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Laboratory Assessment of Shear Strength Parameters of Carpathian Flysch

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Abstract

Carpathian Flysch is a complex sedimentary formation developed as a result of turbidite deposition in a deep-marine basin during the Cretaceous to Miocene period. The sequence consists of rhythmically alternating layers of sandstones, siltstones, mudstones, and shales, formed through successive gravity-driven sediment flows. This characteristic lithological alternation, combined with well-developed foliation and tectonic history of the Carpathian orogen, results in strongly anisotropic mechanical properties of the rock mass. The anisotropy manifests itself in directional variability of stiffness, strength, and deformability, making standard geomechanical characterization particularly challenging. Reliable determination of shear strength parameters of Carpathian Flysch requires careful consideration of sample preparation procedures. Laboratory-prepared reconstituted specimens, commonly used as a cost-effective alternative, fail to preserve the natural fabric, micro-structural discontinuities, and bedding orientation inherent to the intact rock. As a result, triaxial compression tests performed on such specimens systematically overestimate cohesion and misrepresent the friction angle, leading to unconservative geotechnical designs. In contrast, core-derived specimens retain the original structural features of the rock, providing more representative and reliable strength parameters for engineering practice. This study presents a comparative analysis of triaxial test results obtained from reconstituted laboratory specimens and undisturbed core-derived samples of Carpathian Flysch. The experimental program highlights systematic differences in shear strength envelopes between the two specimen types. The findings demonstrate that core-derived specimens should be considered a standard requirement for triaxial testing of anisotropic flysch formations, and that the use of reconstituted samples may introduce significant errors in geomechanical characterization. Practical recommendations for sample preparation and testing procedures are discussed.

Keywords

Carpathian Flysch, Triaxial tests, Shear strength, Sample preparation.

1 Introduction

Carpathian Flysch represents one of the most extensive sedimentary formations in Central Europe, stretching across the outer zones of the Carpathian arc from the Czech Republic through Slovakia, Poland, and Ukraine to Romania (Roure et al. 1993). Successive gravity sedimentation deposited alternating sequences of coarse-grained sandstones and fine-grained mudstones, shales, and siltstones (Leszczyński et al. 2015). This repeated depositional pattern, known as the Bouma sequence, produced a rock mass characterized by pronounced lithological heterogeneity and well-developed bedding planes (Filipek et al. 2025). Subsequent tectonic activity associated with the Alpine-Carpathian orogeny imposed additional structural complexity through folding, faulting, and the development of secondary discontinuity sets, further contributing to the inherently anisotropic nature of the flysch rock mass (Murovskaya et al. 2026).

The geotechnical hazards associated with Carpathian Flysch are numerous and well-documented (e.g. Mihu-Pintilie et al. 2026; Roguska, E., & Russo, R. 2025). The alternation of sandstone beds with weak, clay-rich shale and mudstone interlayers creates preferential failure surfaces that are particularly susceptible to slope instability (Bestyński et al. 2022).

Preliminary geomechanical characterization of flysch formations is commonly based on index testing methods, among which the uniaxial compressive strength (UCS) test and use of Geological Strength Index system as widely employed method (Garzón-Roca et al. 2025). UCS testing provides a fundamental measure of intact rock strength and serves as a key input parameter for rock mass classification systems and empirical failure criteria. However, due to the pronounced anisotropy of flysch, UCS values vary significantly depending on the orientation of the specimen with respect to bedding, with significant strength reductions observed when loading is applied parallel to foliation planes (Durmeková et al. 2022). The GSI system, introduced by Hoek and Brown, offers a qualitative framework for estimating rock mass strength based on field observations of structure and surface conditions. While GSI is broadly applicable and widely adopted in engineering practice, its inherently subjective nature and limited sensitivity to anisotropy reduce its reliability when applied to heterogeneous flysch sequences. These limitations underscore the need for more rigorous laboratory testing approaches when accurate strength characterization is required (Rembiś and Czurczak 2026).

