Boca Raton, USA, 9th edition, 2021.

[134] Grassl, P. and Jirásek, M. Damage-plastic model for concrete failure. *International Journal of Solids and Structures*, 43(22-23):7166–7196, November 2006.

[135] Graziani, A., Boldini, D., and Ribacchi, R. Practical Estimate of Deformations and Stress Relief Factors for Deep Tunnels Supported by Shotcrete. *Rock Mechanics and Rock Engineering*, 38(5):345–372, June 2005.

[136] Green, S. J. and Swanson, S. R. Static constitutive relations for concrete. Technical report AFWL-TR-72-244, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, USA, April 1973.

[137] Groshong, R. H. j. Low-temperature deformation mechanisms and their interpretation. *Geological Society of America Bulletin*, 100(9):1329–1360, September 1988.

[138] Gross, D., Hauger, W., and Wriggers, P. *Technische Mechanik 4: Hydromechanik, Elemente der Höheren Mechanik, Numerische Methoden*. Springer Berlin Heidelberg, 7th edition, 2009.

[139] Großauer, K. *Tunnelling in Heterogeneous Ground—Numerical Investigation of Stresses and Displacements*. Diploma thesis, Graz University of Technology, Graz, Austria, October 2001.

[140] Großauer, K. *Expert System Development for the Evaluation and Interpretation of Displacement Monitoring Data in Tunnelling*. PhD thesis, Graz University of Technology, Graz, Austria, February 2009.

[141] Grübl, P., Weigler, H., and Karl, S. *Beton—Arten, Herstellung und Eigenschaften*. Ernst & Sohn Verlag, Berlin, 2nd edition, 2001.

[142] Gruppe TUNNEL:Monitor. TUNNEL:monitor (v2021.1.4). URL `https://igt-engineering.com/de/forschung-und-entwicklung/tunnelmonitor/`. Last access: 15.11.2022.

[143] Gschwandtner, G. G. *Analytische Berechnungsansätze zum Kennlinienverfahren*. Master's thesis, Montanuniversität Leoben, Leoben, Austria, January 2010.

[144] Gudmundsson, A., Simmenes, T. H., Larsen, B., and Philipp, S. L. Effects of internal structure and local stresses on fracture propagation, deflection, and arrest in fault zones. *Journal of Structural Geology*, 32(11):1643–1655, November 2010.

[145] Guntli, P., Keller, F., Lucchini, R., and Rust, S. Gotthard-Basistunnel: Geologie, Geotechnik, Hydrologie – zusammenfassender Schlussbericht. Technical report 7, Landesgeologie, 2016.

[146] Guo, P. and Su, X. Shear strength, interparticle locking, and dilatancy of granular materials. *Canadian Geotechnical Journal*, 44(5):579–591, May 2007.

[147] Harer, G., Prein, R., Schwab, P., and Wehr, H. Tunnelling in Poor Ground Conditions – Case History Galgenbergtunnel. *Felsbau*, 14(2):82–86, 1996.

[148] Hartog, A. H. *An Introduction to Distributed Optical Fibre Sensors*. CRC Press, May 2017.

[149] Hauggaard-Nielsen, A. B. *Mathematical Modelling and Experimental Analysis of Early Age Concrete*. PhD thesis, Technical University of Denmark, Lyngby, Denmark, October 1997.

[150] Havlásek, P., Šmilauer, V., Hájková, K., and Baquerizo, L. Thermo-mechanical simulations of early-age concrete cracking with durability predictions. In *IOP Conference Series: Materials Science and Engineering*, volume 236, pages 1–7. IOP Publishing, September 2017.

[151] Heinisch, M., Mayr, B., Millen, B., and Holzer, R. Semmering Base Tunnel, construction lot SBT 1.1, access tunnel Göstritz—Geotechnical horizontal and longitudinal section. Project document (in german), 2016.

[152] Heinisch, M., Mayr, B., Millen, B., and Holzer, R. Semmering Base Tunnel, construction lot SBT 1.1, access tunnel Göstritz—Engineering geological documentation. Project document (in german), Austrian Federal Railways, 2016.

[153] Heinrich, P. J. *Effiziente Erfassung viskoelastischer Eigenschaften bei der Spannungsermittlung von gezwängten Betonbauteilen*. PhD thesis, Graz University of Technology, Graz, Austria, November 2018.

[154] Hellmich, C. *Shotcrete as part of the New Austrian Tunneling Method: From Thermochemomechanical Material Modeling to Structural Analysis and Safety Assessment of Tunnels*. PhD thesis, Vienna University of Technology, Vienna, Austria, 1999.

[155] Hellmich, C., Ulm, F.-J., and Mang, H. A. Multisurface Chemoplasticity. I: Material Model for Shotcrete. *Journal of Engineering Mechanics*, 125(6):692–701, 1999.

[156] Hellmich, C., Ulm, F.-J., and Mang, H. A. Multisurface Chemoplasticity. II: Numerical Studies on NATM Tunneling. *Journal of Engineering Mechanics*, 125(6):702–713, 1999.

[157] Hellmich, C., Sercombe, J., Ulm, F.-J., and Mang, H. A. Modeling of Early-Age Creep of Shotcrete. II: Application to Tunneling. *Journal of Engineering Mechanics*, 126(3):292–299, 2000.

[158] Hellmich, C., Mang, H. A., and Ulm, F.-J. Hybrid method for quantification of stress states in shotcrete tunnel shells: combination of 3D in situ displacement measurements and thermochemoplastic material law. *Computers & Structures*, 79(22):2103–2115, 2001.

[159] Henzinger, M. R., Schachinger, T., Lienhart, W., Buchmayer, F., Weilinger, W., Stefaner, R., Haberler-Weber, M., Haller, E.-M., Steiner, M., and Schubert, W. Fibre-optic supported measurement methods for monitoring rock pressure. *Geomechanics and Tunnelling*, 11(3): 251–263, June 2018.

[160] Hettler, A. and Vardoulakis, I. Behaviour of dry sand tested in a large triaxial apparatus. *Géotechnique*, 34(2):183–197, June 1984.

[161] Hill, R. *The mathematical theory of plasticity*. The Clarendon Press, Oxford, 1951.

[162] Hodgson, K. and Cook, N. G. W. The effects of size and stress gradient on the strength of rock. In *Proceedings of the 2nd Congress of the International Society for Rock Mechanics*, volume 2, pages 31–34, Belgrade, Serbia, September 1970.

[163] Hoek, E. and Brown, E. T. Practical estimates of rock mass strength. *International Journal of Rock Mechanics and Mining Sciences*, 34(8):1165–1186, December 1997.

[164] Hoek, E. and Diederichs, M. S. Empirical estimation of rock mass modulus. *International Journal of Rock Mechanics and Mining Sciences*, 43(2):203–215, February 2006.

[165] Hoek, E. *Brittle failure of rock*. Rock Mechanics in Engineering Practice. Wiley: New York, 1968.

[166] Hoek, E. and Brown, E. T. *Underground Excavations in Rock*. CRC Press, 1st edition, 1980.

[167] Hoek, E. and Brown, E. T. Empirical Strength Criterion for Rock Masses. *Journal of the Geotechnical Engineering Division*, 106(9):1013–1035, September 1980.

[168] Holt, E. E. Early age autogeneous shrinkage of concrete. Vtt publications 446, Technical Research Centre of Finland, Espoo, Finland, 2001.

[169] Holter, K. G. *Properties of waterproof sprayed concrete tunnel linings: A study of EVA-based sprayed membranes for waterproofing of rail and road tunnels in hard rock and cold climate*. PhD thesis, Norwegian University of Science and Technology, Trondheim, Norway, December 2015.

[170] Holzer, R. Personal communication, September 2022.

[171] Holzer, R., Prall, K., Wagner, O. K., and Gobiet, G. Semmering Base Tunnel – Tunnelling in challenging geotechnical and geological conditions in major fault zones. *Geomechanics and Tunnelling*, 13(5):509–518, October 2020.

[172] Hösthagen, A. *Thermal Crack Risk Estimation and Material Properties of Young Concrete*. Licentiate thesis, Luleå University of Technology, Luleå, Sweden, 2017.

