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Laboratory Evaluation of Long-Term Behaviour of Different Natural and Cementitious Materials

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Abstract

The long-term behaviour of brittle materials plays a critical role in understanding time-dependent deformation and failure. For example, it is nowadays essential in the design of a nuclear waste disposal system expected to function for a very long period. It is also crucial when the land above underground quarries that are more than a hundred years old is used as a construction zone. Although brittle materials, such as limestones, dolomites, marls, and concrete, also typically have high stiffness and strength under normal loading conditions, their long-term behaviour, including creep processes, reduces their strength properties over engineering time scales. Creep tests under constant load were performed to investigate this behaviour and to compare the properties of different materials. In brittle rocks, the creep response is commonly divided into three stages: primary (decelerating strain rate), secondary (quasi-steady strain rate), and tertiary (accelerating strain rate). The transition from secondary to tertiary creep is particularly important, as it reflects the onset of unstable crack propagation and provides a basis for predicting long-term failure. Time-dependent deformation is strongly influenced by environmental factors, including moisture, rock composition, and stress level. Samples of drilled rock cores obtained from different locations were examined under long-term uniaxial loading conditions. The normal and long-term behaviour of these materials is evaluated and compared. The results will be used in the second phase of the research to calculate the long-term stability of underground structures and determine the differences between the short-term and long-term behaviour of the cellars, taking into account the effect of surface loads.

Keywords

Brittle materials, Long-term performance, Creep test, Uniaxial loading conditions.

1 Introduction

This study examines the long-term behaviour of various rock and cemented materials, including calcareous marl, porous limestone, while dolomite and concrete will be tested in the second phase of the research. The investigated rocks originated from the Dalmatian area of Croatia and from the Budapest area of Hungary. Firstly, the physical and rock mechanical properties of the investigated materials are introduced. The long-term property tests were conducted at the University of Split. Three types of rocks: Eocene calcareous marl from Dalmatia, Eocene Buda Marl from Budapest area and Miocene porous limestone from Budapest area were tested.

Marl is considered a unique transitional rock in engineering, with a mechanical response between that of stiff soils and soft rocks. Its long-term behaviour is defined by a triad of time-dependent deformation (creep), water sensitivity, and weathering-induced degradation. Understanding these processes is essential for the long-term stability design of civil engineering structures, particularly tunnels and slopes (Görög, 2007). For porous limestone it is also essential to know its creep parameters since they are a host rocks of underground cavities in Budapest (Zenah et al. 2022).

Under sustained loading, marl and soft rocks exhibits significant creep deformation; during this process, long-term strength remains considerably lower than short-term, instantaneous strength (Zivaljevic & Tomanovic, 2021). Laboratory creep tests—which can last from 3 to over 180 days—distinguish three phases of the process: in the primary phase, the closure of microporosity dominates; in the secondary phase, a steady-state deformation rate is established; while in the tertiary phase, micro-pores coalesce into cracks, leading to accelerated deformation and eventual failure. Lateral (horizontal) pressure plays a decisive role in these processes, primarily by influencing the initial and long-term creep rates. Research has also highlighted that marl exhibits "softening" behaviour, especially due to unloading effects during excavation (Tomanovic, 2006; Mánica et al., 2018).

The Eocene flysch formation, which outcrops extensively along the Adriatic coast of Croatia, particularly in the Dalmatian region, represents a thick, geotechnically challenging sedimentary sequence. The backbone of this flysch complex consists of various marly lithotypes, which alternate with siltstones, sandstones, and limestones. Due to the intense tectonic history of the Dinarides, these marly soft rocks are frequently folded, faulted, and heavily jointed, directly defining the geomorphology and engineering geological conditions of the coastal zone. The engineering significance of this marl has expanded drastically in recent decades due to rapid urban development, tourism-driven coastal expansion, and the construction of major transport infrastructure, including highways, deep open cuts, and foundations. These flysch marls occupy a complex transitional spectrum between weak rocks and soils. Consequently, they present severe challenges for slope stability, tunnel support design, and foundational bearing capacity. Engineering hazards associated with the Dalmatian marl are its high vulnerability to rapid environmental degradation. During excavation, moisture fluctuations cause the rock matrix to disintegrate rapidly, leading to a drastic reduction in shear strength and inducing shallow landslides or rockfalls along cut slopes (Vlastelica et al. 2018).

