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ORIGINAL PAPER

Strength of composite flysch samples under uniaxial compression

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Abstract This paper presents the results of uniaxial compression strength tests performed on samples composed of sandstone and siltstone discs. Samples are loaded until failure, with the aim of determining the dependency between uniaxial compressive strength and the volumetric percentage of siltstone. In order to precisely determine the moment and mechanism of failure of each composite sample, the process was recorded with a high-speed camera (120 fps). Uniaxial compressive strength decreases exponentially with an increase of siltstone volumetric participation. The critical ratio at which the uniaxial compressive strength of the composite sample equals the strength of the uniform siltstone sample was obtained at a siltstone percentage of 60%. The failure mechanism is highly dependent on the siltstone percentage, and occurs as shear or tensile failure, or combined shear-tensile failure in individual discs or throughout the entire composite sample. Comparison of the obtained exponential equation with empirical suggestions shows a good correspondence. It is suspected that the disagreement between the particular conclusions of this study and conclusions of other laboratory studies is due mainly to sample micro-heterogeneity.

Keywords Siltstone percentage · Composite sample · Uniaxial compressive strength · Micro-heterogeneity

Introduction

Lithologicaly heterogeneous rock masses can be described as formations consisting of two or more lithological members with different physical and mechanical properties. Typical examples are flysch, braided river deposits and mollasic rock masses. Within these deposits, soft (claystone, shale, siltstone, mudstone, marlstone) and hard (usually sandstone) units are rythmically interchanging in different proportions. The difference in strength and deformation parameters among individual types leads to more rapid disintegration and loss of strength of weaker, i.e. softer units. Bearing in mind complex spatial variability, and abrupt and irregular changes of lithological members in the natural environment, it is very difficult to predict rock mass behaviour under common loading conditions.

Goodman (1993) emphasized that any combination of more than one lithological type of rock exhibiting different properties imposes a complex geotechnical engineering problem.

The aim of this study was to investigate the influence of variable siltstone volumetric percentages on the value of uniaxial compressive strength of composite samples.

Literature review

A limited number of studies have examined the loading of composite samples under uniaxial compression. These tests found practical application during underground coal exploitation where the strength of coal pillars, composed of

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rock-coal units, should be determined (Huang and Liu 2013; Liu et al. 2014). Greco et al. (1992) and Greco (1994) performed a study to determine the strength and failure mechanism of composite rocks in a stability analysis of the columns and masonry walls of a Cathedral built of different rock types. Liang et al. (2007) tested natural layered samples of evaporites, composed of halite and anhydrite, concluding that the behaviour of composite samples is influenced by weaker layers, and strength lies in between the homogeneous units. The first application of such analysis to heterogeneous rock masses composed of weathered sandstone and siltstone samples was carried out by Zainab et al. (2007). Saroglou and Steiakakis (2010) tested intact flysch samples with interchanging thin sandstone and siltstone layers. Tziallas et al. (2013) performed a detailed study testing composite samples in uniaxial and triaxial conditions. It is worth mentioning that layered intact flysch samples suitable for laboratory testing are difficult to obtain unless the layering is within the centimetre scale and high quality drilling equipment is used. This is rarely the case in natural environments, thus, discs of different lithology and thickness ratios have to be artificially superimposed to represent natural conditions. In order to connect separate discs, Zainab et al. (2007) used plaster. This was shown as inadequate due to plaster failure at lower loads, causing the disks to displace, and introducing non-uniform stress distribution throughout the disk interfaces. Tziallas et al. (2013) found this procedure unnecessary, considering the pattern of the fracture surfaces, and the fact that no displacements of the disks was observed, even at higher compressive loads. These findings are used in the present study.

Theoretical background

Under uniaxial conditions, a specimen with cross-sectional area A is loaded with quasi-static force P until failure. Vertical force is applied in increments, and failure (value of uniaxial compressive strength denoted as σ_{ci} or UCS) is defined as the maximum force recorded during testing. Force equilibrium in the vertical direction satisfies the following condition:

$$\sigma = \sigma_{\mathrm{pg}} = \sigma_{\mathrm{s}} = \sigma_{\mathrm{pd}} = P/A, \tag{1}$$

where, σ_{pg}, σ_{pd}, σ_{s}, and σ denote the vertical stress on the upper and lower sandstone discs, siltstone disc and composite sample, respectively. In the process of quasi-static loading, the load on the sandstone and siltstone discs are the same. The value of external loading leading to failure will depend largely on the volumetric participation of weaker, i.e. siltstone, material in the composite sample. The strength is inversely proportional to siltstone participation, whereas, at the so-called “critical ratio”, the UCS of composite sample equals the strength of the uniform siltstone sample, thus the strength of the composite sample lies between the strength of the uniform sandstone and siltstone samples. The value of σ_{ci} depends mainly on the following factors: sample micro-heterogeneity, load rate, size and slenderness/shape effect, sample moisture content, environmental temperature during testing, and the angle between vertical force and the plane of weakness, e.g. schistosity or foliation.

For the above reasons, various recommendations and standards have been proposed for different tolerances for cylindrical sample preparation and testing, e.g. ISRM (2007); Eurocode 7 (1997); ASTM D-7012 (2014). ASTM and ISRM proposals recommend a height to diameter ratio between 2–2.5:1 and 2.5–3.0:1, respectively. Load rate is limited to 2–15 and 5–10 min by ASTM and ISRM, respectively. Specimen diameter should not be less than 47 mm according to ASTM standards, and 54 mm according to ISRM recommendations. ISRM suggests that the UCS should be determined as an average value of five tested specimens.

A composite sample can be regarded as a homogeneous sample, with a horizontal crack in the middle of the sample with a thickness equal to the siltstone disc.