[173] Huber, H. *Untersuchungen zum Verformungsverhalten von jungem Spritzbeton im Tunnelbau*. Master's thesis, University of Innsbruck, Innsbruck, Austria, 1991.

[174] Ikumi, T., Salvador, R. P., and Aguado, A. Mix proportioning of sprayed concrete: A systematic literature review. *Tunnelling and Underground Space Technology*, 124(104456): 12, June 2022.

[175] Itasca Consultants S.A.S. Dynamic Analysis in FLAC3D. Electronical, 2020. URL `https://www.itasca.fr/software/dynamic-analysis-in-flac3d`. Last access: 23.12.2020.

[176] Itasca Consulting Group, Inc. *UDEC 5.0 documentation*, 2011.

[177] Itasca Consulting Group, Inc. *FLAC3D 6.0 documentation*, 2017.

[178] Itasca Consulting Group, Inc. *FLAC3D 7.0 documentation*, 2019.

[179] Itasca Consulting Group, Inc. Learning - Itasca Educational Partnership. Electronical, 2023. URL `https://www.itascainternational.com/learning/iep/iep-research-program`. Last access: 05.01.2023.

[180] Jaeger, J. C. and Cook, N. G. W. *Fundamentals of Rock Mechanics*. Chapman & Hall: London, 3rd edition, 1979.

[181] Jaeger, J. C., Cook, N. G. W., and Zimmerman, R. W. *Fundamentals of Rock Mechanics*. Blackwell Publishing, 4th edition, 2007.

[182] Johnson, R. B. and DeGraff, J. V. *Principles of Engineering Geology*. John Wiley & Sons, Inc., 1988.

[183] Johnston, I. W. Strength of Intact Geomechanical Materials. *Journal of Geotechnical Engineering*, 111(6):730–749, June 1985.

[184] Kahraman, S. and Alber, M. Estimating unconfined compressive strength and elastic modulus of a fault breccia mixture of weak blocks and strong matrix. *International Journal of Rock Mechanics and Mining Sciences*, 43(8):1277–1287, December 2006.

[185] Kahraman, S., Alber, M., Fener, M., and Gunaydin, O. Evaluating the geomechanical properties of Misis fault breccia (Turkey). *International Journal of Rock Mechanics and Mining Sciences*, 45(8):1469–1479, December 2008.

[186] Kahraman, S., Gunaydin, O., Alber, M., and Fener, M. Evaluating the strength and deformability properties of Misis fault breccia using artificial neural networks. *Expert Systems with Applications*, 36(3):6874–6878, April 2009.

[187] Kainrath-Reumayer, S., Gschwandtner, G., Schuller, E., and Galler, R. Beitrag zur Anwendung des Kennlinienverfahrens. *Berg- und Hüttenmännische Monatshefte*, 155(2): 83–89, February 2010.

[188] Kainrath-Reumayer, S., Neugebauer, E., Charette, F., Plouffe, M., and Galler, R. Ankerung im Untertagebau - Entwicklungen in Theorie und Praxis. *Geomechanik und Tunnelbau*, 1 (5):345–351, October 2008.

[189] Kaiser, P. K. and Kim, B. H. Rock mechanics challenges of underground constructions and mining. In *Proceedings of the Korean Rock Mechanics Symposium*, pages 1–16, Seoul, South Korea, 2008. Korean Society for Rock Mechanics.

[190] Kaiser, P. K. and Tannant, D. D. The Role of Shotcrete in Hard Rock Mines. In Hustrulid, W. A. and Bullock, R. L., editors, *Underground Mining Methods—Engineering Fundamentals and International Case Studies*, chapter 67, pages 579–592. Society for Mining, Metallurgy, and Exploration, Inc. (SME), 2001.

[191] Kaiser, P. K., Diederichs, M. S., Martin, C. D., Sharp, J., and Steiner, W. Underground Works In Hard Rock Tunnelling And Mining. In *Proceedings of the International Conference on Geotechnical & Geological Engineering (GeoEng2000)*, ISRM International Symposium, pages 841–926, Melbourne, Australia, November 2000. Technomic Publishing Co.

[192] Kaiser, P. K., Amann, F., and Steiner, W. How Highly Stressed Brittle Rock Failure Impacts Tunnel Design. In *Proceedings of the 2010 Regional Symposium of the International Society for Rock Mechanics (EUROCK 2010)*, pages 1–12, Lausanne, Switzerland, June 2010. ISRM-EUROCK-2010-003.

[193] Kalender, A., Sönmez, H., Medley, E. W., Tunusluoglu, C., and Kasapoglu, K. E. An approach to predicting the overall strengths of unwelded bimrocks and bimsoils. *Engineering Geology*, 183:65–79, December 2014.

[194] Kastner, H. *Statik des Tunnel- und Stollenbaues : auf der Grundlage geomechanischer Erkenntnisse.* Springer Berlin Heidelberg, 1962.

[195] Kettunen Linder, M. and Kilic, O. *En studie av sprutbetongförstärkningen i Citybanan - Norrströmstunneln.* Master's thesis, KTH Royal Insitute of Technology, Stockholm, Sweden, March 2011. Examensarbete 326.

[196] Kim, Y.-S., Peacock, D. C. P., and Sanderson, D. J. Fault damage zones. *Journal of Structural Geology*, 26(3):503–517, March 2004.

[197] Kirsch, G. Die Theorie der Elastizität und die Bedürfnisse der Festigkeitslehre. *Zeitschrift des Vereines Deutscher Ingenieure*, 42(29):797–807, 1898.

[198] Klein, C. and Philpotts, A. R. *Earth materials : introduction to mineralogy and petrology.* Cambridge University Press, 1st edition, 2013.

[199] Kluckner, A. *Aspekte der Gebirgscharakterisierung im Tunnelbau.* Master's thesis, Graz University of Technology, Graz, Austria, October 2012.

[200] Kluckner, A. and Schubert, W. Study on the Anisotropic Displacement Pattern at a Conventional Tunnel Drive. In *Proceedings of the 5th ISRM Young Scholars' Symposium on Rock Mechanics and International Symposiumon Rock Engineering for Innovative Future (YSRM2019 & REIF2019)*, pages 1–6, Okinawa, Japan, December 2019.

[201] Knipe, R. J. Deformation mechanism path diagrams for sediments undergoing lithification. *Structural Fabric in Deep Sea Drilling Project Cores From Forearcs*, Memoir 166:151–160, 1986.

[202] Kovler, K. Why sealed concrete swells. *ACI Materials Journal*, 93(4):334–340, 1996.

[203] Kropik, C. and Mang, H. A. Computational mechanics of the excavation of tunnels. *Engineering Computations*, 13(7):49–69, November 1996.

[204] Kulhawy, F. H. Stress deformation properties of rock and rock discontinuities. *Engineering Geology*, 9(4):327–350, December 1975.

[205] Kusterle, W. *Qualitätsverbesserungen beim Spritzbeton durch technologische Massnahmen, durch den Einsatz neuer Materialien und auf Grund der Erfassung von Spritzbetoneigenschaften.* Habilitation dissertation, University of Innsbruck, Innsbruck, Austria, 1992.

[206] Kusterle, W. Comparison of shrinkage behaviour and creep properties under different compressive stress levels for wet-mix sprayed concrete from ten hours up to two weeks. Technical report, Morgan Tunnelling, 1999.

[207] Kusterle, W. and Lukas, W. Spritzbeton hoher Güte für die einschalige Spritzbetonbauweise. In *Tagungsband der 3. Internationalen Fachtagung Spritzbeton-Technologie, Innsbruck, Austria*, pages 29–40, 1990.

[208] Kusterle, W., Jäger, J., John, M., Neumann, C., and Röck, R. Spritzbeton im Tunnelbau. In Bergmeister, K., Fingerloos, F., and Wörner, J.-D., editors, *Beton-Kalender 2014: Unterirdisches Bauen, Grundbau, Eurocode 7*, chapter IX, pages 303–390. Ernst & Sohn GmbH & Co. KG., 2014.

