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THE INFLUENCE OF IMPURITIES AND FABRICS ON MECHANICAL PROPERTIES OF ROCK SALT FOR UNDERGROUND STORAGE IN SALT CAVERNS – A REVIEW

Salt caverns are used for the storage of natural gas, LPG, oil, hydrogen, and compressed air due to rock salt advantageous mechanical and physical properties, large storage capacity, flexible operations scenario with high withdrawal and injection rates. The short- and long-term mechanical behaviour and properties of rock salt are influenced by mineral content and composition, structural and textural features (fabrics). Mineral composition and fabrics of rock salt result from the sedimentary environment and post sedimentary processes. The impurities in rock salt occur in form of interlayers, laminae and aggregates. The aggregates can be dispersed within the halite grains or at the boundary of halite grains. Mineral content, mineral composition of impurities and their occurrence form as well as halite grain size contribute to the high variability of rock salt mechanical properties. The rock or mineral impurities like claystone, mudstone, anhydrite, carnallite and sylvite are discussed. Moreover, the influence of micro fabrics (in micro-scale) like fluid inclusions or crystals of other minerals on rock salt mechanical performance is described.

In this paper the mechanical properties and behaviour of rock salt and their relation to mineral composition and fabrics are summarised and discussed. The empirical determination of impurities and fabrics impact on deformation mechanism of rock salt, qualitative description and formulation of constative models will improve the evaluation and prediction of cavern stability by numerical modelling methods. Moreover, studying these relations may be useful in risk assessment and prediction of cavern storage capacity.

Keywords: mechanical properties of rock salt, impurities, fabrics, underground storage, salt caverns

1. Introduction

Salt caverns offer a suitable location for storage of power sources such as oil, natural gas, compressed air, and hydrogen due to their large capacity, flexible operation scenario and multiple

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cycles of injection and production in a year [1-3]. The specific physical and mechanical properties of rock salt, such as the ability to creep, healing fractures, high solubility in water, very low permeability, chemical inertness, and the availability of salt deposits in many locations, means that salt caverns are suitable for underground storage and making strategic reserves of power sources [4-7].

The design of salt caverns is a complex engineering problem that involves identifying of geological and geotechnical conditions, choosing leaching method and construction works. Geological and geotechnical conditions are particularly complex issues influenced by many factors including the thickness of rock salt layers, inner structure of salt deposits, tectonically disturbed zones e.g. shear zones, mineralogy, impurity content and occurrence form e.g. interlayers, laminae and mechanical properties of rock salt.

The mechanical behaviour of rock salt is influenced by the mineral composition as well as structural and textural features like grain size, grain shape and grains arrangement within the sample [8-10]. The mineral composition, form of impurity occurrence, structure and texture (fabrics) resulted from the occurrence depth, sedimentary environment and post-sedimentation processes [11,12]. Impurities can affect creep deformation and strength of rock salt [13]. The impact that impurities have on the mechanical properties of rock salt can be very complicated [14-16]. The mechanical parameters of rock salt are applied to the numerical modelling and have an impact on cavern stability performance [17-28]. Moreover, both the mineral composition and internal fabrics of the rock salt influence the cavern shape and consequently, long-term cavern operation and stability [8,9,29,30]. Nowadays, storage caverns have been built in salt formations with several non-salt interlayers e.g. Jintan salt formation in China [23,31] and average impurity content of 25% e.g. Northwick Halite Formation in the UK [32] as well as complex internal structure e.g. close to edge of the salt dome [33]. Thus, studying the relationship between mineral composition, fabrics and mechanical behaviour of rock salt contribute to the improvement of cavern stability predictions and evaluations.

In this paper, a comprehensive review on the mechanical properties of rock salt that are determined in short- and long-term standard laboratory tests and their dependence on mineral content and composition, and fabrics are summarised. Firstly, deformation mechanisms of rock salt observed in these tests are introduced. Secondly, the long and short-term mechanical properties of different petrological types of rock salt are described. Next, a relation between deformation mechanisms of rock salt and petrological features visible in both macroscale like laminae, interlayers, grain size and grain orientation and microscale (under a microscope) like fluid inclusions at grain boundaries, crystals and aggregates of other minerals dispersed within halite grains. The rock and mineral impurities like claystone, mudstone, anhydrite, carnallite and sylvite are discussed.

2. Fabrics of rock salt

The rock salt characterises a wide variety of fabrics due to differences in occurrence depth, sedimentary conditions and post-sedimentary processes. The rock salt mainly consists of halite but may contain other minerals (impurities) such as anhydrite, gypsum, clay matter, carnallite, polyhalite and sylvite [34]. Their volume and distribution vary significantly between salt deposits, within a salt deposit, cavern field and even within a single well [30]. The mineral impurities compose of several cm thick interlayers, several mm thick laminae or they are dispersed within halite grains or occur around halite grains. The banded rock salt shows alternating grey and white layers and is known from e.g. Kłodawa salt dome, Bochnia salt mine [35,36], Gulf Coast salt domes in the USA [8,9,30]. The structural features like grain size, grain shape and their arrangement of component grains are differentiated. The size of halite crystals ranges from a few millimetres to more than 10 cm [34]. However, very fine grains (below 1 mm) and very coarse grains (above 10 cm) were noticed in the salt domes as a result of large deformation, differential stress and recrystallisation. Moreover, halite grain elongation resulted from shear stress. The shape-preferred orientation of these elongated grains is parallel to flow direction [6,30].