Poisson’s ratio and elastic moduli of sandstone and siltstone parts satisfy the following condition: $v_{\mathrm{p}} < v_{\mathrm{s}}$, $E_{\mathrm{s}} < E_{\mathrm{p}}$, where, in the case of uniaxial compression, $\sigma_p = \sigma_{\mathrm{s}}$, it follows that $\varepsilon_{\mathrm{p}} < \varepsilon_{\mathrm{s}}$. In the above equations ε_{p} and ε_{s} are the strains of the sandstone and siltstone parts in the horizontal direction, respectively; v_{p} and v_{s} is the Poisson’s ratio of sandstone and siltstone, respectively; σ_{s} and σ_{p} are the axial stress in the sandstone and siltstone parts, respectively, and E_{p} and Es are the elastic modulus of sandstone and siltstone, respectively.

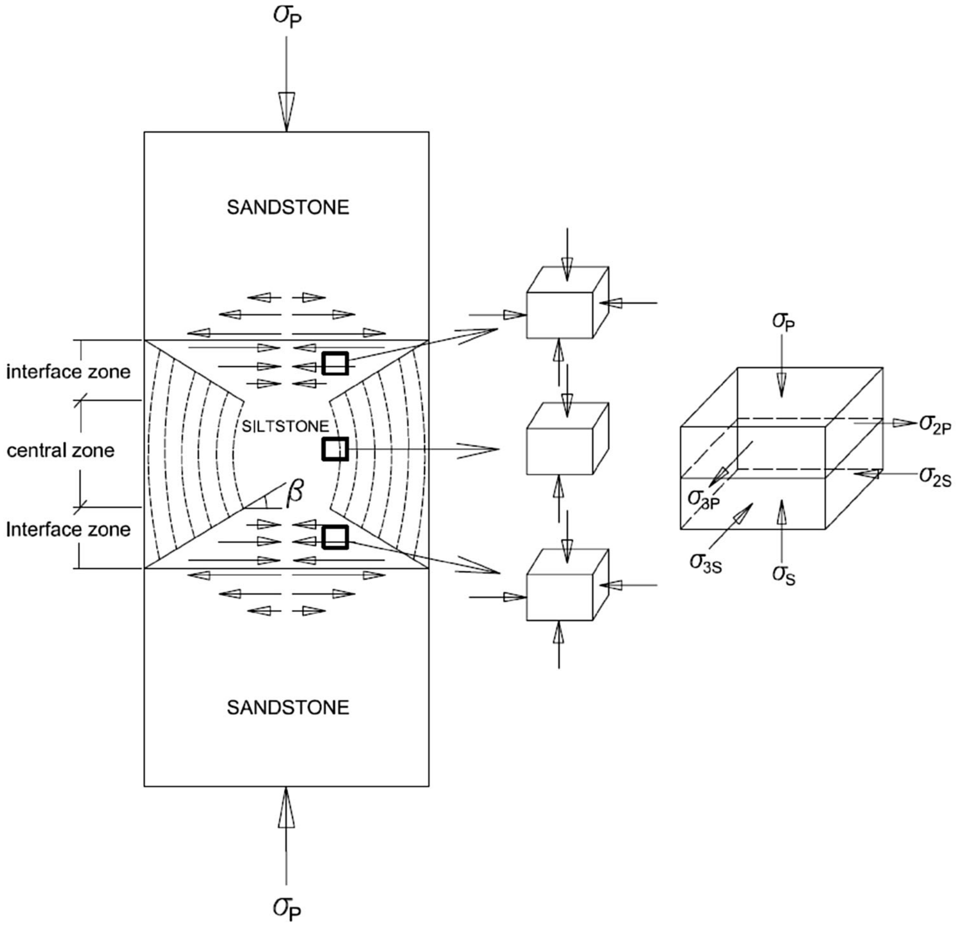
It can be further inferred that frictional force must exist on the sandstone–siltstone interface due to different horizontal deformations of sandstone and siltstone discs.

With an assumption of strain compatibility at the interface contact, stronger sandstone disc introduce a certain confinement to siltstone discs. This reduces horizontal strain and produces an increase in strength in the siltstone disc. In the region under the influence of end effects, the composite sample is under triaxial compression, Fig. 1. The thickness of the zone under the influence of triaxial conditions depends on the stiffness ratio of weaker and stronger material. The friction force can be expressed as:

$$\sigma_{2\mathrm{p}} = \mu \cdot \sigma_{\mathrm{p}}, \tag{2}$$

where μ is the coefficient of friction between sandstone and siltstone surfaces (for notation of stresses, refer to Fig. 1). The friction coefficient varies with the distance from the interface centre. The relative displacement is different in the interface of sandstone and siltstone. The relative

Fig. 1 Schematics of stress distribution in the composite sample (modified after Liu et al. 2014)



displacement is zero in the centre of the interface, and it increases far away from the centre. Therefore, the coefficient of friction varies with the distance from the centre of the specimen.

The Mohr–Coulomb failure criterion in the principal stress space is expressed as:

$$\sigma_1 = \frac{1 + \sin\varphi}{1 - \sin\varphi}\sigma_3 + \sigma_{ci}, \tag{3}$$

where σ_1 and σ_3 are the vertical and horizontal ultimate principal stresses, respectively; φ is the angle of shearing resistance. When no friction exists on the interface, i.e. $\sigma_3 = 0$, we have $\sigma_1 = \sigma_{ci}$. Figure 1 shows that $\sigma_1 = \sigma_p$, and $\sigma_3 = -\sigma_{2p}$. Having this in mind, and combining Eqs. (2) and (3), it can be concluded that the strength of the sandstone sample in the zone of contact equals:

$$\sigma_p = \frac{\sigma_{cip}}{1 + \frac{1+\sin\varphi_p}{1-\sin\varphi_p}\mu}, \tag{4}$$

where the “p” index denotes the sandstone sample. A similar equation can be derived for the strength of siltstone in the zone of contact:

$$\sigma_S = \frac{\sigma_{cis}}{1 - \frac{1+\sin\varphi_s}{1-\sin\varphi_s}\mu}, \tag{5}$$

where index “s” denotes the siltstone sample. If Eqs. (4) and (5) are compared with the case when no friction exists $(\sigma_1 = \sigma_{ci})$ it can be concluded that the UCS of the sandstone sample is lower, whereas that of the siltstone sample is higher for the second term in the denominator of the proposed equations.