[209] Kuwajima, F. M. Early Age Properties of Shotcrete. In Celestino, T. B. and Parker, H. W., editors, *Proceedings of the Eighth International Conference on Shotcrete for Underground Support*, São Paulo, Brazil, April 1999. American Society of Civil Engineers.

[210] Lackner, R. and Mang, H. A. Cracking in shotcrete tunnel shells. *Engineering Fracture Mechanics*, 70(7–8):1047–1068, May 2003.

[211] Lackner, R., Hellmich, C., and Mang, H. A. Constitutive modeling of cementitious materials in the framework of chemoplasticity. *International Journal for Numerical Methods in Engineering*, 53(10):2357–2388, 2002.

[212] Lackner, R., Macht, J., Hellmich, C., and Mang, H. A. Hybrid Method for Analysis of Segmented Shotcrete Tunnel Linings. *Journal of Geotechnical and Geoenvironmental Engineering*, 128(4):298–308, April 2002.

[213] Lama, R. D. and Vutukuri, V. S. *Handbook on Mechanical Properties of Rocks*, volume 2 of *Series on Rock and Soil Mechanics.* Trans Tech Publications, Clausthal, Germany, 1978.

[214] Laplante, P. *Propriétés mécaniques des bétons durcissants: analyse comparée des bétons classiques et à très hautes performances [Mechanical properties of hardening concrete: a comparative analysis of classical and high strength concretes].* PhD thesis, Ecole Nationale des Ponts et Chaussées, Paris, France, 1993.

[215] Laplante, P. and Boulay, C. Evolution du coefficient de dilatation thermique du béton en fonction de sa maturité aux tout premiers âges. *Materials and Structures*, 27(10):596–605, December 1994.

[216] Leber, C. *Einfluss der Primärspannungsorientierung auf die Verschiebungscharakteristik.* Master's thesis, Graz University of Technology, Graz, Austria, March 2009.

[217] Lebschy, D. *Investigation of the influence of the tunnel lining on the displacement development.* Master's thesis, Graz University of Technology, Graz, Austria, September 2014.

[218] Lenz, G. *Displacement monitoring data in tunnelling—Development of a semiautomatic evaluation system.* Diploma thesis, Graz University of Technology, Graz, Austria, April 2007.

[219] Lenz, G. *Characterization of ground and system behaviour in water-bearing fault zones.* PhD thesis, Graz University of Technology, Graz, Austria, July 2020.

[220] Lenz, G. Personal communication, May 2022.

[221] Lenz, G. Personal communication, July 2022.

[222] Lenz, G. Personal communication, November 2022.

[223] Lepique, M. Empfehlung Nr. 10 des Arbeitskreises 3.3 "Versuchstechnik Fels" der Deutschen Gesellschaft für Geotechnik e. V.: Indirekter Zugversuch an Gesteinsproben - Spaltzugversuch. *Bautechnik*, 85(9):623–627, September 2008.

[224] Lienhart, W., Schubert, W., Henzinger, M. R., Buchmayer, F., Weilinger, W., and Stefaner, R. Faseroptisch unterstützte Messmethoden zur Beobachtung von Gebirgsdruck. Research report, Federal Ministry Republic of Austria, Climate Action, Environment, Energy, Mobility, Innovation and Technology, Vienna, Austria, October 2018.

[225] Lindlar, B., Jahn, M., and Schlumpf, J. *Sika Sprayed Concrete Handbook.* Sika AG, 2020. URL https://www.sika.com/content/dam/dms/corporate/n/glo-sprayed-concrete-handbook-2021.pdf. Last access: 14.01.2023.

[226] Lindquist, E. S. and Goodman, R. E. Strength and deformation properties of a physical model melange. In Nelson, P. P. and Laubach, S. E., editors, *Rock Mechanics - Models and Measurements - Challenges from Industry: Proceedings of the 1st North American Rock Mechanics Symposium (NARMS)*, pages 843–850. The University of Texas at Austin, A.A. Balkema: Rotterdam, June 1994.

[227] Lindquist, E. S. *The Strength and Deformation Properties of Melange.* PhD thesis, University of California, Berkeley, California, USA, 1994.

[228] Lockner, D. A. *Rock Physics and Phase Relations: A Handbook of Physical Constants*, volume 3 of *AGU Reference Shelf*, chapter Rock Failure, pages 127–147. American Geophysical Union, Washington, D.C., USA, 1st edition, January 1995.

[229] Logan, J. M., Friedmann, M., Higgs, N., Dengo, C., and Shimamoto, T. Experimental studies of simulated gouge and their application to studies of natural fault zones. In *Proceedings of Conference VIII—Analysis of Actual Fault Zones in Bedrock*, pages 305–343, Menlo Park, California, USA, April 1979. United States Department of the Interior, Geological Survey, Office of Earthquake Studies. Open-file report 79-1239.

[230] Lu, T. *Autogenous shrinkage of early age cement paste and mortar.* PhD thesis, Delft University of Technology, Delft, Netherlands, 2019.

[231] Lucarelli, A. Personal communication, June 2022.

[232] Luna Innovations Inc. Datasheet: Luna Optical Backscatter Reflectometer (OBR) Model 4600. Version: LTOBR4600 REV. 004 02/13/2014. Technical report, Blacksburg, Virginia, USA, 2014.

[233] Luna Innovations Inc. Datasheet: Luna Optical Backscatter Reflectometer (OBR) Model 4600. Version: LTOBR4600 REV. 006 03/09/2018. Technical report, Blacksburg, Virginia, USA, 2018.

[234] Lupini, J. F., Skinner, A. E., and Vaughan, P. R. The drained residual strength of cohesive soils. *Géotechnique*, 31(2):181–213, June 1981.

[235] Ma, J. *Faserfreier Ultrahochfester Beton—Entwicklung und Materialeigenschaften.* PhD thesis, Leipzig University, Leipzig, Germany, 2010.

[236] Macht, J. *Hybrid Analysis of Shotcrete Tunnel Linings: Assessment and Online Monitoring of the Level of Loading.* PhD thesis, Vienna University of Technology, Vienna, Austria, 2002.

[237] Mair, K., Frye, K. M., and Marone, C. Influence of grain characteristics on the friction of granular shear zones. *Journal of Geophysical Research: Solid Earth*, 107(B10):ECV 4–1–ECV 4–9, October 2002.

[238] Małkowski, P., Ostrowski, Ł., and Brodny, J. Analysis of Young's modulus for Carboniferous sedimentary rocks and its relationship with uniaxial compressive strength using different methods of modulus determination. *Journal of Sustainable Mining*, 17(3):145–157, 2018.

[239] Mandl, G. Discontinuous fault zones. *Journal of Structural Geology*, 9(1):105–110, January 1987.

[240] Mandl, G. *Mechanics of Tectonic Faulting: Models and Basic Concepts.* Developments in Structural Geology, 1. Elsevier Science Publishers B.V.: Amsterdam, 1988.

[241] Mandl, G. *Faulting in Brittle Rocks: An Introduction to the Mechanics of Tectonic Faults.* Springer Berlin Heidelberg, 1st edition, 2000.

[242] Mang, H. A. and Hofstetter, G. *Festigkeitslehre.* Springer Berlin Heidelberg, 5th edition, 2018.

[243] Manton, N. and Mee, N. *The Physical World.* Oxford University Press, 1st edition, April 2017.

[244] Marcher, T. Personal communication, January 2021.

[245] Marinos, P. V. and Tsiambaos, G. Strength and Deformability of Specific Sedimentary and Ophiolithic Rocks. *Bulletin of the Geological Society of Greece*, 43(3):1259–1266, January 2010.

[246] Marshak, S. *Earth : portrait of a planet.* New York : W.W. Norton & Company, 6th edition, 2019.

[247] Martin, J. *Back-analysis of rock mass parameters at the Semmering Base Tunnel based on the convergence confinement method.* Master's thesis, Graz University of Technology, Graz, Austria, December 2022.