The Eocene Buda Marl is a regional sedimentary formation that outcrops extensively across the Buda Mountains and directly underlies major urban zones of Budapest, Hungary. As a classical transitional lithotype, the Buda Marl occupies a complex geotechnical position between hard rocks and cohesive soils. Its spatial occurrence and variable lithological composition—ranging from clayey marl to highly cemented calcareous marl—have fundamentally influenced both the geomorphological evolution of the capital and its historical urban development (Görög and Török 2026). From an engineering geological perspective, the significance of the Buda Marl is heavily highlighted by its role as the host formation for critical infrastructure, deep foundations, and historic subterranean structures in Budapest. Notable historical structures, such as the underground cellars, tunnels, and foundational retaining walls of the Budapest Castle Hill, are structurally tied to or cut into this formation. Furthermore, due to the expansion of modern metropolitan subway networks and deep multi-story underground parking garages, civil engineering activities routinely interact with this marly sequence. While the highly cemented calcareous marl profiles behave as a stable, medium-to-strong soft rock mass, the lower-carbonate, clay-rich variants often exhibit soil-like plasticity and are highly susceptible to rapid slaking and shear strength degradation upon moisture fluctuations (Görög 2007). The presence of distinct lamination, bedding planes, and tectonic jointing further complicates the in-situ rock mass behaviour, potentially triggering anisotropic failure mechanisms.

The Miocene porous limestone is one of the most significant and historically relevant sedimentary dimension stones in Hungary, particularly within the urban area of Budapest. Due to its favourable workability and availability, this bioclastic and oolitic limestone was extensively quarried for centuries, serving as the primary building material for major historical monuments including the Hungarian Parliament Building, the Citadel, and the Matthias Church (Török et al. 2004). The most intensive surface and subsurface quarrying activities occurred in the Budafok and Kőbánya districts of Budapest. As a direct result of these extensive historic subsurface mining operations, a massive, interconnected network of underground galleries and cellar systems was created. Over time, these shallow underground cavities found secondary use, serving as brewery storage, winery facilities, and mushroom growing. In recent decades, however, the expansion of the urban environment and the critical shortage of greenfield development sites in Budapest have led to intense infrastructural and civil construction directly above these historic quarry zones. Managing the stability of these shallow cavities presents a severe engineering geological challenge. The limestone host rock inherently behaves as a weak, soft rock with extremely high effective macro-porosity (Zenah et al. 2024).Therefore, a precise laboratory and numerical assessment of the long-term behaviour of this porous limestone framework is indispensable.

2 Test methodology

Specimens were obtained from the cellar and tested under laboratory conditions. Several rock physical tests were done according to national standards, such as American Society for Testing and Materials (ASTM) and European Standards (EN): the dry density was calculated according to EN 1936:2006. The uniaxial compressive strength (UCS) test for dry conditions was performed according to ASTM D7012-23.The indirect tensile strength tests (Brazilian tests) were done according to the ASTM D3967-23 descriptions. The rheological test methods are described in the ISRM Suggested Methods (Aydan et al. 2014), and in the code ASTM D7070. In our case, the long-term tests were conducted in accordance with ASTM D7070. Specimens about 100 mm in diameter and about 300 mm in height were cut from the cores of each type of rock. Before the long-term test, the uniaxial compressive strength of each rock type was measured. Drilled specimens were cut with a diamond saw for the compressive strength and creep tests. Specimens were prepared using a diamond-grinding machine to meet the requirements of the standards. Creep tests were conducted in a creep testing machine with a force capacity of 300 kN.

The long-term tests were performed under uniaxial stress conditions, with a constant stress rate applied for a long period. For the long-term test, the 30% of the measured UCS value was applied to each rock type as a long-term load. The load was constant, and the axial displacements of the specimens were measured, allowing the creep characteristics of each specimen to be recorded. For the displacement measurement, a manual displacement indicator with 0.001 precision was used. During the test, strains were measured at the left and right sides of the specimens. Herein, dial gauges and length comparators were used, with an accuracy of 0.001 mm. The strain was measured at the midpoint of the specimens, over a 200 and 220 mm (Fig. 1).