As described above, the salt fabric refers to structural and textural patterns resulted from both sedimentary and post-sedimentary processes. Anomalous salt is related to post-sedimentary processes [8,9,12,30]. The term “anomalous salt” was originally defined by Kupfer [37,38] for rock salt from salt domes in Gulf Coasts (USA) but it is also used to explain discontinuities in bedded salt [12]. This term describes atypical local physical and structural features of rock salt e.g. very coarse grains, black colour, salt with flow banding, salt with elongated grains and preferred grains orientation [12,33]. The anomalous salt features are related to different creep and strength properties as well as dissolution characteristics that have an impact on the operation of the storage caverns [9,30].

The fabrics can be divided into macroscopic patterns like grains, bands or laminae. Fluid inclusions, crystals of anhydrite and other minerals located inside halite grains related to crystal growth, recrystallisation or healing fractures [39-41], are microscopic fabrics. The influence of these fabrics and impurities on the long- and short-term mechanical properties, as well as mechanical behaviour of rock salt was studied in many papers during the last 30 years [7,42-49]. Findings presented in these papers and the author’s own experience were presented in sections 3 and 4 of this paper.

3. Short-term mechanical properties

The short-term properties of rock salt are usually evaluated in the uniaxial compression and triaxial compression tests. The rock mechanical behaviour and deformation characteristic in these tests consist of five stages [50]. In the first stage (Fig. 1), at low stress, the compaction is caused by the closure of some primary pores and cracks (Stage 1). After the compaction, the elastic behaviour dominates the stress-strain relationship (Stage 2, Fig. 1, point A). Then, the volume gradually increases because of microcracks development (Fig. 1). The stable crack growth process (Stage 3) overlapping the final elastic deformation results in the dilatancy boundary (Fig. 1, point B). The dilatancy boundary is defined as the turnover point, damage threshold, damage critical point where permanent damage begins [51-56]. In the next stage, the unstable rapid development of cracks begins and causes the volume to increase (Stage 4). This stage ends with the plasticity for rock salt at point C (Fig. 1). Next, the growth of the cracks continues, the volumetric strain increases and the rock salt exhibits a visco-plastic deformation (Stage 5) that leads to damage [50].

The short-term mechanical parameters differ between salt deposits (Fig. 2).

The volume increase, called dilatancy, related to rock salt microcracking of rock salt, occurs both during load application (e.g. uniaxial and triaxial compression tests) and during creep tests when loads are held constant [51]. The cracks develop mainly at rock salt crystalline boundaries

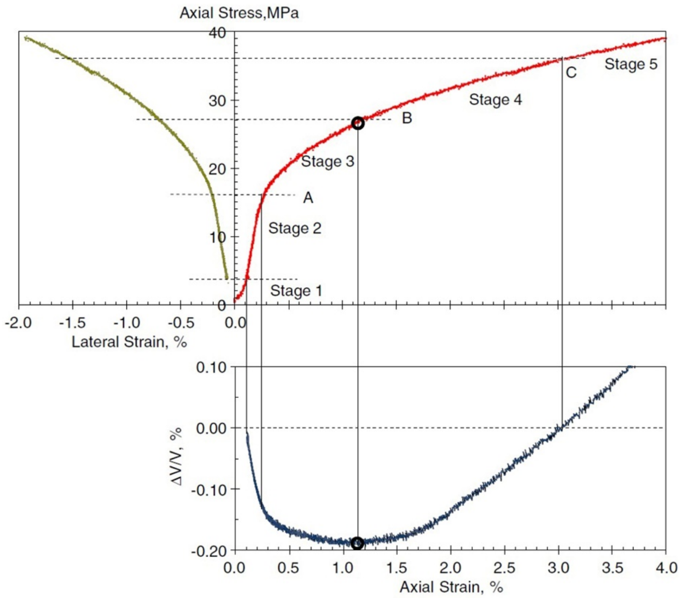

Fig. 1. The general stress-strain relationship for a rock salt sample from the Asse salt dome [50]