[248] Medley, E. W. Using stereological methods to estimate the volumetric proportions of blocks in melanges and similar block-in-matrix rocks (bimrocks). In Oliveira, R., Rodrigues, L. F., Coelho, A. G., and Cunha, A. P., editors, *Proceedings of the 7th International Congress of the International Association of Engineering Geology (IAEG)*, pages 1031–1040. A.A. Balkema: Rotterdam, September 1994.

[249] Medley, E. W. Systematic Characterization of Melange Bimrocks and Other Chaotic Soil/Rock Mixtures. *Felsbau*, 17(3):152–162, 1999.

[250] Medley, E. W. Orderly Characterization of Chaotic Franciscan Melanges. *Felsbau*, 19(4): 20–33, 2001.

[251] Medley, E. W. Observations on Tortuous Failure Surfaces in Bimrocks. *Felsbau*, 22(5): 35–43, 2004.

[252] Medley, E. Tunneling Through Fault Zones and Melanges. Lecture slides of lecture 4 of the short course "Anticipating and addressing the characterization, design and construction problems of fault rocks, melanges and other bimrocks", Geological Engineering Department, Hacettepe University, Ankara, Turkey, June 2004.

[253] Medley, E. W. Estimating Block Size Distributions of Melanges and Similar Block-in-Matrix Rocks (Bimrocks). In Hammah, R., Bawden, W., Curran, J., and Telesnicki, M., editors, *Proceedings of 5th North American Rock Mechanics Symposium (NARMS)*, pages 599–606, Toronto, Canada, July 2002. University of Toronto Press.

[254] Medley, E. W. and Zekkos, D. Geopractitioner approaches to working with antisocial mélanges. In *Mélanges: Processes of Formation and Societal Significance*, number 480, pages 261–277. The Geological Society of America, 2011.

[255] Medley, E. W. *The Engineering Characterization of Melanges and Similar Block-in-Matrix Rocks (Bimrocks).* PhD thesis, University of California, Berkeley, California, USA, 1994.

[256] Medley, E. W. and Lindquist, E. S. The engineering significance of the scale-independence of some Franciscan melanges in California, USA. In Daemen, J. J. K. and Schultz, R. A., editors, *Proceedings of the 35th U.S. Symposium on Rock Mechanics*, pages 907–914. A.A. Balkema, Rotterdam, 1995.

[257] Meixner, T. *Trigger Values for tunnel monitoring in SCL shallow tunnels*. Master's thesis, Graz University of Technology, Graz, Austria, September 2016.

[258] Menétrey, P. and Willam, K. J. Triaxial Failure Criterion for Concrete and its Generalization. *ACI Structural Journal*, 92(3):311–318, 1995.

[259] Merriam-Webster, Inc. Dictionary: Autogenous. Electronical, 2020. URL https://www.merriam-webster.com/dictionary/autogenous. Last access: 23.06.2020.

[260] Meschke, G. Consideration of aging of shotcrete in the context of a 3-D viscoplastic material model. *International Journal for Numerical Methods in Engineering*, 39:3123–3143, 1996.

[261] Meschke, G., Kropik, C., and Mang, H. A. Numerical analyses of tunnel linings by means of a viscoplastic material model for shotcrete. *International Journal for Numerical Methods in Engineering*, 39:3145–3162, 1996.

[262] Michelis, P. N. Work-softening and hardening behaviour of granular rocks. *Rock Mechanics*, 14(3):187–200, December 1981.

[263] Mindess, S., Young, J. F., and Lawrence, F. V. Creep and drying shrinkage of calcium silicate pastes I. Specimen preparation and mechanical properties. *Cement and Concrete Research*, 8(5):591–600, 1978.

[264] Mitchell, T. M. and Faulkner, D. R. The nature and origin of off-fault damage surrounding strike-slip fault zones with a wide range of displacements: A field study from the Atacama fault system, northern Chile. *Journal of Structural Geology*, 31(8):802–816, August 2009.

[265] Mödlhammer, H. *Spritzbeton: In situ Versuche*. Bachelor's thesis, Montanuniversität Leoben, Leoben, Austria, April 2008.

[266] Monsberger, C. M., Lienhart, W., Kluckner, A., Wagner, L., and Schubert, W. Continuous strain measurements in a shotcrete tunnel lining using distributed fibre optic sensing. In *Proceedings of the 9th European Workshop on Structural Health Monitoring*, pages 1–13, Manchester, United Kingdom, July 2018.

[267] Monsberger, C. M., Lienhart, W., Kluckner, A., and Schubert, W. In-situ assessment of distributed strain and curvature characteristics in shotcrete tunnel linings based on fiber optic strain sensing. In *Proceedings of the 14th International Congress on Rock Mechanics and Rock Engineering*, pages 1–8, Foz do Iguassu, Brazil, September 2019.

[268] Monsberger, C. M. and Lienhart, W. Distributed fiber optic shape sensing along shotcrete tunnel linings: Methodology, field applications, and monitoring results. *Journal of Civil Structural Health Monitoring*, 11(2):337–350, January 2021.

[269] Monsberger, C. M., Bauer, P., Buchmayer, F., and Lienhart, W. Large-scale distributed fiber optic sensing network for short and long-term integrity monitoring of tunnel linings. *Journal of Civil Structural Health Monitoring*, 12(6):1317–1327, March 2022.

[270] Moritz, B., Grossauer, K., and Schubert, W. Short Term Prediction of System Behaviour of Shallow Tunnels in Heterogeneous Ground. *Felsbau*, 22(5):44–52, 2004.

[271] Müller, M. *Kriechversuche an jungen Spritzbetonen zur Ermittlung der Parameter für Materialgesetze*. mathesis, Montanuniversität Leoben, Leoben, Austria, October 2001.

[272] Mutschler, T. Neufassung der Empfehlung Nr. 1 des Arbeitskreises “Versuchstechnik Fels” der Deutschen Gesellschaft für Geotechnik e. V.: Einaxiale Druckversuche an zylindrischen Gesteinsprüfkörpern. *Bautechnik*, 81(10):825–834, October 2004.

[273] Naylor, M. A., Mandl, G., and Supesteijn, C. H. K. Fault geometries in basement-induced wrench faulting under different initial stress states. *Journal of Structural Geology*, 8(7): 737–752, January 1986.

[274] Nefeslioglu, H. A. Evaluation of geo-mechanical properties of very weak and weak rock materials by using non-destructive techniques: Ultrasonic pulse velocity measurements and reflectance spectroscopy. *Engineering Geology*, 160:8–20, June 2013.

[275] Neuner, M., Cordes, T., Drexel, M., and Hofstetter, G. Time-Dependent Material Properties of Shotcrete: Experimental and Numerical Study. *Materials*, 10(9):1067, September 2017.

[276] Neuner, M., Gamnitzer, P., and Hofstetter, G. An Extended Damage Plasticity Model for Shotcrete: Formulation and Comparison with Other Shotcrete Models. *Materials*, 10(1): 1–22, January 2017.

[277] Neuner, M., Schreter, M., Unteregger, D., and Hofstetter, G. Influence of the Constitutive Model for Shotcrete on the Predicted Structural Behavior of the Shotcrete Shell of a Deep Tunnel. *Materials*, 10(6):1–17, May 2017.

[278] Neuner, M., Gamnitzer, P., and Hofstetter, G. Correction: An Extended Damage Plasticity Model for Shotcrete: Formulation and Comparison with Other Shotcrete Models. *Materials*, 11(1):135, January 2018.

[279] Neville, A. M. *Properties of Concrete*. Prentice Hall, 4th edition, 1995.

[280] Neville, A. M., Dilger, W. H., and Brooks, J. J. *Creep of plain and structural concrete*. Construction Press (Longman), Harlow, UK, 1983.

[281] Nielsen, L. F. Composite creep analysis of concrete: A rational, incremental stress-strain approach. Byg Rapport R-178, Technical University of Denmark, Lyngby, Denmark, 2007.

[282] Nilsson, M. *Restraint Forces and Partial Coefficients for Crack Risk Analyses of Early Age Concrete Structures*. PhD thesis, Luleå University of Technology, Luleå, Sweden, 2003.

[283] Nübel, K. and Huang, W. A study of localized deformation pattern in granular media. *Computer Methods in Applied Mechanics and Engineering*, 193(27-29):2719–2743, July 2004.