Triaxial compression testing becomes indispensable in geotechnical investigations where the confining stress conditions of the in-situ rock mass must be replicated and where the determination of both cohesion and friction angle is required (Zhang et al. 2024). Such conditions arise in the design of deep tunnels, high slopes, retaining structures, and foundations subjected to significant lateral stresses (Li, et al. 2022). For flysch formations, the need for triaxial testing is further reinforced by the inability of uniaxial and index tests to capture the stress-path dependency of strength in anisotropic and heterogeneous materials (Comegna et al. 2024). Furthermore, empirical classifications such as GSI-based Hoek-Brown criteria require validation against laboratory-derived Mohr-Coulomb or Hoek-Brown parameters, particularly in cases where the rock mass quality is poor or highly variable, as is commonly observed in tectonically disturbed flysch zones (Ghourtlar 2025).

Existing studies on the triaxial shear strength of flysch provide a useful reference framework, though results exhibit considerable variability reflecting differences in lithology, testing procedures, and sample quality. Flysch rock masses based on GSI classification, using Hoek-Brown, Mohr-Coulomb, and hyperbolic failure criteria demonstrated that assuming a linear strength envelope across the full stress range may produce erroneous results when envelope curvature is pronounced (Berisavljević et al. 2015). Additionally, triaxial studies on clastic rocks of varying diagenetic grade confirm that lithological variability within flysch sequences, particularly differences in grain size and diagenesis, fundamentally controls mechanical behaviour, with weakly diagenised porous rocks exhibiting high strainability and transitional failure, while fine-grained high-strength rocks maintain brittle fracture up to 90 MPa confining pressure. These findings underline the necessity of specimen-specific testing approaches when characterising mechanically heterogeneous flysch formations (Łukaszewski 2008).

This paper presents a laboratory investigation of shear strength parameters of Carpathian Flysch obtained through triaxial compression testing of core-derived and reconstituted specimens. The study aims to demonstrate the systematic differences in strength envelopes between the two specimen types and to highlight the critical importance of using undisturbed core samples for reliable geomechanical characterisation of anisotropic flysch formations.

2 Material and Methods

2.1 Material

The investigated rock specimens were sourced from the Carpathian Flysch of the Magura Nappe, which constitutes the dominant geological unit in the Lubień area of the Beskid Makowski range in southern Poland. The Magura Nappe consists of rhythmically alternating sequences of flysch deposits of Cretaceous to Paleogene age, formed through turbidite sedimentation in a deep-marine fore-arc basin and subsequently thrust northward during the Alpine-Carpathian orogeny. The two investigated lithological end-members a) a sandstone-dominated flysch (BH-1) and b) a clay-bearing shale-dominated flysch (BH-2) represent the characteristic compositional variability of the Magura Nappe, in which competent massive sandstone beds alternate with weak, water-sensitive shale interlayers.

BH-1 represents a sandstone-dominated flysch complex with a sandstone content exceeding 85%, corresponding to Thiel's structural Model I, subtype B (layer thickness below 0.3 m). The rock mass is moderately fractured, with a mean joint spacing of approximately 2 cm and low joint surface roughness and alteration. Based on the Q-system classification, the rock quality designation (RQD) is estimated at 50–60, with a joint set number Jn of 2–3, joint roughness number Jr of 1.0, and joint alteration number Ja of 1.0, yielding a Q' index of approximately 22. This corresponds to RMR class III (fair rock mass) and a Geological Strength Index (GSI) of 35–45. The sandstone component exhibits high resistance to water-induced degradation, with compressive strength reduction upon saturation of approximately 10%.

BH-2 represents a shale-dominated flysch complex, classified as Thiel's structural Model IV–V. The rock mass is intensely fractured, with a mean joint spacing of approximately 1 cm. Joint roughness and alteration parameters are similarly low (Jr = 1.0, Ja = 1.0); however, the closely spaced discontinuities yield an estimated RQD of 20–35 and a joint set number Jn of 3–4, resulting in a Q' index of approximately 7.7. The corresponding classification places this material in RMR class IV–V (poor to very poor rock mass) with a GSI of 20–30. A critical characteristic of BH-2 is the high susceptibility of its clay-bearing shale matrix to water-induced degradation; upon contact with water, the material undergoes rapid strength loss approaching complete disintegration, a behaviour consistent with the presence of swelling clay minerals such as smectite and illite.