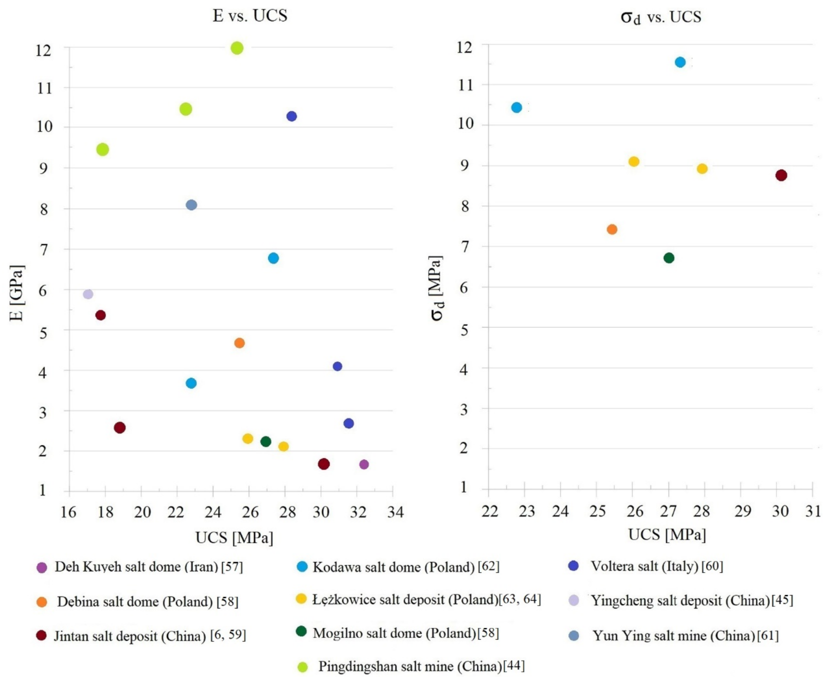

Fig. 2. The diversity of selected mechanical parameters: Young's modulus (E), uniaxial compressive strength (UCS) and stress at dilatancy threshold (σ_d) in different rock salt deposits [6,44,45,57-64]

with grain sliding and dislocation processes. The fracture plains are irregular and form twists and turns along the grain boundaries [50,55,65]. The irregular shape of these cracks is well visible under the microscope as voids at the grain boundaries (Fig. 3). The failure mode of rock salt under uniaxial compression is primarily tensile-shear failure [56-65]. In the triaxial tests, the development of macro-cracks is not observed as confining pressure prevents their formation, although numerous tiny cracks occur at grain boundaries and some transgranular cracks [65].

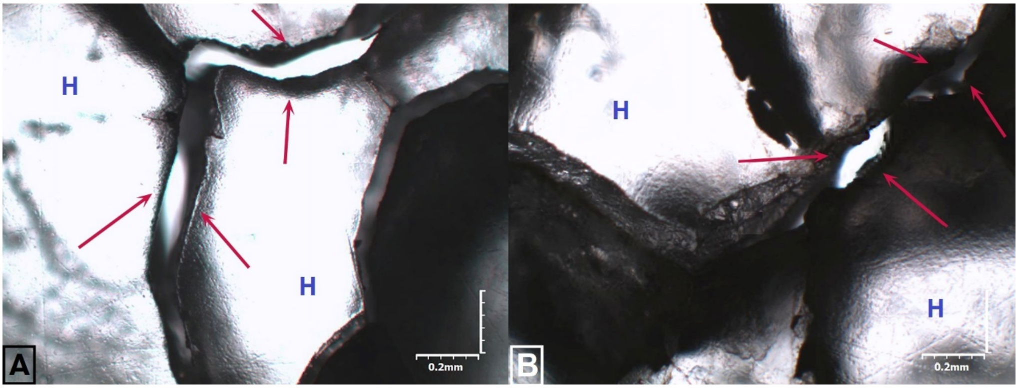

Fig. 3. The cracks at the crystal boundaries in a pink rock salt samples (double polished sections about 1-3 mm thick, parallel nicols) from the Kłodawa salt dome after uniaxial compression tests: H – halite, cracks are marked by red arrows

The determination of dilatancy boundary which initiate a micro-cracks induction and propagation is considered as a critical condition for the stability and integrity of the salt storage caverns [50,66]. The dilatancy is evaluated during numerical simulations to predict cavern stability in a long-term operation. There are several dilatancy criteria elaborated by Spiers et al. [67], Ratigan et al. [68], Hunsche [69], deVries et al. [19]. The micro-cracks are a path for fluids migration that may induce serious consequences such as gas leakage, wall collapse or cavern roof failure [46,53,70]. The stress value at dilatancy boundary varies in different salt series and petrological type of rock salt (Fig. 2).

The significant differences in dilatancy and volumetric strains between the different petrological types of rock salt can be explained by rock salt heterogeneity [42]. Numerical simulations of triaxial compression tests on rock salt samples with impurities showed that such heterogeneity can induce dilatancy, and results in the formation of tensile zones translated into a micro-cracking activity [42].

The impurities in rock salt are represented by several forms e.g. interlayers, laminae and can be dispersed as single grains or/and their aggregates within the halite grains or occur at halite grain boundaries. These forms have an impact on the mechanical performance of rock salt and consequently on salt caverns stability performance and safety of storage operations.