Mineralogical characteristics of flysch

Determination of rock type and the main mineral constituents is performed on thin sections subjected to polarized microscopy (Fig. 2). Thin sections are prepared only for sandstone material. Bluish to yellowish siltstones are identified by visual inspection.

At the grain scale, sandstone consists mainly of quartz, feldspars, detritial carbonate grains, micas and fossil remains, with calcium carbonate as cementing material. The degree of cementation is variable, thus influencing the mechanical properties. Angular to sub-angular quartz grains are usually 0.3–0.5 mm in size. Feldspars are

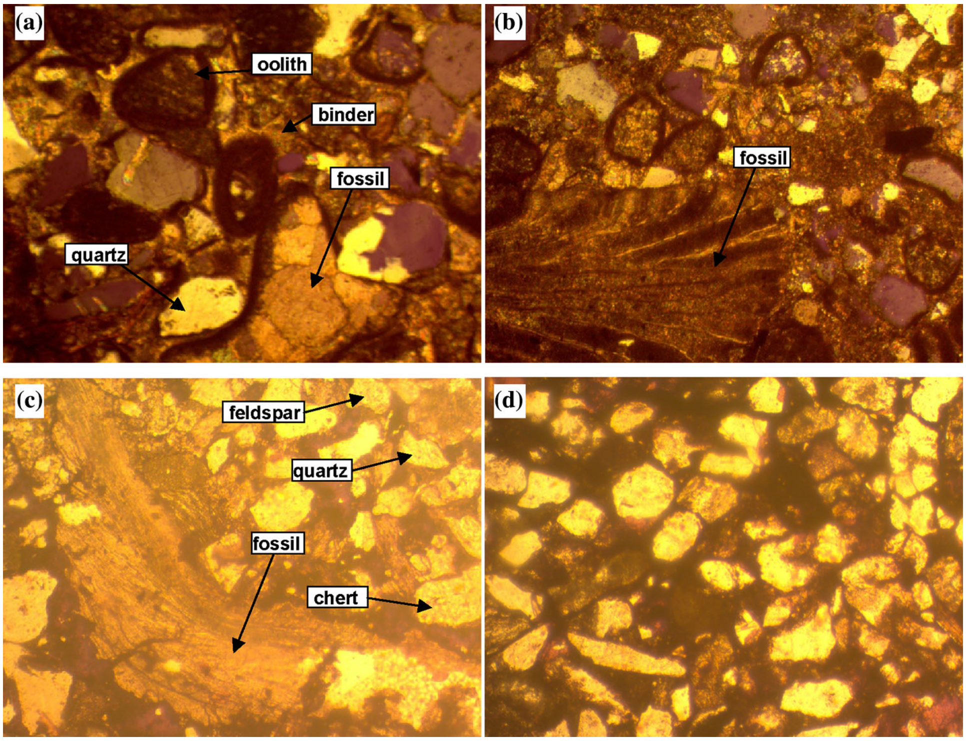


Fig. 2 Mineral grain structure of sandstone observed in polarized light thin section, section width ≈3 mm. **a** Sample No. 1 (*crossed nicols*), **b** sample No. 2 (*crossed nicols*), **c**, **d** sample No. 3 (*parallel nicols*)

usually alkali, with rare plagioclase grains. Chert fragments are rounded to subrounded, and 0.5 mm in size. Rare micas are of crescent shape, 1 mm in size. Fossil remains have different shapes and sizes with micrite envelopes, between 0.3 and 3 mm. Oncoids and ooids are spherical in shape, and between 0.2 and 2.3 mm in size. the nucleus is usually quartz grain, but calcite grains are also observed. The sandstone rock is termed calcarenite.

Methodology of sample preparation and testing

Rock mass samples for testing were taken in the zone of "Gradinje" cutting, located in the southern part of the Republic of Serbia, in the vicinity of the border crossing with the Republic of Bulgaria (Fig. 3). Cutting, ca. 800 m long, is part of the Dimitrovgrad bypass section of the E80 highway project. The main material encountered is Dimitrovgrad flysch, described in detail by Berisavljević et al. (2015).

Fig. 3 View of Gradinje cutting as a part of the E80 highway project

Three trial pits were executed up to a depth of 1.5 m, where unweathered material was found.

Intact rock blocks (maximum dimensions of 20 × 20 × 20 cm) of different lithological types were taken, wrapped in polyethylene bags and transported to the laboratory. Cylindrical samples, 47 mm in diameter, were extracted from rock blocks by using high quality drilling equipment with a diamond bit. No drilling fluid was used during sample extraction. The ends of the specimens were than cut, polished, and shaped to the required height/diameter ratio with tolerances as per ASTM recommendations (2014). The entire proces is shown in Figs. 4 and 5.

The height to diameter ratio of all composite samples varied between $2.0 < h/d < 2.5$. Samples were tested at room temperature, and the time between testing and field extraction of samples was not longer than 20 days. The application of force was perpendicular to the specimen ends, and the time to failure was between 3 min and 8 min. Overall, 14 composite samples, 5 siltstone and 4 sandstone samples were tested. One specimen represents one sample.

Results of uniaxial compressive strength tests

The range of values of bulk unit weight and moisture content determined on sandstone and siltstone discs is shown in Table 1. Bulk unit weight was determined on

Fig. 4 Methodology of sample preparation. **a** Extraction of intact rock blocks from trial pits. **b** Rock blocks in the laboratory prepared for drilling. **c** Drilling process. **d** Final appearance of individual sandstone and siltstone discs

Fig. 5 Composite samples prepared for testing

Table 1 Main physical properties of sandstone and siltstone

Sample type	Bulk unit weight (kN/m^3)	Average bulk unit weight (kN/m^3)	Moisture content (%)	Average moisture content (%)
Sandstone	25.01–27.39	25.54	0.38–0.60	0.49
Siltstone	23.79–25.11	24.48	0.85–1.48	1.10

each disc sample prior to UCS testing, and moisture content was determined on remnants immediately after testing. Results of UCS testing on composite samples are shown in Table 2.