A summary of the geomechanical classification parameters for both investigated materials is presented in Table 1.

Table 1. Geomechanical classification of investigated Carpathian Flysch specimens.

Parameter	**BH-1 (Sandstone flysch)**	**BH-2 (Shale flysch)**
Thiel structural model	Model I-B	Model IV–V
Mean joint spacing	~2 cm	~1 cm
RQD [%]	50–60	20–35
Jn	2–3	3–4
Jr	1.0	1.0
Ja	1.0	1.0
Q' index	~22	~7.7
GSI	35–45	20–30
RMR class	III (fair)	IV–V (poor–very poor)
Water sensitivity	Very Low (~2% strength reduction)	Medium (significant disintegration)
Depth	30-35m	25-30m

2.2 Method

Two specimen types were prepared for triaxial testing. The first type consisted of undisturbed core-derived specimens (denoted as U-BH-1 and U-BH-2) obtained directly from borehole cores recovered during site investigation works. Core specimens standard dimensions were of 98 mm in diameter and approximately 200 mm in height, with end surfaces ground perpendicular to the specimen axis to ensure uniform load application. Throughout the preparation process, specimens were handled with care to preserve the natural fabric, bedding orientation, and micro-structural discontinuities inherent to the intact rock. The second type consisted of reconstituted specimens (denoted as R-BH-1 and R-BH-2) prepared in the laboratory from crushed and recompacted material derived from the same source rock. Reconstituted specimens were prepared at equivalent dry density and water content to the core-derived specimens to allow direct comparison of strength envelopes, while deliberately eliminating the original structural features of the rock mass.

Prior to shearing, all specimens underwent isotropic consolidation under three target effective confining pressures of 50 kPa, 100 kPa, and 400 kPa, applied using a standard triaxial cell with a back-pressure system to ensure full saturation. Saturation was verified by measuring the Skempton*B*-parameter prior to consolidation, with a minimum value of 0.95 accepted as the saturation criterion. Volume changes during consolidation were monitored continuously through a digital volume gauge connected to the drainage line, and consolidation was considered complete when the rate of volume change fell below a defined threshold. Full consolidation curves were recorded for each specimen and confining pressure level, providing volumetric data used to determine specimen dimensions at the onset of shearing.

Following consolidation, specimens were subjected to drained triaxial compression (CID - Consolidated Isotopically Drained) at a constant strain rate selected to ensure fully drained conditions throughout shearing, preventing the generation of excess pore water pressure. The strain rate was determined based on the time to failure estimated from the consolidation data in accordance with BS 1377-8:1990. During shearing, the following quantities were recorded continuously: axial displacement d_1, axial loadF_1, cell pressure *CP*, back pressure *BP*, and volumetric drainage *dV*. From these measurements, effective principal stresses σ'_1 and σ'_3, deviatoric stress q, and axial strain ε_1 were calculated and plotted as stress-strain curves and effective stress paths in p'-q space.

Shear strength envelopes were determined by fitting a linear Mohr-Coulomb failure criterion to the peak stress states obtained at the three confining pressures for each specimen series. Mohr circles were constructed for each test and a common tangent line was fitted to determine the effective cohesion c' and effective friction angle φ'. The shear strength parameters were determined independently for core-derived and reconstituted specimens of both lithological types (BR-1 and BR-2), enabling direct quantitative comparison of the influence of specimen preparation method on the resulting strength envelopes.