Generally, the dip of geological layers and inclination of the bedding planes and foliation influence their deformation [71]. It is generally known that the rocks are deformed perpendicular to bedding planes or foliation showed higher compressive strength than that deformed parallel to the bedding [72]. The uniaxial and triaxial compression tests performed on samples from

Yingcheng salt deposit (Hubei Province, China) and Pingdingshan Salt Mine (He'nan Province, China) showed [44,45] that the failure mode of rock salt samples with interbeds is far more complex than "pure" rocks salt (without interlayers and visible admixtures). The pick strength (in uniaxial compressive tests) of samples built of halite and horizontal anhydrite interlayers were higher than the pure rock salt with the slightly lower Young's modulus and largest Poisson's ratio [44]. The tensile cracks developed because of different mechanical responses of anhydrite and rock salt to loading. One of these components may dominate the behaviour e.g. the samples where rock salt prevails were weaker and showed higher lateral deformability but in the samples with more anhydrite interlayers, the anhydrite developed high tensile strength and increased the strength. The difference between rock salt and anhydrite interlayers becomes less visible as the confined stress increases in triaxial compression tests [45]. It was noticed that in confining stress higher than 10.0 MPa, brittle-ductile transition for rock salt occurred. The halite expanded laterally in a viscoplastic mode, whereas the adjacent non-salt beds experience shearing and the development of tensile vertical cracks [45]. The behaviour of rocks salt samples with mudstone interbeds was different. Although the uniaxial compression strength of mudstone is higher than pure rock salt, the mudstone interlayers fractured firstly. The authors stated that the specific relationship between interbeds and rock salt is complex issues influenced by the texture and geometry of the interbedding [44,45]. Another deformation mechanism was observed for rock salt with claystone interlayers from the Łężkowice salt deposit (Poland) (Fig. 4). The claystone interlayers underwent compaction during the uniaxial test. The tensile cracks formed at contact between salt and interlayers and propagated into the salt (Fig. 4).

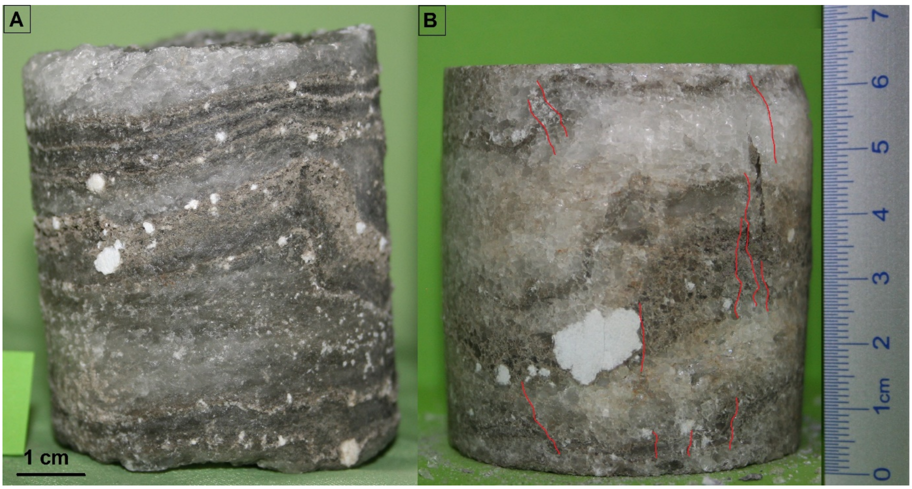

Fig. 4. The rock salt sample with claystone interlayers from the Łężkowice salt deposit:
A – before test, B – after uniaxial compression test

The inclination of interbeds at the angle of 20-30° cause a difference in deformation and fracturing process and stimulates more complex stress state than in the case of horizontal interlayers [44]. The cracks initiated in contact (interface) between the rock salt and interbeds. The cracks propagation causes different stress state and resulted in different crack geometries. In the samples with interlayers <10 cm thick the deformation characteristics and fracturing are mainly controlled by rock salt. The samples with thick interlayers (<10 cm) and medium interlayers (0-20 cm), showed more ductility and a larger probability of micro-cracks formation. In the triaxial tests, the confining pressure decreased the stress difference in the rock salt and interlayers consequently, the difference in fracture morphologies reduced [44].

The rock salt lamination and its orientation to loading direction have impact on mechanical parameters and deformation characteristics. The samples of laminated rock salt (1.0-1.7 mm laminae of insoluble components such as marl, quartz, clay, and carbonates) from Guma Rocksalt Mines (India) were deformed in uniaxial compression tests. The samples were oriented in a way that loading direction was perpendicular, parallel, and oblique to bedding [43]. All samples [43] showed the influence of bedding orientation on the stress-strain behaviour and mechanical properties. The samples with loading direction perpendicular to bedding showed the highest value of compaction stress, yield stress, failure stress and Young's modulus. However, samples with loading direction parallel to bedding showed the highest values of Poisson's ratio, compaction strain, yield strain and failure strain and total strain. The results for the samples with a loading direction oblique to bedding showed the lowest values of all parameters. This difference was explained [43] by the formation of the tensile and shear crack along the bedding planes that run perpendicular, parallel, or oblique to the stress axis and propagate due to the availability of weak planes. However, with a high stress rate, all samples exhibited similar deformation patterns due to the increased contribution of the shear crack in comparison to tensile cracks (Fig. 5).