[284] Oberdörfer, W. *Auswirkung von unterschiedlichen Betonnachbehandlungsmassnahmen auf die Qualität des Nassspritzbetons*. Master’s thesis, University of Innsbruck, Innsbruck, Austria, 1996.

[285] Obert, L. and Duvall, W. I. *Rock Mechanics and the Design of Structures in Rock*. John Wiley & Sons, New York, 1967.

[286] Obert, L., Windes, S. L., and Duvall, W. I. Standardized tests for determining the physical properties of mine rock. Report of Investigations 3891, United States Department of the Interior–Bureau of Mines, August 1946.

[287] Obrzud, R. F. and Truty, A. *The Hardening Soil Model–A practical guidebook (Z_Soil.PC 100701 report, revised 21.10.2018).* Zace Services Ltd, October 2018.

[288] ÖBV. Spritzbeton: Teil 1—Anwendung. Guideline, Österreichischer Betonverein (ÖBV), 1989.

[289] ÖBV. Sprayed Concrete. Guideline, Österreichische Bautechnik Vereinigung (ÖBV), April 2013.

[290] ÖGG. Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation. Guideline, Austrian Society for Geomechanics (ÖGG), Salzburg, Austria, 2010. Translated from German version 2.1.

[291] ÖGG. *Geotechnical Monitoring in Conventional Tunnelling.* Austrian Society for Geomechanics (ÖGG), Salzburg, Austria, 2014.

[292] Oluokun, F. A., Burdette, E. G., and Deatherage, J. H. Splitting Tensile Strength and Compressive Strength Relationships at Early Ages. *ACI Materials Journal*, 88(2):115–121, 1991.

[293] Ord, A. Deformation of rock: A pressure-sensitive, dilatant material. *Pure and Applied Geophysics (PAGEOPH)*, 137(4):337–366, 1991.

[294] Oreste, P. P. A Procedure for Determining the Reaction Curve of Shotcrete Lining Considering Transient Conditions. *Rock Mechanics and Rock Engineering*, 36(3):209–236, June 2003.

[295] Oreste, P., Spagnoli, G., and Ceravolo, L. A. A numerical model to assess the creep of shotcrete linings. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, 172(4):344–354, August 2019.

[296] Palkovic, S. D., Brommer, D. B., Kupwade-Patil, K., Masic, A., Buehler, M. J., and Büyüköztürk, O. Roadmap across the mesoscale for durable and sustainable cement paste – A bioinspired approach. *Construction and Building Materials*, 115:13–31, July 2016.

[297] Palmström, A. and Singh, R. The deformation modulus of rock masses — comparisons between in situ tests and indirect estimates. *Tunnelling and Underground Space Technology*, 16(2):115–131, April 2001.

[298] Parent, T., Domede, N., Sellier, A., and Mouatt, L. Mechanical characterization of limestone from sound velocity measurement. *International Journal of Rock Mechanics and Mining Sciences*, 79:149–156, October 2015.

[299] Passchier, C. W. and Trouw, R. A. J. *Microtectonics.* Springer Verlag, Berlin, 1996.

[300] Paulini, P. Reaction mechanisms of concrete admixtures. *Cement and Concrete Research*, 20(6):910–918, November 1990.

[301] Peacock, D. C. P., Dimmen, V., Rotevatn, A., and Sanderson, D. J. A broader classification of damage zones. *Journal of Structural Geology*, 102:179–192, 2017.

[302] Pichler, B. and Hellmich, C. Hybrid methods for shotcrete and segmental linings tunnel shells - Combining displacement and rotation measurements with computational multiscale mechanics. *Geomechanics and Tunnelling*, 11(3):226–235, June 2018.

[303] Pichler, B., Hellmich, C., and Eberhardsteiner, J. Spherical and acicular representation of hydrates in a micromechanical model for cement paste: prediction of early-age elasticity and strength. *Acta Mechanica*, 203(3-4):137–162, June 2008.

[304] Pichler, B., Hellmich, C., and Eberhardsteiner, J. Reaktionskinetik und Kriecheigenschaften des Spritzbetons, der im Zuge des Vortriebs des Koralmtunnels (Baulos KAT2) verwendet wird. Technical report (preliminary), Institute for Mechanics of Materials and Strcutures, Vienna University of Technology, Vienna, Austria, December 2011.

[305] Pilgerstorfer, T. *Prediction of displacement development using closed form solutions*. Diploma thesis, Graz University of Technology, Graz, Austria, May 2008.

[306] Pilgerstorfer, T. *Mechanical Characterization of Fault Zones*. PhD thesis, Graz University of Technology, Graz, Austria, 2014.

[307] Pilgerstorfer, T. Personal communication, January 2022.

[308] Pilgerstorfer, T., Radončić, N., Moritz, B., and Goricki, A. Evaluation and interpretation of monitoring data in the test adit EKT Paierdorf. *Geomechanics and Tunnelling*, 4(5): 423–434, October 2011.

[309] Pittino, G., Galler, R., Bonin, K., and Bezler, J. Experiences with polymer-modified shotcrete. In Amberg, F. and Knut, F. G., editors, *Proceedings of the 11th Conference on Shotcrete for Underground Support*, pages 1–18, Davos, Switzerland, June 2009. Engineering Conferences International (ECI).

[310] Pötsch, M. *The analysis of rotational and sliding modes of failure for slopes, foundations, and underground structures in blocky, hard rock*. PhD thesis, Graz University of Technology, Graz, Austria, March 2011.

[311] Potts, D. M. and Zdravković, L. *Finite element analysis in geotechnical engineering: theory*. Thomas Telford Ltd, London, 1999.

[312] Poturovic, S., Schubert, W., and Blümel, M. Comparison of Constant Normal Load (CNL) and Constant Normal Stiffness (CNS) Direct Shear Tests. In Schubert, W. and Kluckner, A., editors, *Proceedings of the ISRM Regional Symposium EUROCK 2015 & 64th Geomechanics Colloquium—Future Development of Rock Mechanics*, pages 1–6, Salzburg, Austria, October 2015. Austrian Society for Geomechanics.

[313] Powers, T. C. Causes and Control of Volume Change. *Journal of the PCA Research and Development Laboratories*, pages 30–39, January 1959. Portland Cement Association (PCA).

[314] Powers, T. C. and Brownyard, T. L. Studies of the Physical Properties of Hardened Portland Cement Paste. In *Bulletin No. 22*, pages 1–342. Portland Cement Association (PCA), March 1948.

[315] Probst, B. *Entwicklung einer Langzeitdruckversuchsanlage für den Baustellenbetrieb zur Bestimmung des Materialverhaltens von jungem Spritzbeton*. Diploma thesis, Montanuniversität Leoben, Leoben, Austria, 1999.

[316] Pusch, R. Alteration of the Hydraulic Conductivity of Rock by Tunnel Excavation. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 26(1):79–83, January 1989.

[317] Püstow, H. *Tunnelling in a tectonic melange of high structural complexity.* mathesis, Aachen University of Technology, Aachen, Germany, 2001.

[318] R Core Team. *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing, Vienna, Austria, 2022. URL `https://www.R-project.org/`. Last access: 14.01.2023.

[319] Radončić, N. *Tunnel design and prediction of systembehaviour in weak ground.* PhD thesis, Graz University of Technology, Graz, Austria, March 2011.

[320] Rastrup, E. Heat of hydration in concrete. *Magazine of Concrete Research*, 6(17):79–92, September 1954.

[321] Raymond, L. A. Classification of melanges. In Raymond, L. A., editor, *Melanges: Their Nature, Origin, and Significance*, pages 7–20. The Geological Society of America, 1984.

[322] Reyes, O. and Einstein, H. H. Failure Mechanisms of Fractured Rock—A Fracture Coalescence Model. In Wittke, W., editor, *Proceedings of the 7th International ISRM Congress*, pages 333–339, Aachen, Germany, September 1991. A.A. Balkema.