The composite sample U-6 has a minimal siltstone percentage of 13.3%, while sample U-12 has a maximal siltstone percentage of 64.52%. Values of UCS of uniform siltstone samples range between 12.37 and 16.58 MPa

Table 2 Test results. *sl* Siltstone, σ_{ci} uniaxial compressivestrength

Sample type	Sample no.	sl (%)	σ_{ci} (MPa)
Sandstone	U-19	0	78.78
	U-20	0	68.74
	U-21	0	54.79
	U-22	0	83.04
Composite sample	U-6	13.3	32.53
	U-4	14.23	34.08
	U-5	17.65	25.78
	U-2	21.12	34.31
	U-7	29.31	28.49
	U-9	35.93	17.82
	U-3	41.33	31.83
	U-1	42.9	19.43
	U-10	45.71	22.55
	U-13	47.88	23.41
	U-11	54.01	11.13
	U-14	57.48	13.78
	U-8	62.15	16.44
	U-12	64.52	15.97
Siltstone	U-16	100	16.58
	U-17	100	12.37
	U-18	100	13.68
	U-23	100	14.47
	U-24	100	13.95

(with average value of 14.21 MPa). UCS values of sandstone samples varies between 54.79 and 83.04 MPa (average of 71.33 MPa).

Figure 6 shows some characteristic failure mechanisms of composite samples with different siltstone percentage. The failure of sample U-4 (sl% = 14%) was initiated in the upper sandstone disc with the occurrence of a tension crack. Further loading led to failure of the entire composite sample. With an increase in siltstone volumetric participation, as in the case of sample U-9 (sl% = 36%), shear failure encompassed the entire composite sample. The continuity of the failure surface indicates the fact that the presence of bonding material is not necessary at the interface zone. For a certain thickness of weaker disc, the angle between the shear failure surface and the horizontal line, β, becomes larger with increasing strength of the stronger disc (Liu et al. 2014). Any further increase of siltstone participation leads to failure in tension of the siltstone disc (e.g. sample U-13, sl% = 48%). Schematics of some failure patterns are shown in Fig. 7.

The entire process was recorded with a high-speed camera (120 fps) (Fig. 8). This enabled detailed analysis of failure process, leading to the following conclusions:

(1) When the siltstone percentage is <20%, the failure is restricted to sandstone disk and represents a combination of shear and tension.

2. In the case when the siltstone percentage is $20\% < \text{sl} < 45\%$, the shear failure encompasses the entire composite sample.
3. When the siltstone percentage is >45%, failure is restricted to siltstone disk and its mechanism is tensile in nature.

This implies that the failure pattern of lithologicaly heterogeneous rock masses is complex in nature, as represented by combined failures in shear and tension.

The variation in UCS with siltstone percentage is shown in the form of diagram on Fig. 9. It can be seen that the UCS decreases exponentially with an increase of siltstone percentage up to the siltstone participation of 60%. Volumetric participation of siltstone above 60% provides UCS equal to the strength of uniform siltstone sample.

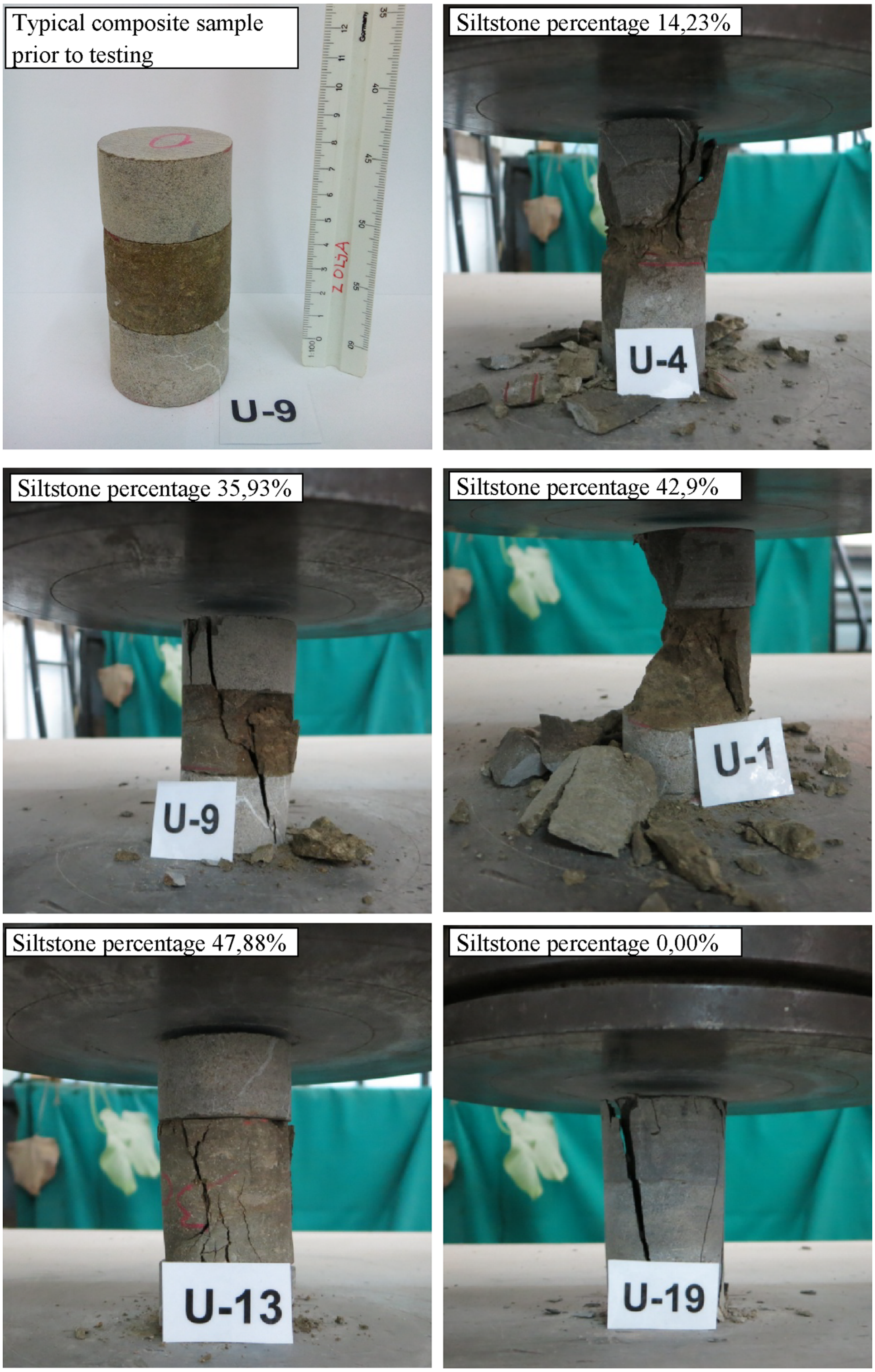
Discussion of results and comparison with previously published data