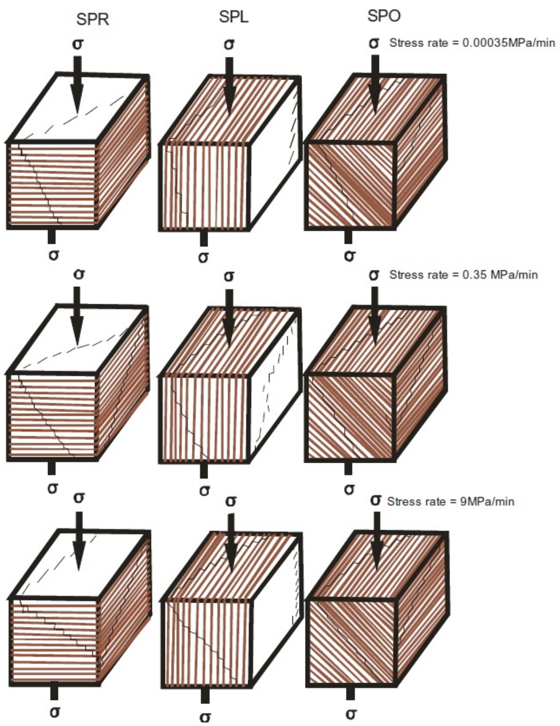

Fig. 5. Crack patterns developed in samples deformed perpendicular, parallel, and oblique to bedding [43]

Impurity (insolubles) effects on strength parameters and the stress-strain characteristics of the rock salt were analysed in several papers [7,46,63,64,73]. The strength of rock salt in both uniaxial and triaxial compression increases with impurity content as well as the bearing capacity of the rock salt. The impurity (insolubles like mudstone, anhydrite, glauberite) content increases the brittleness of rock salt. Thus, rock salt with impurity content above 50% showed failure mode with a single shear crack [7]. The same failure mode characterises salty clays (Fig. 6) with according to Łaszkiewicz [74] characterise by impurity content above 85%. In the pure rock salt and the rock salt with low impurity content (below 5.0%), the development of tensile-shear failure is observed [7]. Moreover, the rock salt (insolubles content 14.32%, mainly as clay minerals) with clay minerals located at the halite grain boundaries and within the grains behaved as modified material [44,46]. Impurities located among the boundaries of halite grain, acting as cement to strengthen the connecting of halite grains. Many paralleled lateral shear fractures were found near the parts rich in impurities. The presence of impurities could improve the strength of the rock salt, and the brittleness of the rock was also increased [44,75].

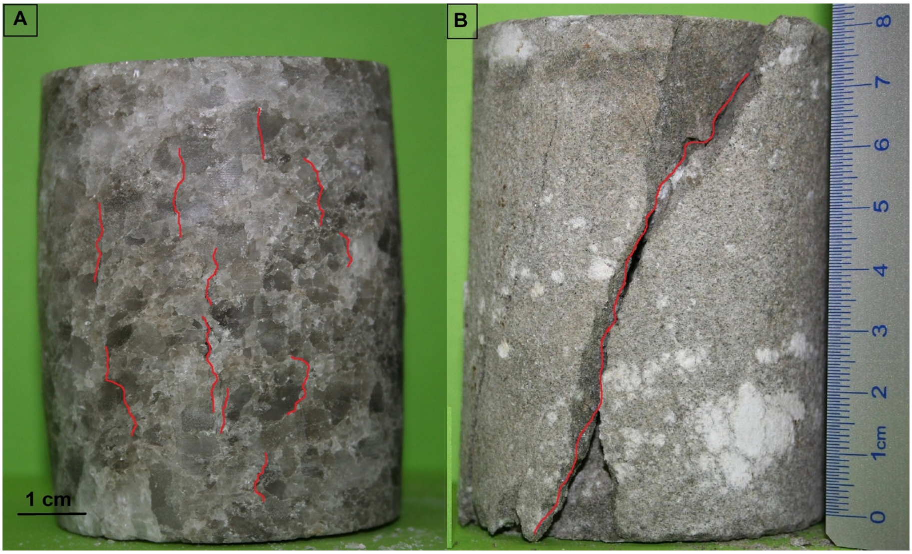

Fig. 6. Comparison between failure mode of rock salt and salty claystone from the Łężkowice salt deposit: A – tensile-shear failure mode of rock salt, B – single shear crack in salty claystone

On the contrary, laboratory tests of rock salt from Saskatchewan (Canada) showed [47] that sylvite content has no measurable effect on elastic properties like Young's modulus and Poisson's ratio as well as dilatancy strength of rock salt. However, tests for the Maha Sarakham rock salt showed [13] that the strengths at dilation and at failure decrease with increasing carnallite content. Moreover, the carnallite tends to dilate more than halite probably due to lack of cleavage planes [13]. However, in these papers, there is no information about the form of carnallite and sylvite occurrence.

In the rock salt with low insolubles content (0.13-2.11%), the mechanical parameters and failure mechanism can differ between samples however, they are independent of impurity content.