Fig. 1 Calcareous marl from Budapest prepared for the creep test.

The creep load was slowly increased to the test level over about 60 seconds; thereafter, the load was maintained at a constant level until failure. The temperature and humidity were kept constant in the lab during the test (T = 22°C, RH = 55%).A total of six specimens were prepared for the creep test. Four specimens (C1, C2, C3, and C4) were taken from the underground cellar system in the Kőbánya region of Budapest. The material of them is a very soft rock, the porous limestone, with different grain sizes. Specimens C1 and C3 were fine-grained, and specimens C2 and C4 were coarse-grained. Specimen Varosmajor was drilled at the Buda side of Budapest, while specimen GV was drilled at Dalmatia in the Split region. Both samples were calcareous marl with different strengths (Fig. 1).

3 Rock mechanical properties of the investigated materials

3.1 Marl

Marl is a rock that contains clastic material of the clay fraction (<0.002 mm) and carbonate (calcite); therefore, it is defined as a transitional rock between clastic and chemical sedimentary rocks (Pettijohn 1975). The coastal region of Croatia (Dalmatia) lies on the Eocene flysch formations. The most common lithotypes of the flysch formations in Dalmatia are breccias, breccia conglomerates, sandstones, detrital limestones, and marls, with varying $CaCO_3$ content (Šestanović 2000).The Eocene Buda Marl Formation plays an important role in the geology of Hungary. The Buda Marl is mainly associated with Budapest, as its name indicates. It occurs several construction sites in Budapest, construction pits, man-made and natural underground cavities.

The physical and mechanical properties of the Eocene flysch marls from the Dalmatian coastal region (Croatia) are introduced based on an extensive laboratory database according to Duhović et al. (2022). The dry unit weight was measured on 370 specimens; the mean is 22.06 kN/m^3, with a range of 14.14 kN/m^3 to 25.92 kN/m^3. Reflecting its micro-fabric texture dominated by calcitic micrite and varying clay matrix proportions, the mean effective porosity determined from 369 specimens is 15.31% (ranging from a highly compact 0.31% up to a highly porous 45.63%).The Uniaxial Compressive Strength (UCS) dataset, compiled from 400 intact rock specimens, exhibits highly heterogeneous behaviour, with a mean strength of 17.38 MPa. The overall strength spans a broad range from an extremely low 0.04 MPa to a maximum of 89.69 MPa. Notably, approximately 25% of the tested marl samples exhibit a UCS above the traditional soft rock upper limit of 25 MPa, which corresponds directly to the highly cemented, carbonate-rich calcareous marl variants. The tangent Young's modulus measured at 50% of the peak UCS for 192 samples ranged from 0.03 GPa (highly deformable) to 41.46 GPa, with a mean of 6.70GPa.

Among the Hungarian marls, the properties of the Eocene Buda Marl Formation were most extensively investigated due to its widespread distribution around Budapest. As with the marls from the Dalmatian region, the lime content determines their properties (Görög 2007). The physical and mechanical properties of all types of Buda Marl are described by Görög (2007), Duhović et al. (2022), Davarpanah et al. (2022) and Görög and Török (2026). The introduction to its properties in this research focuses on the calcareous type, since the long-term test was conducted on that type of marl.

The following physical and rock mechanical parameters of the calcareous type of Buda Marl ($CaCO_3$ content of 60–80%) are from the research papers mentioned above. Based on 86 tested specimens under air-dry conditions, the intact material has a mean density of 2468 kg/m^3 (median of 2487 kg/m^3 and standard deviation of 83 kg/m^3). Reflecting its highly cemented fabric, the effective porosity measured across 17 specimens yields a low mean value of 2.85% (median of 2.84%, and standard deviation of 0.26%).The uniaxial compressive strength (UCS) data obtained from 90 specimens represent a highly variable distribution due to microstructural heterogeneity, with a mean of 43.41 MPa (median of 38.97 MPa, standard deviation of 21.77 MPa). Under optimal diagenetic cementation, the peak intact compressive strength of the air-dry calcareous marl matrix can reach 100 MPa. The indirect tensile strength determined by Brazilian tests on 89 intact rock samples reveals a mean value of 3.81 MPa (median of 3.68 MPa, standard deviation of 2.04 MPa).The modulus of elasticity, measured from 71 specimens, shows significant scatter due to varying clay-to-carbonate ratios, yielding a mean elastic modulus of 6.87 GPa (median of 5.75GPa, standard deviation of 4.16GPa).