For the sake of further discussion, the results of the present study are compared with the findings of Tziallas et al. (2013), which also determined an exponential dependancy between UCS and siltstone percentage, but found a critical ratio at which the strength of composite sample equals the strength of siltstone material of 37% (Fig. 10). The samples used in their study were collected from the Kalydona tunnel of the Ionia Odos Highway. The light-gray to gray, medium- to coarse-grained, fresh, sandstone samples with siltstone lenses, which did not exceed 1–2%, and gray-green to dark-gray, homogeneous siltstone samples were prepared either from intact sandstone and siltstone blocks or from borehole cores.

Laboratory prepared samples are an idealised representation of actual field conditions, with siltstone participation in the laboratory being not necessarily equivalent to that in the natural environment. In this study, composite samples assume placing a siltstone disc between two sandstone discs. The spatial variability of different lithological types is abrupt and irregular in natural environments. This is mainly due to a lack of continuity between alterations of different lithological members. For this reason, Tziallas et al. (2013) proposed a scheme for correlating siltstone proportions at the field and laboratory scale, indicating that laboratory specimens should have lower proportion of siltstone than actually encountered under field conditions (Fig. 11).

For example, a heterogeneous rock mass with equal proportions of siltstone to sandstone (sl:st = 1:1) will have

Fig. 6 Samples with different siltstone/sandstone (sl/st) ratio before and after testing



a percentage of siltstone equal to 30% in the laboratory specimen, as shown for specimen B in Fig. 11. Geotechnical models are rarely formed by including all flysch alterations, as it would be impossible in practice to consider all of them, especially if thin layered. Marinos and Hoek (2001) proposed that a weighted average of the intact strength properties σ_{ci} and m_i of strong and weak layers should be used, depending on siltstone and sandstone participation in the flysch sequence.

In the following, the proposed exponential dependency is compared with the empirical suggestions of Marinos and Hoek (2001). Five distinct rock mass types with varying

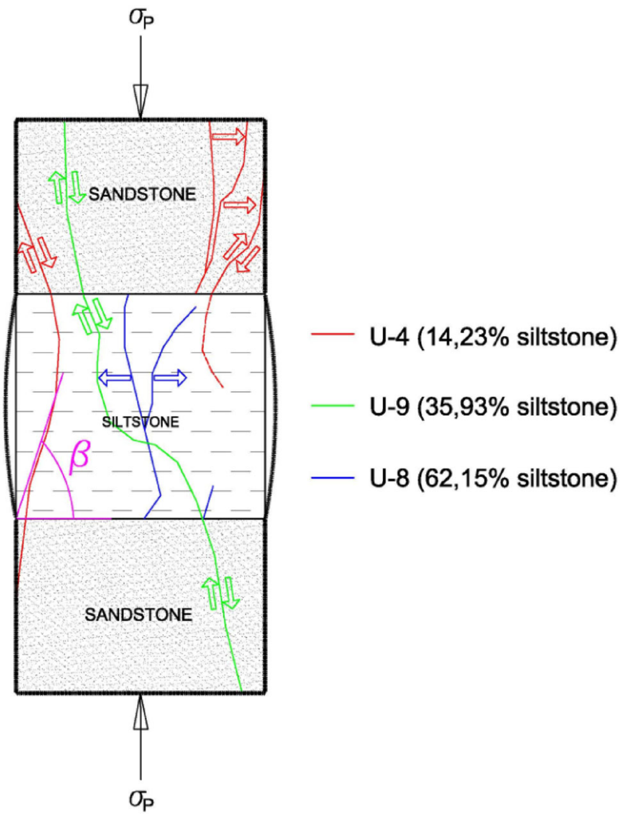


Fig. 7 Schematics of failure mechanisms of tested samples with variable siltstone percentage

siltstone-sandstone proportions were determined during face mapping of more than 1500 m of cuts in the zone of "Gradinje" slope (Berisavljević et al. 2015). Weighted average values of intact rock parameters for each geotechnical type were determined according to Marinos and Hoek (2001), as shown in Table 3.

Field scale siltstone participation was correlated to the laboratory scale according to the proposed procedure of Tziallas et al. (2013) (Table 4). Average values of uniaxial compressive strength of proposed intervals (Table 3) are adopted for geotechnical types GT I to GT V, as shown in Table 4.