Rock salt samples from the LGOM area [73], in which the main impurity is anhydrite, showed the uniaxial compressive strength (UCS) in a range from 32.61 MPa (insoluble content of 1.44%) to 18.34 MPa (insoluble content of 1.09%). Microscopic observations indicated that this difference is related to anhydrite distribution within the halite grains. The anhydrite occurred at the grain boundaries in the samples with the highest UCS (Fig. 7A). However, in the samples with low UCS, the anhydrite crystals were dispersed inside the halite grains (Fig. 7B). The anhydrite at the grain boundaries increased the stiffness of the halite grains and strengthened the boundaries between halite grains. In these samples the dilatancy boundary was at a stress of 17.82 MPa (54.75% of the UCS) and the Young's modulus reached 7.23 GPa. Otherwise, the anhydrite crystals located inside the halite grains contributed to the initiation of microcracks and their propagation. The dilatancy boundary for these samples is much lower 6.87 MPa (37.05% of the UCS) as well as Young's modulus (4.56 GPa) (Fig. 7C, D).

There are types of rock salt where mineral grains or aggregates (impurities) are distributed unequally within halite grains. A particular type is banded rock salt characterised by alternating

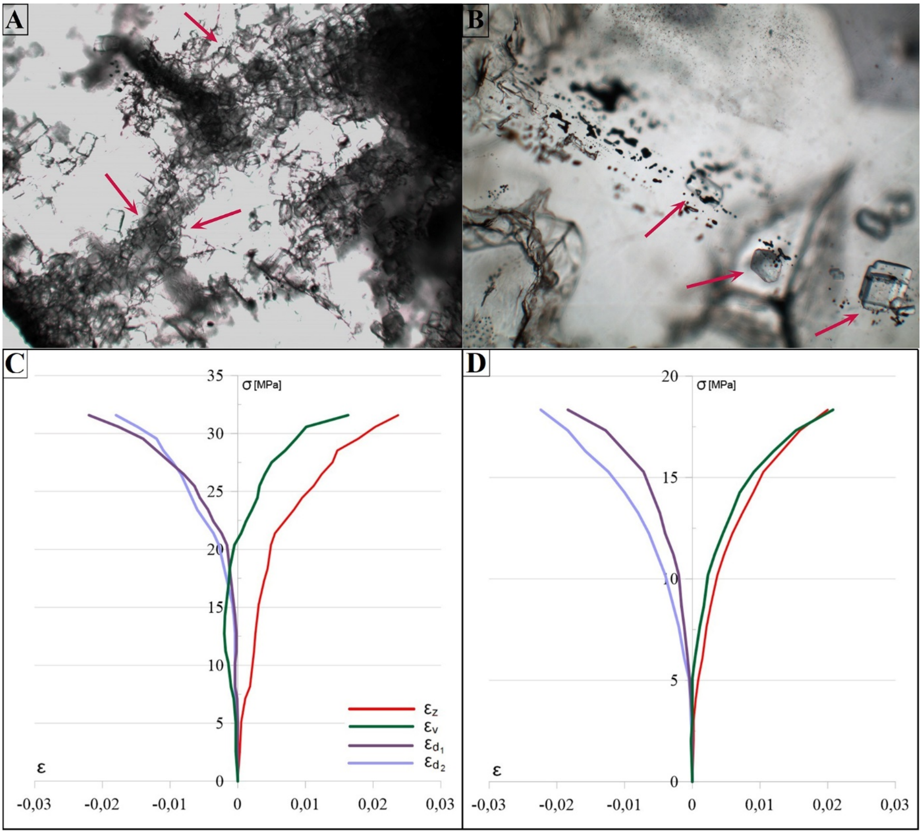

Fig. 7. The of samples rock salt from the LGOM characterise by different mechanical properties: A – microscopic image of sample with high UCS, B – microscopic image of sample with low UCS, C – stress-strain characteristic of sample with high UCS, D – stress-strain characteristic of sample with low UCS ([73] modified)

layers of white and grey rock salt. The banded rock salt occurs in a bedded Miocene formation (Poland) that underwent strong tectonic deformations [76]. The studied sample (Fig. 8A) is characterised by grey layers of irregular boundaries when in contact with white salt and with varying thickness that can result from tectonic deformation. Moreover, the banded salt was described in salt domes and referred to as anomalous salt associated with the salt flow [8,9,30]. The deformation mechanism of rock salt with unevenly distributed impurities (UDI) was explained by [77]. These impurities tend to cause uncoordinated deformation and local fracture, which can even induce the sample to split [77]. The banded salt from the Łężkowice deposit showed a deformation mode different from rock salt with UDI (Fig. 8A,B). The deformation mode of banded rock salt is a mixture of modes described for rock salt with inclined interlayers and unevenly distributed impurities (UDI) (Fig. 8C,F). The cracks are initiated at the boundary between white and grey layers and propagate to white salt but there are also local fractures between halite crystals. Furthermore, the stress-strain characteristics and mechanical parameters obtained in uniaxial compression tests of banded salt and rock salt with UDI showed the different value of UCS, Young's modulus and dilatancy threshold (Fig. 8C,F). The UCS of banded rock salt is 30.3 MPa and Young's modulus is 2.020 GPa but for rock salt with UDI is 41.09 MPa and 2.78 GPa, respectively. The dilatancy threshold is 12.80 MPa for banded salt and 11.10 MPa for rock salt with UDI.