3 Results

3.1 Stress-Strain Behaviour

The normalized deviatoric stress ratio q/σ'_3 plotted against axial strain ε_1 for both borehole series and specimen types is presented in Figure 1. Undisturbed core-derived specimens of both series exhibited a well-defined peak strength followed by post-peak softening, indicative of brittle to semi-brittle failure behavior characteristic of structured, intact rock. For series U-BH-1, peak normalized deviatoric stress values ranged from approximately 3.7 to 4.8, reached at axial strains between 8% and 15%. Series U-BH-2 displayed higher peak stress ratios, reaching values of approximately 4.7 to 5.3 at lower axial strains of 5% to 10%, suggesting a more brittle response consistent with the stiffer sandstone-dominated flysch. The pronounced post-peak strength reduction observed in both undisturbed series reflects the progressive destruction of the natural rock fabric and discontinuity structure upon shearing.

In contrast, reconstituted specimens of both series exhibited a markedly different stress-strain response, characterized by strain-hardening behavior without a discernible peak, and significantly lower normalized stress ratios throughout shearing. Peak q/σ'_3 values for R-BH-1 and R-BH-2 did not exceed 2.3 and 2.0 respectively, representing a reduction of approximately 50–60% relative to the corresponding undisturbed specimens. Furthermore, the stress ratio in reconstituted specimens showed limited sensitivity to the applied confining pressure, suggesting that the reconstitution process effectively homogenized the material response and eliminated the structural anisotropy inherent to the intact flysch. These observations confirm that the preparation of reconstituted specimens fundamentally alters the mechanical behavior of Carpathian Flysch and cannot be considered a reliable surrogate for core-derived testing in geomechanical characterization.

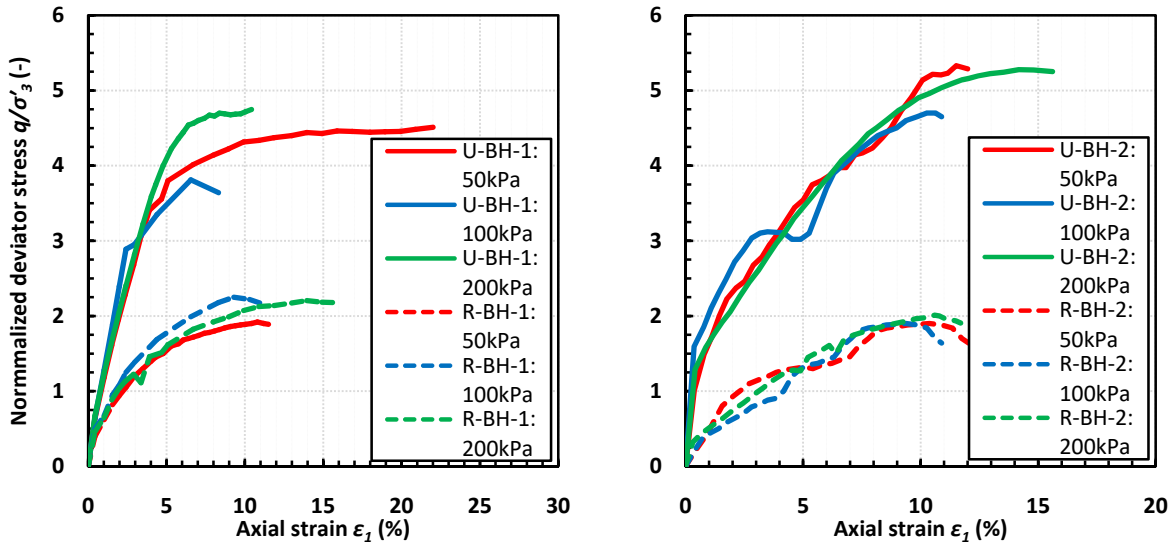


Fig. 1 Normalised deviatoric stress ratio q/σ'_3 versus axial strain ε_1 for undisturbed core-derived (U-BH) and reconstituted (R-BH) specimens of Carpathian Flysch tested at confining pressures of 50, 100, and 200 kPa: (a) sandstone-dominated flysch BH-1; (b) shale-dominated flysch BH-2.

3.2 Effective Stress Paths and Failure Envelopes

The stress paths plotted in *t-s* space (where $t = (\sigma'_1 - \sigma'_3)/2$ and $s = (\sigma'_1 + \sigma'_3)/2$) and the corresponding Kf-lines for both specimen series are presented in Figure 2. Linear regression applied to the peak stress points yielded well-defined failure envelopes for all four specimen groups, with coefficients of determination indicating a consistent linear relationship across the investigated confining pressure range.