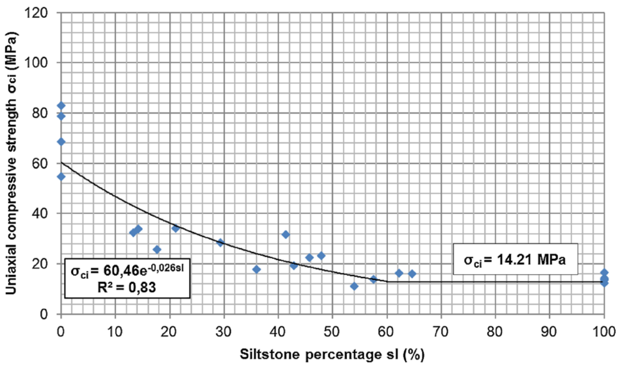


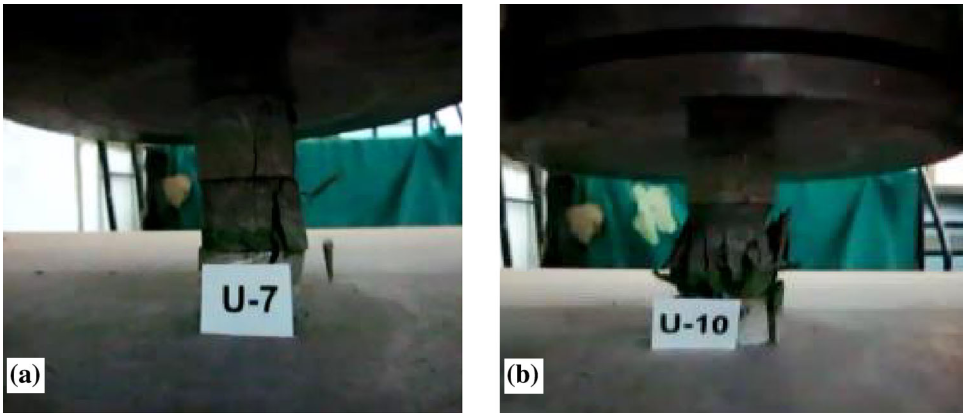
Fig. 9 Value of uniaxial compressive strength (UCS) against siltstone percentage

Comparison between laboratory characteristics of five flysch types, as per Table 4, and the proposed exponential equation is shown in Fig. 12. The comparisons show good agreement. The critical siltstone percentage at which the strength of heterogeneous flysch rock mass in the field conditions corresponds to that of a siltstone is 80%.

Due to the differences in strength of the original materials, and in order that the laboratory results of different studies be comparable, the UCS values of each sample can be normalized by the average strength of sandstone material ($\sigma_{ci}/\sigma_{ci\ strong}$ ratio), as shown on Fig. 13. Tziallas et al. (2013) concluded that the decrease of strength with siltstone percentage depends on the ratio of compressive strength of the original materials. For a ratio of $\sigma_{ci\ strong}/\sigma_{ci\ weak} = 4.4$ (Zainab et al. 2007), the decrease in strength has a steeper gradient than in the case where $\sigma_{ci\ strong}/\sigma_{ci\ weak} = 2.2$ (Tziallas et al. 2013). In the present study, the ratio of $\sigma_{ci\ strong}/\sigma_{ci\ weak} = 5$, but the strength decrease has a lower gradient than in the studies cited, and corresponds to empirical suggestions.

An explanation for this should be sought in the strength heterogeneity of individual discs. For example, the strength

Fig. 8 The moment of failure of composite sample recorded with high-speed camera. **a** U-7, **b** U-10



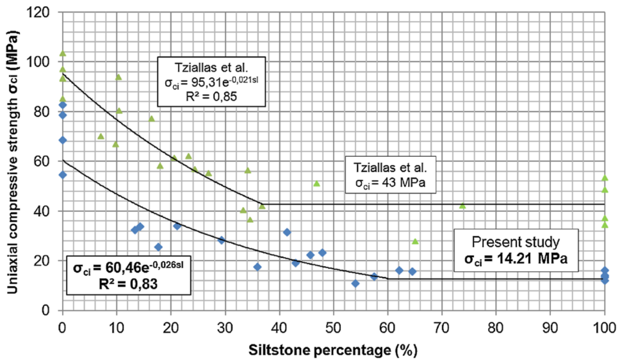


Fig. 10 Comparison of the present results with the study of Tziallas et al. (2013)

Table 3 Field characteristics of flysch, after Marinos and Hoek (2001)

	sl:st	σ_{ci} (MPa)
GT I	“Sandstone”	60–70
GT II	1:5	42–47
GT III	1:1	27–30
GT IV	2:1	18–20
GT V	5:1	10–12

of sandstone samples U-19 to U-22 ranges between 54 MPa and 83 MPa (with standard deviation of 12.55), implying that the different sandstone discs within the composite samples may have different strength values, thus influencing the final result. Tziallas et al. (2013) and Zainab et al. (2007) obtained much lower dispersion of data after tests on sandstone samples, i.e. values of standard deviations of 6.67 and 2.68, respectively. This probably has to do with the more homogeneous nature of the rock materials tested. It can be further assumed that the uniaxial compressive strength value of the sandstone discs within the composite sample with relatively low siltstone participation lies on the lower boundary limit of all tested sandstone samples, and the strength of the siltstone disc has a value corresponding to the lower bound value of all tested siltstone samples. On the other hand, the composite sample with relatively high siltstone volumetric participation may have the strength of discs on the upper bound side of the strength of the source materials. Depending on the ratio of siltstone volumetric participation of the two composite samples, this strength variation produces similar, or even higher, overall strength of composite sample with higher siltstone participation compared to the composite sample with lower siltstone volumetric participation. As a