[323] Riedmüller, G. and Schubert, W. Tunnelling in Fault Zones - Innovative Approaches. In *Proceedings of the 4th North American Rock Mechanics Symposium (NARMS 2000): Rock Around The Rim*, pages 1–12, Seattle, Washington, USA, July 2000. Balkema: Rotterdam. ARMA-2000-0113.

[324] Riedmüller, G., Brosch, F. J., Klima, K., and Medley, E. W. Engineering Geological Characterization of Brittle Faults and Classification of Fault Rocks. *Felsbau*, 19(4):13–19, 2001.

[325] Rokahr, R. B. and Lux, K. H. Einfluß des rheologischen Verhaltens des Spritzbetons auf den Ausbauwiderstand. *Felsbau*, 5(1):11–18, 1987.

[326] Rombach, G. *Spannbetonbau.* Wiley-VCH Verlag GmbH, April 2010.

[327] Roscoe, K. H. The Influence of Strains in Soil Mechanics. *Géotechnique*, 20(2):129–170, June 1970.

[328] Rosso, R. S. A comparison of joint stiffness measurements in direct shear, triaxial compression, and In Situ. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 13(6):167–172, June 1976.

[329] Rostami, J., Kahraman, S., Yu, X., Copur, H., Balci, C., Bamford, W., and Asbury, B. The relation between uniaxial compressive and Brazilian tensile strength. In Ulusay, R., Aydan, O., Gercek, H., and Hindistan, M. A., editors, *Proceedings of the 2016 Regional Symposium of the International Society for Rock Mechanics (EUROCK 2016)—Rock Mechanics and Rock Engineering: From the Past to the Future*, volume 1, pages 147–152, Ürgüp, Cappadocia Region, Turkey, August 2016. Turkish National Society for Rock Mechanics, CRC Press.

[330] Rowe, P. W. The stress-dilatancy relation for static equilibrium of an assembly of particles in contact. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 269(1339):500–527, October 1962.

[331] Rowe, R. K., editor. *Geotechnical and geoenvironmental engineering handbook.* Springer US, 2001.

[332] Ruetz, W. Das Kriechen des Zementsteins im Beton und seine Beeinflussung durch gleichzeitiges Schwinden. In *Deutscher Ausschuss für Stahlbeton*, number 183. Wilhelm Ernst & Sohn, Berlin, 1966.

[333] Rust, W. *Nichtlineare Finite-Elemente-Berechnungen*. Springer Fachmedien Wiesbaden, 3rd edition, 2016.

[334] Sadd, M. *Elasticity*. Academic Press, 3rd edition, 2014.

[335] Sainsbury, B. L. and Sainsbury, D. P. Practical Use of the Ubiquitous-Joint Constitutive Model for the Simulation of Anisotropic Rock Masses. *Rock Mechanics and Rock Engineering*, 50(6):1507–1528, February 2017.

[336] Salamon, M. D. G. Energy considerations in rock mechanics: fundamental results. *Journal of the South African Institute of Mining and Metallurgy*, 84:233–246, 1984.

[337] Saldivar, G. G. and Sánchez, F. A. *Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art*, chapter Comparative study on shotcrete performance in tunnels based on different constitutive approaches, pages 1–10. CRC Press, 1st edition, April 2019.

[338] Sammis, C. G. and Biegel, R. L. Fractals, fault-gouge, and friction. *Pure and Applied Geophysics PAGEOPH*, 131(1-2):255–271, 1989.

[339] Sausgruber, T. and Brandner, R. The Relevance of Brittle Fault Zones in Tunnel Construction—Lower Inn Valley Feeder Line North of the Brenner Base Tunnel, Tyrol, Austria. *Mitteilungen der Österreichischen Geologischen Gesellschaft*, 94:157–172, August 2003.

[340] Saw, H. A., Villaescusa, E., Windsor, C. R., and Thompson, A. G. Non-linear, elastic-plastic response of steel fibre reinforced shotcrete to uniaxial and triaxial compression testing. In Amberg, F. and Garshol, K. F., editors, *Shotcrete for Underground Support XI*, ECI Symposium Series, pages 1–18, June 2009.

[341] SBT 1.1 Tunnel Gloggnitz: ARGE. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz—Daily construction records. Project document (in german), Joint venture (ARGE): Implenia Österreich GmbH, HOCHTIEF Infrastructure GmbH, THYSSEN SCHACHTBAU GMBH, 2016.

[342] SBT 1.1 Tunnel Gloggnitz: ARGE. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz—Daily construction records. Project document (in german), Joint venture (ARGE): Implenia Österreich GmbH, HOCHTIEF Infrastructure GmbH, THYSSEN SCHACHTBAU GMBH, 2017.

[343] SBT 1.1 Tunnel Gloggnitz: PGST. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz—Tender documents: Geotechnical prognosis underground. Project document (in german), Austrian Federal Railways, 2014. Planungsgemeinschaft Semmering-Basistunnel neu Tunnelbau (PGST).

[344] SBT 1.1 Tunnel Gloggnitz: site team. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz—Presentation for the 13th meeting on the geotechnical conditions. Project document (in german), 2016.

[345] SBT 1.1 Tunnel Gloggnitz: site team. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz—Report on the site decisions on support. Project document (in german), 2016.

[346] SBT 1.1 Tunnel Gloggnitz: site team. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz—Report on the site decisions on support. Project document (in german), 2017.

[347] Schädlich, B. and Schweiger, H. F. Shotcrete Model: Implementation, validation and application. Internal technical report, Graz University of Technology, Graz, Austria, October 2016.

[348] Schädlich, B. and Schweiger, H. F. A new constitutive model for shotcrete. In Hicks, M. A., Brinkgreve, R. B. J., and Rohe, A., editors, *Numerical Methods in Geotechnical Engineering – Proceedings of the 8th European Conference on Numerical Methods in Geotechnical Engineering, NUMGE 2014*, volume 1, pages 103–108, Delft, Netherlands, June 2014. Taylor & Francis Group, London, UK.

[349] Schädlich, B., Schweiger, H. F., Marcher, T., and Saurer, E. Application of a novel constitutive shotcrete model to tunnelling. In *Rock Engineering and Rock Mechanics: Structures in and on Rock Masses*, pages 799–804. CRC Press, May 2014.

[350] Schanz, T., Vermeer, P. A., and Bonnier, P. G. The hardening soil model: Formulation and verification. In *Proceedings of the 1st PLAXIS symposium: Beyond 2000 in Computational Geotechnics–10 Years of PLAXIS*, pages 1–16. Balkema: Rotterdam, 1999.

[351] Scheiner, S. and Hellmich, C. Continuum Microviscoelasticity Model for Aging Basic Creep of Early-Age Concrete. *Journal of Engineering Mechanics*, 135(4):307–323, April 2009.

[352] Scheydt, J. C. Influence of the reactive Components on Shotcrete Performance. *Tunnel*, (3):22–27, 2015.

[353] Schlicke, D. Mindestbewehrung für zwangbeanspruchten Beton: Festlegung unter Berücksichtigung der erhärtungsbedingten Spannungsgeschichte und der Bauteilgeometrie. In *Monographic Series TU Graz, Schriftenreihe des Instituts für Betonbau*, volume 4. Verlag der Technischen Universität Graz, Graz, Austria, 2nd edition, 2016.

[354] Schlicke, D. Personal communication, February 2018.

[355] Schlicke, D. Personal communication, June 2020.

[356] Schmid, S. M. and Handy, M. R. *Controversies in Modern Geology. Evolution of Geological Theories in Sedimentology, Earth History and Tectonics.*, chapter 16. Towards a Genetic Classification of Fault Rocks: Geological Usage and Tectonophysical Implications, pages 339–361. Academic Press Limited, London, 1991.

[357] Schön, J. H. Developments in Petroleum Science. In *Physical Properties of Rocks–Fundamentals and Principles of Petrophysics*, volume 65. Elsevier B.V., 2nd edition, December 2015.

[358] Schubert, P. Beitrag zum rheologischen Verhalten von Spritzbeton. *Felsbau*, 6(3):150–153, 1988.