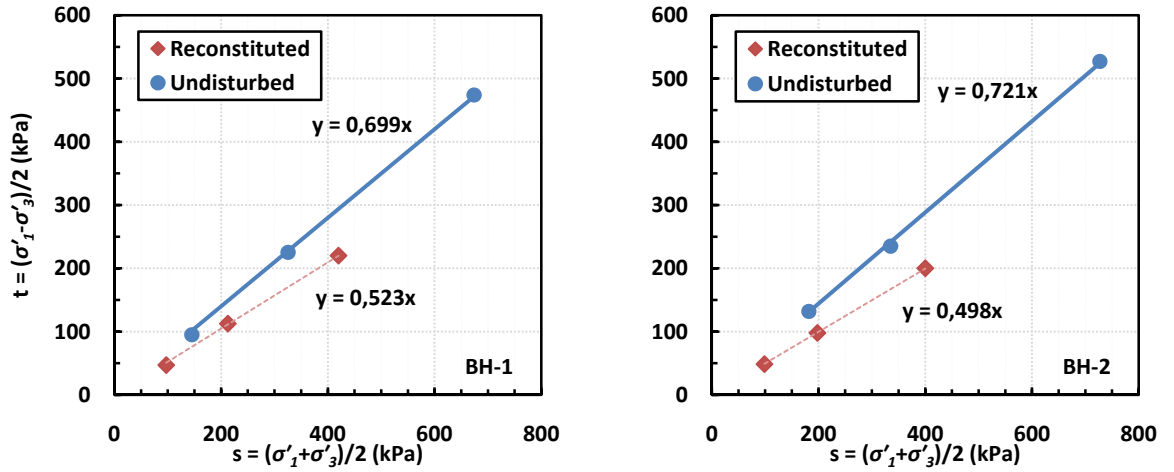


Fig. 2 Effective stress paths and *Kf*-line failure envelopes in *t-s* stress space for undisturbed core-derived and reconstituted specimens of Carpathian Flysch: (a) sandstone-dominated flysch BH-1; (b) shale-dominated flysch BH-2.

For undisturbed core-derived specimens, the slope of the *Kf*-line (tan α) was determined as 0.700 and 0.721 for BH-1 and BH-2 respectively, corresponding to effective friction angles φ' of 44.3° and 46.1°. The intercept of both undisturbed failure envelopes passed through the origin, indicating negligible effective cohesion ($c' \approx 0$ kPa), which is consistent with the behavior of a frictional rock mass in which peak strength is governed primarily by the interlocking of natural discontinuities and the roughness of fracture surfaces.

Reconstituted specimens exhibited markedly lower failure envelope gradients of 0.523 and 0.499 for BH-1 and BH-2 respectively, corresponding to friction angles of 31.5° and 29.9°. Similarly to the undisturbed series, the reconstituted envelopes passed through the origin with negligible cohesion intercept. The reduction in friction angle between undisturbed and reconstituted specimens amounts to approximately 13° for BH-1 and 16° for BH-2, representing a strength reduction of the order of 30–35%. This systematic difference is attributed to the destruction of the original rock fabric during reconstitution, which eliminates the contribution of structural interlocking, bedding-parallel discontinuities, and natural cementation to the overall shear resistance of the Carpathian Flysch.

4 Conclusions

This study demonstrates that specimen preparation methodology is a critical influence on the measured shear strength parameters of Carpathian Flysch. Undisturbed core-derived specimens consistently yielded significantly higher peak friction angles (44–46°) compared to reconstituted specimens (30–32°), representing a strength reduction of approximately 30–35%. The pronounced post-peak softening observed in core-derived specimens, absent in reconstituted counterparts, further confirms that reconstitution irreversibly destroys the natural rock fabric, discontinuity structure, and structural anisotropy inherent to intact flysch.

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