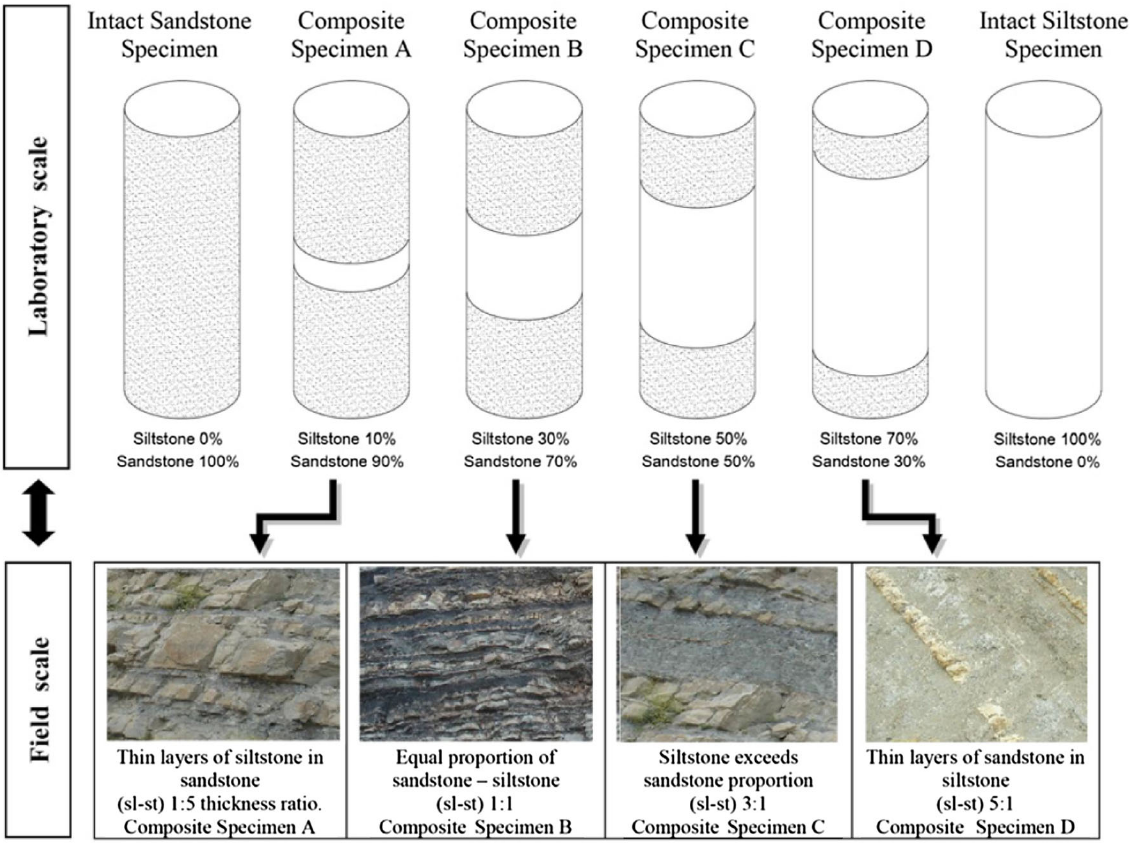


Fig. 11 Different proportions of sandstone and siltstone in laboratory and field conditions, after Tziallas et al. (2013)

Table 4 Laboratory characteristics of flysch according to Fig. 11

	% sl	σ_{ci} (MPa)
GT I	0	65
GT II	10	45
GT III	30	29
GT IV	40	19
GT V	70	11

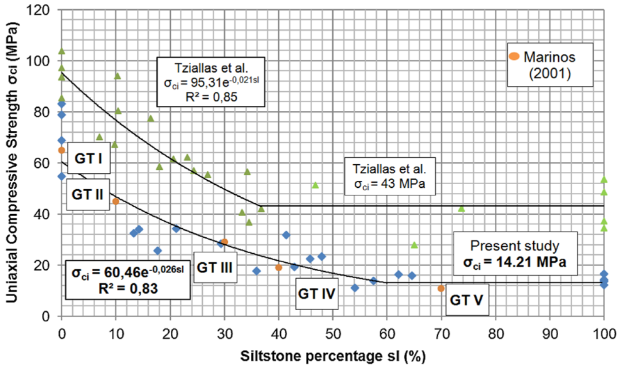


Fig. 12 Comparison of proposed exponential function with empirical proposals

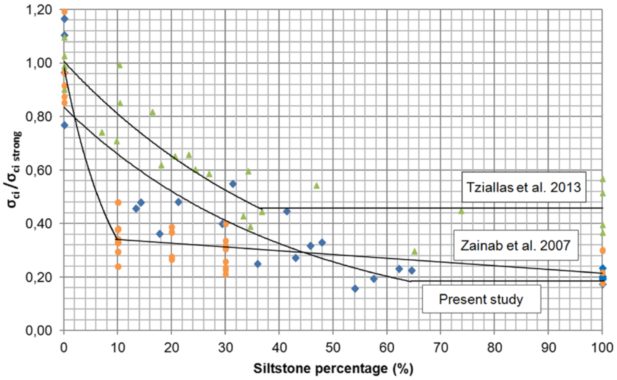


Fig. 13 Variaton in $\sigma_{ci}/\sigma_{ci\ strong}$ with siltstone percentage

consequence, a lower gradient of the strength decrease should be expected compared to the findings of Tziallas et al. (2013).

Mineral grains are distributed randomly within rock specimens. Different grain types have different strengths and deformation parameters. Failure modes of specimens are sensitive to local variations in mechanical properties, thus failure patterns are likely to be unknown prior to testing. The influence of micro-heterogeneity on the value of UCS was studied numerically by Tang et al. (2000). The specialized software package RFPA (Tang 1997), which uses the principles of linear elastic fracture mechanics was used for these purposes. The medium is assumed to be composed of many mesoscopic elements with different strengths and deformation properties. The mechanical parameters of the particles involved are reduced following a Weibull distribution. Heterogeneity is defined by means of the homogeneity index *m*. According to the definition, a larger *m* implies a more heterogeneous material and vice versa (Tang et al. 2000). The results of this study are shown in Fig. 14. The stress–strain curves in Fig. 14c show a drastic decrease in peak strength in heterogeneous samples (ca. 15 MPa), compared to the strength of homogeneous samples (ca. 80 MPa). Testing of a larger number of composite samples may partly eliminate the effect of heterogeneity.