[359] Schubert, P., Hölzl, H., Sellner, P., and Fasching, F. Geomechanical knowledge gained from the Paierdorf investigation tunnel in the section through the Lavanttal main fault zone. *Geomechanics and Tunnelling*, 3(2):163–173, April 2010.

[360] Schubert, W. Erfahrungen bei der Durchörterung von Störzonen bei österreichischen Tunneln. In *Proceedings of the "Nachdiplomkurs in angewandten Erdwissenschaften: Herausforderung Geologie im Untertagebau"*, pages 1–10, CSF Monte Veritá, Ascona, Switzerland, May 1996. ETH Zurich.

[361] Schubert, W. Experience of tunnel construction in weak ground. *Geomechanics and Tunnelling*, 4(3):211–220, June 2011.

[362] Schubert, W. and Riedmüller, G. Geotechnisches Gutachten zum Verbruch Galgenbergtunnel / Vortrieb Leoben Ost Sta. 1326 bis 1333,6. Technical report, The Austrian Federal Railways, Graz, Austria, April 1995. Unpublished.

[363] Schubert, W. and Riedmüller, G. Geotechnische Nachlese eines Verbruches - Erkenntnisse und Impulse. In Semprich, S., editor, *Proceedings of the 10th Christian Veder Colloquium: Innovation in der Geotechnik - Entwicklungen der letzten Jahre*, number 13 in Mitteilungshefte, pages 59–68, Graz, Austria, 1995. Institute of Soil Mechanics and Foundation Engineering, Graz University of Technology.

[364] Schubert, W. and Riedmüller, G. Tunnelling in Fault Zones – State of the Art in Investigation and Construction. *Felsbau*, 18(2):7–15, 2000.

[365] Schubert, W., Brandtner, M., Schweiger, H. F., Helmberger, A., Marcher, T., and Radončić, N. Proposed design strategy for tunnels. In Schubert, W. and Kluckner, A., editors, *Proceedings of the ISRM Regional Symposium EUROCK 2015 & 64th Geomechanics Colloquium—Future Development of Rock Mechanics*, pages 37–47, Salzburg, Austria, October 2015. Austrian Society for Geomechanics.

[366] Schubert, W., Blümel, M., Brunnegger, S., Staudacher, R., and Sellner, P. J. Aspekte des Ausbaus. In Schubert, W. and Kluckner, A., editors, *Proceedings of the Workshop on Tunnelbau in Störungszonen—Eine Herausforderung*, pages 49–62, Graz, Austria, November 2016. Institute of Rock Mechanics and Tunnelling, Graz University of Technology.

[367] Schubert, W., Blümel, M., Staudacher, R., and Brunnegger, S. Support aspects of tunnels in fault zones. *Geomechanics and Tunnelling*, 10(4):342–352, August 2017.

[368] Schütz, R., Potts, D. M., and Zdravković, L. Advanced constitutive modelling of shotcrete: Model formulation and calibration. *Computers and Geotechnics*, 38(6):834–845, September 2011.

[369] Schütz, R. *Numerical Modelling of Shotcrete for Tunnelling.* PhD thesis, Imperial College London, London, UK, February 2010.

[370] Sercombe, J., Hellmich, C., Ulm, F.-J., and Mang, H. A. Modeling of early-age creep of shotcrete. I: Model and model parameters. *Journal of Engineering Mechanics*, 126(3): 284–291, 2000.

[371] Sezaki, M., Kibe, T., Ichikawa, Y., and Kawamoto, T. An experimental study on the mechanical properties of shotcrete. *Journal of the Society of Materials Science*, 38(434): 1336–1340, 1989.

[372] Sibson, R. H. Fault rocks and fault mechanisms. *Journal of the Geological Society*, 133(3): 191–213, March 1977.

[373] Sibson, R. H. Structural permeability of fluid-driven fault-fracture meshes. *Journal of Structural Geology*, 18(8):1031–1042, August 1996.

[374] Simo, J. C., Kennedy, J. G., and Govindjee, S. Non-smooth multisurface plasticity and viscoplasticity. Loading/unloading conditions and numerical algorithms. *International Journal for Numerical Methods in Engineering*, 26(10):2161–2185, October 1988.

[375] Skempton, A. W. Residual strength of clays in landslides, folded strata and the laboratory. *Géotechnique*, 35(1):3–18, March 1985.

[376] Sönmez, H., Gokceoglu, C., Tuncay, E., Medley, E. W., and Nefeslioglu, H. A. Relationships between Volumetric Block Proportions and Overall UCS of a Volcanic Bimrock. *Felsbau*, 22(5):27–34, 2004.

[377] Sönmez, H., Tuncay, E., and Gokceoglu, C. Models to predict the uniaxial compressive strength and the modulus of elasticity for Ankara Agglomerate. *International Journal of Rock Mechanics and Mining Sciences*, 41(5):717–729, July 2004.

[378] Sönmez, H., Gokceoglu, C., Medley, E. W., Tuncay, E., and Nefeslioglu, H. A. Estimating the uniaxial compressive strength of a volcanic bimrock. *International Journal of Rock Mechanics and Mining Sciences*, 43(4):554–561, June 2006.

[379] Sönmez, H., Kasapoglu, K. E., Coskun, A., Tunusluoglu, C., Medley, E. W., and Zimmerman, R. W. A conceptual empirical approach for the overall strength of unwelded bimrocks. In Vrkljan, I., editor, *Proceedings of the 2009 Regional Symposium of the International Society for Rock Mechanics (EUROCK 2009)—Rock Engineering in Difficult Ground Conditions – Soft Rocks and Karst*, pages 357–360, Dubrovnik, Croatia, October 2010. Taylor & Francis: London.

[380] Stadlmann, T., Vanek, R., and Goricki, A. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz—Tender documents: Rock mass types. Project document (in german), Austrian Federal Railways, 2014.

[381] Staudacher, R. F. *Anschlüsse für Arbeitsfugen bei Spritzbetonauskleidungen.* Master's thesis, Graz University of Technology, Graz, Austria, November 2016.

[382] Steindorfer, A. F. *Short Term Prediction of Rock Mass Behaviour in Tunnelling by Advanced Analysis of Displacement Monitoring Data.* PhD thesis, Graz University of Technology, Graz, Austria, November 1997.

[383] Stini, J. *Tunnelbaugeologie – Die geologischen Grundlagen des Stollen- und Tunnelbaues.* Springer Vienna, 1st edition, 1950.

[384] Swanson, M. T. Late Paleozoic strike-slip faults and related vein arrays of Cape Elizabeth, Maine. *Journal of Structural Geology*, 28(3):456–473, March 2006.

[385] Tazawa, E.-i., editor. *Autogenous Shrinkage of Concrete: Proceedings of the International Workshop, organized by the JCI (Japan Concrete Institute)*, Hiroshima, Japan, June 1999. Taylor & Francis.

[386] Terzaghi, K. *Theoretical Soil Mechanics.* John Wiley & Sons, Inc.: New York, 1943.

[387] Thomas, A. *Numerical modelling of sprayed concrete lined (SCL) tunnels.* PhD thesis, University of Southampton, Southampton, United Kingdom, 2003.

[388] Thomas, A. *Sprayed Concrete Lined Tunnels—An introduction.* Taylor & Francis, 2009.

[389] Thomas, A. *Sprayed Concrete Lined Tunnels—second edition.* CRC Press, 2020.

[390] Thomée, B. *Physikalisch nichtlineare Berechnung von Stahlfaserbetonkonstruktionen.* PhD thesis, Technical University Munich, Munich, Germany, 2005.

[391] Thornton, C. Numerical simulations of deviatoric shear deformation of granular media. *Géotechnique*, 50(1):43–53, February 2000.

[392] Thuro, K., Plinninger, R. J., Zäh, S., and Schütz, S. Scale effects in rock strength properties. Part 1: Unconfined compressive test and Brazilian test. In Särkkä and Eloranta, editors, *Proceedings of the 2001 Regional Symposium of the International Society for Rock Mechanics (EUROCK 2001)—Rock Mechanics – A Challenge for Society*, pages 169–174. Swets & Zeitlinger Lisse, 2001.