3.2 Porous limestone

The other rock type, which is important and widespread in and around Budapest, is the Miocene Porous Limestone. This oolitic limestone was used as the most important dimension stone in Budapest. The quarrying of this stone resulted in significant areas covered by this rock type being undermined. Investigating it is important for the stability calculations of these areas.

The physical and rock mechanical properties of the Miocene porous limestone were analysed by several researchers, such as Török et al. (2004), Zenah et al (2022), Szabó et al. (2022), Zenah and Görög (2024). The porous limestone is characterised by a highly open, macroporous fabric, which inherently results in lower density and significantly higher effective porosity than the calcareous marl. The laboratory testing of intact air-dry specimens yields a mean density of 1710 kg/m^3 (with values typically spanning a range between 1410 kg/m^3 and 1920 kg/m^3). Due to the bioclastic and oolitic texture of the limestone, the effective porosity is exceptionally high, with a mean value of 32.8% (ranging from 22.0% to 41.2%). Under air-dry conditions, the intact porous limestone behaves as a classic weak rock, exhibiting brittle failure mechanisms during laboratory loading. The UCS is governed heavily by the total porosity of the individual core specimens. The statistical mean UCS under air-dry conditions is 8.12 MPa. The broader laboratory database reveals an experimental range from a very weak 3.22 MPa up to 14.88 MPa for the denser profiles. Brazilian tensile tests performed on the specimen show a mean tensile strength of 1.11 MPa (with an experimental spread between 0.49 MPa and 1.95 MPa). The Young's modulus, reflecting the highly compressible framework of the porous matrix, exhibits a mean value of 2120 MPa (spanning from a flexible 950 MPa up to 3410 MPa in low-porosity core samples).

4 Test results and discussion

Prior to the creep tests, the uniaxial compressive strength of the materials was measured in accordance with ASTM D7012-23. The test results are presented in Table 1, and the UCS values of the materials are in accordance with the descriptions in Chapter 3. The measured UCS of the porous limestone is lower than the average, whereas that of the calcareous marl is higher, especially for the Dalmatian sample.

Table 1. Uniaxial compressive strength of the tested materials.

Specimen	UCS [MPa]
C1	3.69
C2	3.04
C3	4.66
C4	2.85
Varosmajor	52.16
GV	115.71

Since the load was applied at approximately 30% of each material's compressive strength, specimens were divided into groups to apply different axial forces due to the different compressive strengths of the materials. Table 2 shows the dimensions, applied creep load, and creep stress for all specimens.

Table 2. Uniaxial compressive strength of the tested materials.

Specimen	Diameter [mm]	Height [mm]	Base [mm]	Applied creep load [kN]	Applied stress [MPa]
C1	105.1	300	200	6.0	0.7
C2	105.0	300	200	6.0	0.7
C3	105.4	300	200	6.0	0.7
C4	104.9	300	200	6.0	0.7
Varosmajor	101.4	300	220	130.0	16.1
GV	84.8	300	220	190.0	33.6

Immediately after the test began, specimens C2 and C3 failed, therefore the test was stopped. Also, the Varosmajor specimen failed immediately due to a pre-existing crack, leading to material cracking under compressive force (Fig. 2 left side picture). Specimens C1 and C4 maintained load, as well as specimen GV. The successful creep test was performed on two porous limestone specimens (C1 and

C4) and one calcareous marl sample (GV). After 15 days, the specimen C4 began to crush at the top, and several days later, a crack formed in its upper part (Fig. 2, right side), leading to instability of the test system; thus, the measurement of specimen C1 also stopped. The C4 specimen was a coarse-grained porous limestone with the smallest uniaxial compressive strength of 2,8 MPa. Therefore, the prediction was that it would fail first under the long-term constant load.