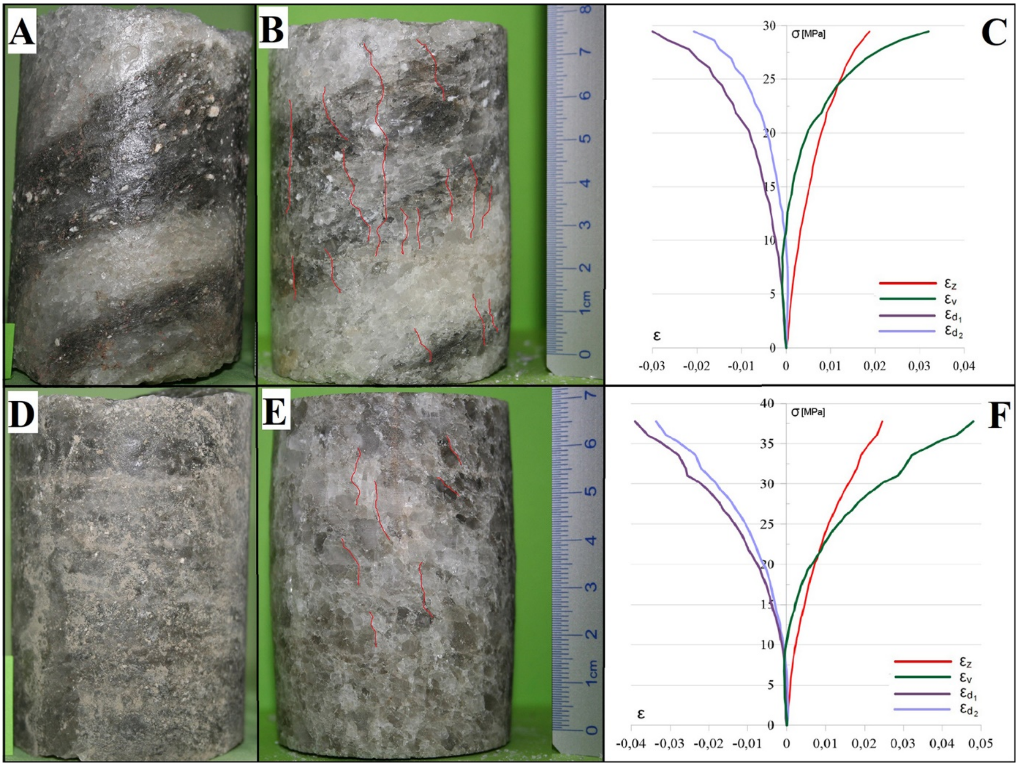

Fig. 8. Rock salt samples characterised by unevenly distributed impurities from the Łężkowice salt deposit ([63] modified): A-C banded rock salt, D-F – grey salt with unevenly distributed impurities within halite grains, A, D before tests, B, E – after uniaxial compression test, C, F, stress-strain characteristics

Moreover, uniaxial compression tests of rock salt from LGOM [73] and Kłodawa salt dome indicated that the presence of fluid inclusions at the grain boundaries and inside the grains contribute to decreasing in the mechanical parameters and accelerated the plastic deformations (Fig. 9). In samples from LGOM characterised by low mechanical parameters, the fluid inclusions were present at the grain boundaries (Fig. 9A). The samples of pink salt from Kłodawa characterised by many fluid inclusions inside the halite grains and at the halite grains boundaries (Fig. 9B). The UCS determined for this pink salt sample is lower (21.22 MPa) than white rock salt which characterises by an average value of 27.33 MPa [62]. The dilatancy threshold for pink salt is 7.03. MPa but for white rock salt reported in the paper by Kolano & Flisiak [62] is 15.17 MPa. Fluid inclusions inside the halite grains are gas-liquid secondary inclusions in the shape of linear arrays, these features suggest that they were formed as a result of healing fractures (Fig. 9). Secondary fluid inclusions are always present at crystal grain boundaries and healed fractures as the result of fluid transfer during deformation/recrystallisation processes [39,41,60,78-82]. The salt from LGOM and pink salt from the Kłodawa salt dome are rich in fluid inclusions and showed low dilatancy boundary. This may result from the mobility of secondary fluid inclusions network at grain boundaries. This mobility may enhance deformation mechanisms and crystals seem to become softer and deform more easily [60,83].