[393] Tigges, V. E. *Die Hydratation von Hüttensanden und Möglichkeiten ihrer Beeinflussung zur Optimierung von Hochofenzementeigenschaften.* PhD thesis, Clausthal University of Technology, Clausthal-Zellerfeld, Germany, 2009.

[394] Tourenq, C. and Denis, A. La resistance a la traction des roches. Rapport de Recherches 4A, Laboratoire Central des Ponts et Chaussées, Paris, France, 1970.

[395] Traina, L. A. Experimental stress-strain behaviour of a low strength concrete under multiaxial states of stress. Technical report AFWL-TR-82-92, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, USA, 1983.

[396] Tsesarsky, M., Hazan, M., and Gal, E. Estimating the elastic moduli and isotropy of block in matrix (bim) rocks by computational homogenization. *Engineering Geology*, 200:58–65, January 2016.

[397] Twiss, R. J. and Moores, E. M. *Structural Geology.* W. H. Freeman and Company, New York, USA, 2nd edition, 2007.

[398] Tziallas, G. P., Tsiambaos, G., and Saroglou, H. Determination of Rock Strength and Deformability of Intact Rocks. *Electronic Journal of Geotechnical Engineering (EJGE)*, 14 (G):1–12, 2009.

[399] Ulm, F.-J. Couplages thermochémomécaniques dans les bétons: Un premier bilan. Monograph LCPC OA31, Laboratoire Central des Ponts et Chaussées, Paris, France, 1998.

[400] Ulm, F.-J. and Acker, P. Le point sur le fluage et la recouvrance des bétons. *Bulletin Liaison des Laboratoires des Ponts et Chaussées*, (XX):73–82, 1998. Special issue.

[401] Ulm, F.-J. and Coussy, O. Modeling of Thermochemomechanical Couplings of Concrete at Early Ages. *Journal of Engineering Mechanics*, 121(7):785–794, 1995.

[402] Ulm, F.-J. and Coussy, O. Strength Growth as Chemo-Plastic Hardening in Early Age Concrete. *Journal of Engineering Mechanics*, 122(12):1123–1132, 1996.

[403] Ulusay, R., Türeli, K., and Ider, M. H. Prediction of engineering properties of a selected litharenite sandstone from its petrographic characteristics using correlation and multivariate statistical techniques. *Engineering Geology*, 38(1-2):135–157, December 1994.

[404] U.S. Department of the Interior - Bureau of Reclamation. *Engineering geology field manual*, volume I. U.S. Government Printing Office, 2nd edition, 1998.

[405] U.S. Department of the Interior - Bureau of Reclamation. Glossary of commonly used terms by the Bureau of Reclamation. Electronical, 2016. URL `https://www.usbr.gov/library/glossary/index.html`. Last access: 20.12.2016.

[406] van der Pluijm, B. A. and Marshak, S. *Earth structure : an introduction to structural geology and tectonics*. W. W. Norton & Company, Inc.: New York, 2nd edition, 2004.

[407] Vanek, R. and Stadlmann, T. Semmering Base Tunnel new—Legal railway approval procedure documents: Report on the construction geology. Project document (in german), Austrian Federal Railways, May 2010.

[408] Vanek, R., Fasching, F., and Fasching, A. Ingenieurgeologische Charakterisierung von Störungszonen. In Schubert, W. and Kluckner, A., editors, *Proceedings of the Workshop on Tunnelbau in Störungszonen—Eine Herausforderung*, pages 1–11, Graz, Austria, November 2016. Institute of Rock Mechanics and Tunnelling, Graz University of Technology.

[409] VBE. Semmering Base Tunnel, construction lot SBT 1.1, tunnel Gloggnitz—Concrete test report. Project document (in german), Verein für Baustoffprüfung und -entwicklung (VBE), 2016.

[410] Vermeer, P. A. and de Borst, R. Non-associated plasticity for soils, concrete and rock. *HERON*, 29(3):1–64, 1984.

[411] Vlachopoulos, N. and Diederichs, M. S. Improved Longitudinal Displacement Profiles for Convergence Confinement Analysis of Deep Tunnels. *Rock Mechanics and Rock Engineering*, 42(2):131–146, April 2009.

[412] Volpe, R., Ahlgren, C., and Goodman, R. Selection of engineering properties for geologically variable foundations. In *Proceedings of the 17th International Congress on Large Dams, Vienna:Paris*, pages 1087–1101. International Commission on Large Dams, 1991.

[413] von Rabcewicz, L. Die Ankerung im Tunnelbau ersetzt bisher gebräuchliche Einbaumethoden. *Schweizerische Bauzeitung*, 75(9):123–131, March 1957.

[414] von Terzaghi, K. *Ingenieurgeologie*, chapter Tunnelgeologie, pages 365–407. Julius Springer: Vienna, 1st edition, 1929.

[415] Wagner, L. *Concept and realisation of a distributed fibre-optic sensing system for direct and continuous strain measurement in a shotcrete lining.* Master's thesis, Graz University of Technology, Graz, Austria, September 2017.

[416] Wagner, L., Kluckner, A., Monsberger, C. M., Wolf, P., Prall, K., Schubert, W., and Lienhart, W. Direct and Distributed Strain Measurements Inside a Shotcrete Lining: Concept and Realisation. *Rock Mechanics and Rock Engineering*, 53(2):641–652, August 2019.

[417] Wen-jie, X., Zhong-qi, Y., and Rui-lin, H. Study on the mesostructure and mesomechanical characteristics of the soil–rock mixture using digital image processing based finite element method. *International Journal of Rock Mechanics and Mining Sciences*, 45(5):749–762, July 2008.

[418] Wen-Jie, X., Qiang, X., and Rui-Lin, H. Study on the shear strength of soil–rock mixture by large scale direct shear test. *International Journal of Rock Mechanics and Mining Sciences*, 48(8):1235–1247, December 2011.

[419] Wesche, K. *Baustoffe für tragende Bauteile—Band 2: Beton, Mauerwerk*. Bauverlag GmbH: Wiesbaden, Berlin, 3rd edition, 1993.

[420] Wibberley, C. A. J., Yielding, G., and Toro, G. D. Recent advances in the understanding of fault zone internal structure: a review. *Geological Society, London, Special Publications*, 299(1):5–33, 2008.

[421] Wittmann, F. Bestimmung physikalischer Eigenschaften des Zementsteins. In *Deutscher Ausschuss für Stahlbeton*, number 232. Wilhelm Ernst & Sohn, Berlin, 1974.

[422] Wuilpart, M. *Advanced Fiber Optics: Concepts and Technology*, chapter Rayleigh scattering in optical fibers and applications to distributed measurements, pages 1–56. EPFL Press, Lausanne, Switzerland, 1st edition, 2011.

[423] Wullschläger, D. *Ein Verbundwerkstoffmodell für die Systemankerung im Tunnelbau*. PhD thesis, Universität Karlsruhe, Karlsruhe, Germany, 1988.

[424] Yin, J. *Untersuchungen zum zeitabhängigen Tragverhalten von tiefliegenden Hohlräumen im Fels mit Spritzbetonausbau*. PhD thesis, Technische Universität Clausthal, Clausthal-Zellerfeld, Germany, February 1996.

[425] ZAMG. Zentralanstalt für Meteorologie und Geodynamik: Klimamonitoring. Electronical, 2021. URL https://www.zamg.ac.at/cms/de/klima/klima-aktuell/klimamonitoring/?view=fullscreen&param=t&period=period-ymd-2016-11-17&ref=3. Last access: 02.12.2021.

[426] Zhang, H.-Y., Xu, W.-J., and Yu, Y.-Z. Triaxial tests of soil–rock mixtures with different rock block distributions. *Soils and Foundations*, 56(1):44–56, February 2016.

[427] Zhao, X. G. and Cai, M. A mobilized dilation angle model for rocks. *International Journal of Rock Mechanics and Mining Sciences*, 47(3):368–384, April 2010.

[428] Zi, G. and Bažant, Z. P. Continuous Relaxation Spectrum for Concrete Creep and its Incorporation into Microplane Model M4. *Journal of Engineering Mechanics*, 128(12):1331–1336, December 2002.