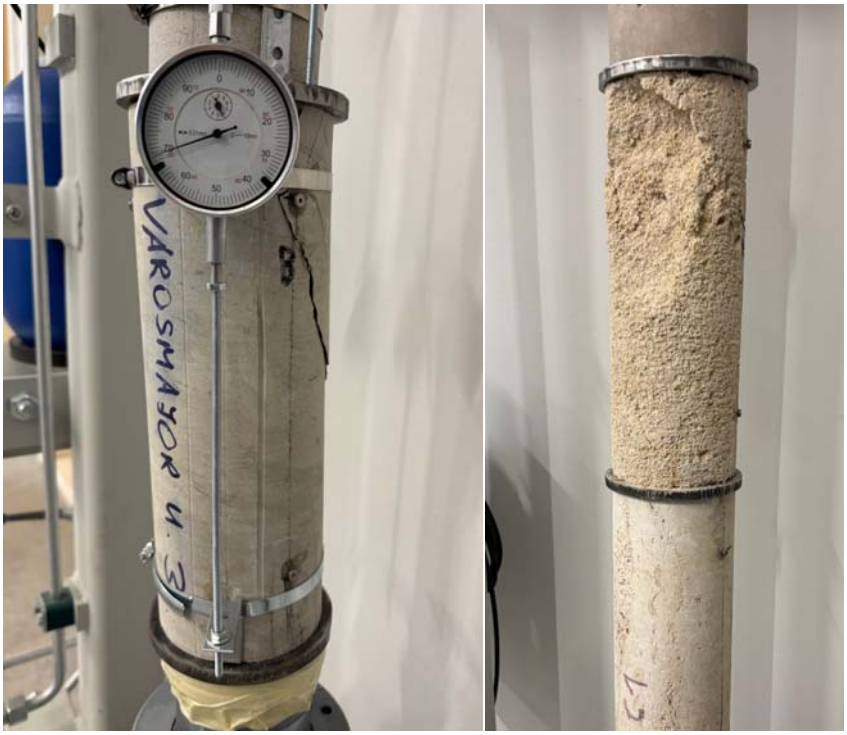


Fig. 2 Failure of the sample Varosmajor (left side) and failure of the sample C4 after 23 days (right side).

Fig. 3 on the left side shows the creep characteristic curve for rocks according to Tarifard at al. (2024). The right side of Fig. 3 shows the measured creep of specimen C4 for the 23-day period. Rock creep deformation is divided into three phases: primary (first or transient), steady-state (secondary), and tertiary (accelerated) creep. The initial stress leads to immediate strain, and the strain rate decreases over time during the transient creep stage, as seen in the measured dataset. In the secondary creep stage, the strain rate remains constant over time, and creep is stable. For the coarse-grained porous limestone (specimen C4), the creep process was rapid, with the transient phase ending after the first day and the secondary stable creep phase beginning. The second phase lasted 17 days according to the measurements, but the first crack appeared on the 15th day. The third phase of creep behaviour is characterised by increased microcracking, which reduces strength and stiffness. After 18 days, the accelerated creep phase was started, and the specimen failed on the 23rd day.