On the other hand, Liang et al. (2007) and Liu et al. (2014) consider that the value of UCS depends solely on the strength of the weaker material. Results of minimal, maximal and average strengths of composite samples consisting of rock-coal discs are shown in Fig. 15. Coal volumetric participation is 40% for all tested samples, and the samples differ in the strength of the rock discs. The UCS of coal samples is ca. 5.4 MPa and that of the rock varies between 38 MPa and 94 MPa. The $\sigma_{ci\ strong}/\sigma_{ci\ weak}$ ratio of these samples varies between 7 and 17.4. Figure 15 shows that the average strength of all tested composite samples is practically the same, and thus is not influenced by the strength of rock material. This conclusion seems valid just for the particular case under consideration for which the $\sigma_{ci\ strong}/\sigma_{ci\ weak}$ ratio is higher than 7. Figure 6 shows that for the low siltstone participation of only 14% the failure is initiated in the stronger sandstone disc, thus the strength of stronger material determines the strength of the entire composite sample.

Concluding remarks

In order to inspect the influence of lithological heterogeneity on the value of UCS, specially prepared composite samples were tested. Composite samples were comprised of sandstone and siltstone discs with different thickness ratios. With an increase of siltstone volumetric participation from 0 to 60%, UCS decreases exponentially. Volumetric participation of siltstone above 60% provides UCS equal to the strength of the uniform siltstone sample. These findings were compared with empirical relations for determination of UCS of heterogeneous rock masses with different siltstone and sandstone proportions. Comparisons showed good agreement. When the siltstone percentage is <20%, the failure is restricted to sandstone disk, and represents a combination of shear and tension. In the case where the siltstone percentage is 20% < sl < 45%, the shear failure encompasses the entire composite sample. When the siltstone percentage is >45%, the failure is restricted to the siltstone disk, and its mechanism is tensile in nature.

The gradient of the strength decrease (as indicated by the $\sigma_{ci\ strong}/\sigma_{ci\ weak}$ ratio) did not match the findings of Tziallas

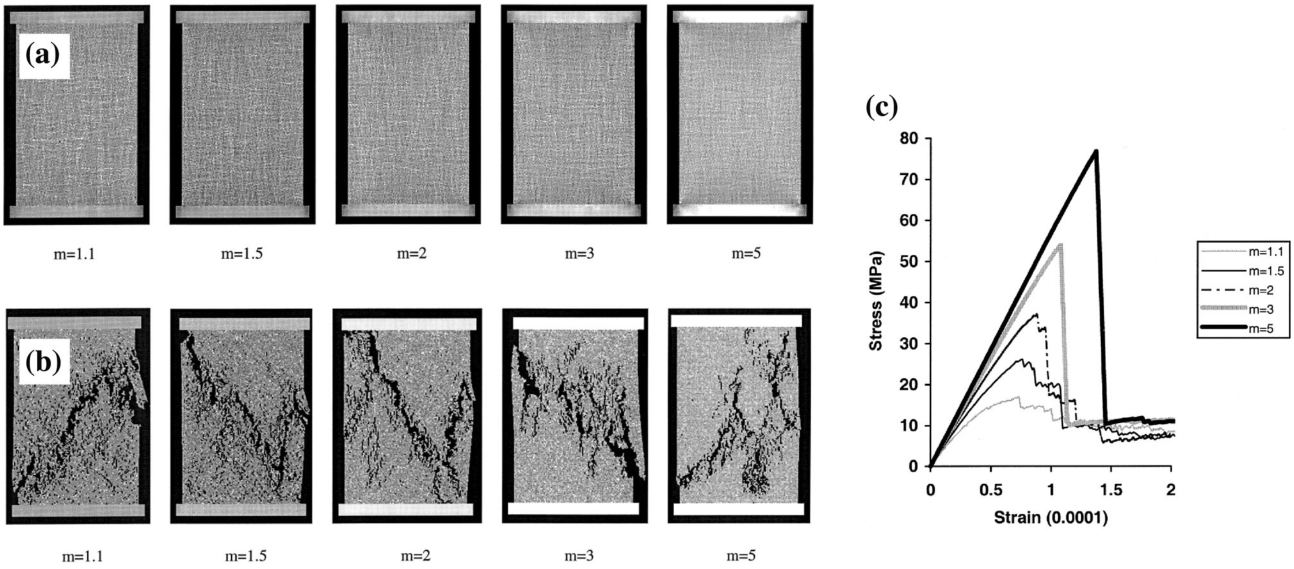


Fig. 14 Influence of heterogeneity on failure mode for five different homogeneity indices *m*. **a** Specimens prior to numerical simulations. **b** Specimens after the failure simulation. **c** Stress–strain curves [after Tang et al. (2000)]

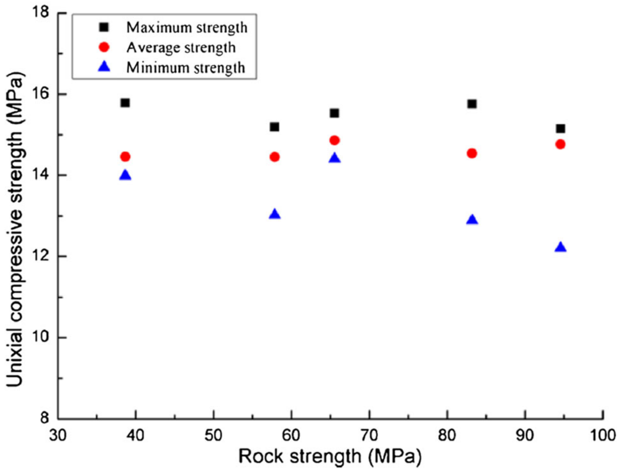


Fig. 15 Variation of composite sample strength with increasing rock strength (Liu et al. 2014)

et al. (2013). The reasons for this should be sought in the effect of micro-heterogeneity (heterogeneity on the level of mineral grains of individual rock types). The effects of micro-heterogeneity can be partly eliminated by testing a larger number of composite samples. Further studies are needed in order to conclude how the $\sigma_{\text{ci strong}}/\sigma_{\text{ci weak}}$ ratio influences the strength of the composite sample.

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