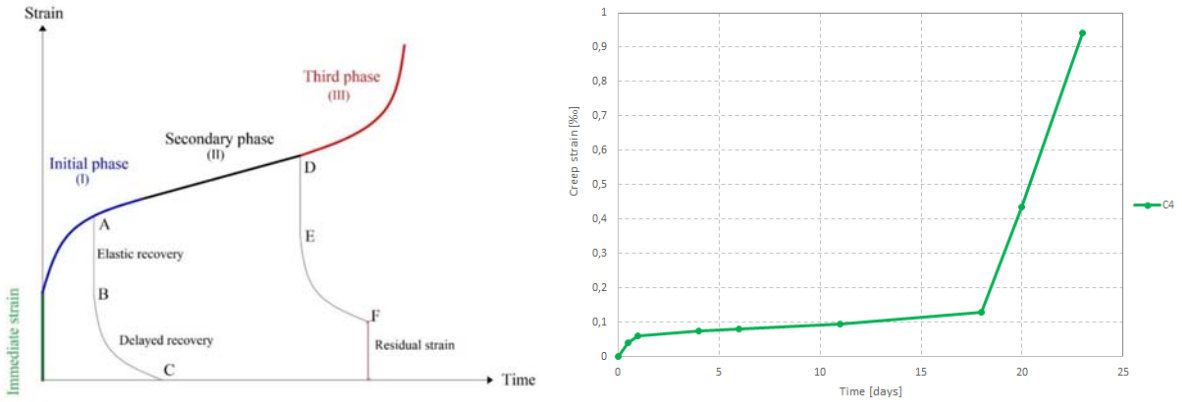


Fig. 3 The three stages of rock creep (left side, Tarifard et al. 2024) and measured creep of sample C4 (right side).

Fig. 4 shows the measured creep for all three specimens without the tertiary creep phase. For the C4 sample, the test ends with sample failure; for the C1 and GV samples, the measurements are only in the secondary phase. The creep measurement for sample GV is still in progress. The first creep stage finished after the first day for all the samples. The creep curve for sample C1 can be compared to C4

since both are porous limestones. C1 is a fine-grained one, while C4 is a coarse-grained one. The creep process, according to the creep curves, is the same, but for the coarse-grained one, the creep strain is almost twice as big as for the fine-grained one. The tangent for the line fitted on the secondary phase creep points 0.004 for sample C4 and 0.0024 for sample C1. Therefore, the slope of the coarse-grained sample is twice as steep as that of the fine-grained sample. It means that the same creep load in the secondary phase produces greater creep strain in the coarse-grained type. While the marl from Dalmatia has an almost horizontal creep curve in the secondary phase.

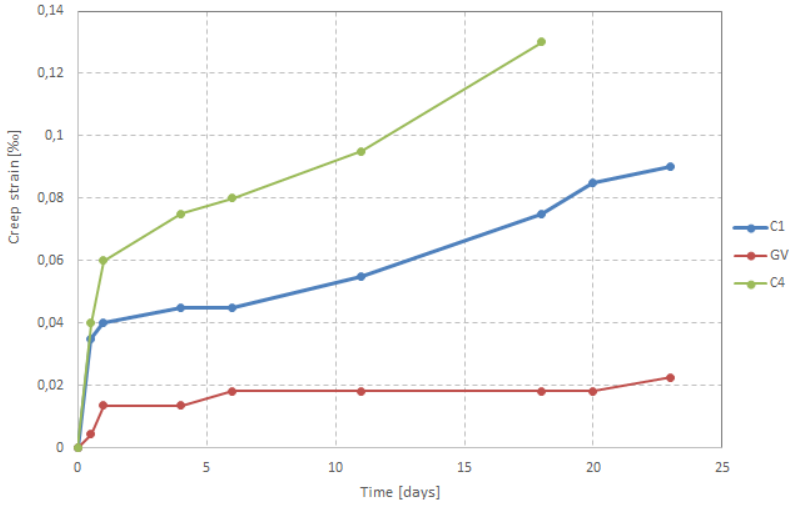


Fig. 4 Measured creep until secondary phase for all three specimens.

5 Conclusions

This study presented a comparative creep analysis for different cementitious rock materials. In this research phase, several materials were planned for testing, but due to limited testing capacity and inhomogeneous samples with microcracks, only three creep tests were performed. One fine-grained, one coarse-grained porous limestone sample originated from cellars from the Budapest area, and one calcareous marl sample from the Dalmatian area. The porous limestone is a very soft rock with high porosity; the calcareous marl behaves like a hard rock. The maximum secondary creep rate was the smallest for the calcareous marl, around 0,02‰. But there were significant differences between the creep of the two different porous limestone types as well. The maximum creep in the secondary creep phase was around 0,09‰ for the fine-grained type and 0,13‰ for the coarse-grained type, but these measurements were taken on different days. For the coarse-grained type, the third, accelerated creep phase was also registered, and after it, the specimen failed.

The creep tests are still in progress, so these results will be completed. The measured data will be used for creep analysis for the underground cellars. The surface above the cellars will be loaded with industrial buildings, and the creep of the unsupported cavities can be significant.

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