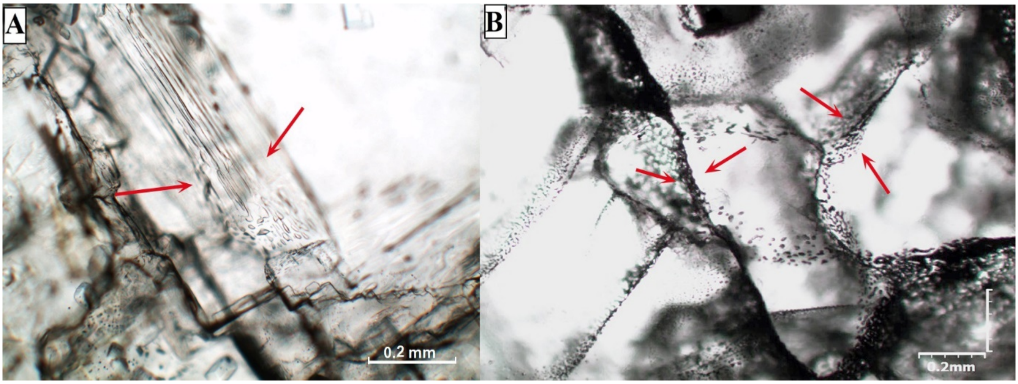

Fig. 9. Fluid inclusion plains at halite grain boundaries: A – rock salt from LGOM (double polished sections about 1–3 mm thick, parallel nicols) rock salt, B – pink rock salt from the Kłodawa salt dome

The impact of grain size and orientation on salt deformation mechanism in laboratory tests was studied by Bauer et al. [84], Speranza et al. [60], Liang et al. [85]. The rock salt samples characterised by small crystals are stronger during uniaxial deformation [60]. The Young's modulus is directly proportional to the average crystal area, and shape uniformity but elastic limit and strain at peak stress are inversely proportional to the average crystal area [60]. Numerical simulations showed that both the grain size and the uniformity of grain shapes have a positive impact on the mechanical parameters because the stress is distributed more evenly in each grain. Moreover, a larger density of grain boundaries (larger number of grain boundaries per unit) is associated with fine-grained rock salt samples than with large crystals. The density of the grain boundary is related to the path of crack propagation during the damage. With the larger number of grain boundaries, the crack propagation path is longer and requires more energy [85].

The elongated grains are found both in the domal and bedded salt formations. In domal salt, grain elongation is caused by the flow of rock salt during the formation of the salt dome, in bedded salt from the post-sedimentary processes [80]. It was suggested [60] that the secondary salt is formed and a progressive increase in crystals elongation and preferred orientation as well as, a crystal size decreases. This salt is dominated by the smaller crystals and is likely to be stronger during uniaxial deformation at room temperature (20°C) [60].

4. Long-term mechanical properties

The long-term properties and behaviour of rock salt are studied in the laboratory creep tests. In these tests, the rock salt shows noticeable rheological properties displayed by creep and stress relaxation. The creep rate and strain for engineering purposes like underground storage or mining determined in laboratory tests are characterised by limited duration. The long-term creep process (halokinesis, tectonics) are known from the salt bodies. The studies of naturally deformed rock salt [60,81,82,86-90] contributed to major progress in understanding the creep mechanisms. At the same time, the internal fabrics (microstructural features) resulted from these natural processes influence on results of laboratory tests performed for engineering purposes. Repeated changes in natural stress conditions during deformation and recrystallisation processes in a salt body affect the mechanical and rheological properties of rock salt [91-93] e.g. the elastic limit and Young's modulus of samples that underwent creep test was larger than for intact samples [57].

Rock salt strain during creep can be divided into three distinct stages: transient creep (primary), steady-state creep (secondary) and tertiary creep (Fig. 10). The transient creep stage is characterised by high deformation in a short time. As rock salt is subjected to constant loading, the rate of deformation increases in a decreasing creep rate until it reaches the steady-state creep. The secondary creep is the longest stage during which the strain rate tends to become constant. The tertiary creep occurs when the rate of deformation increases exponentially until the failure is reached [94,95].

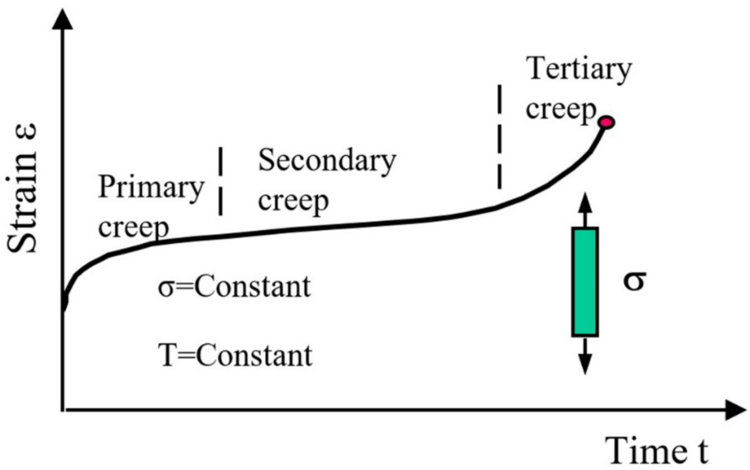

Fig. 10. Idealized creep curve showing three creep stages [96]

Many constitutive models of rock salt creep based on laboratory tests results or a combination of generally known rheological models like Norton Power Law, Maxwell or Kelvin models were elaborated [7,97]. The most popular are: time dependent creep-damage model [98], Lubby 2 model [98], BGR constitutive model [100], Lux/Hou model [101], Günther model [102], TUBSalt model [103]. Several papers present constitutive models based on micromechanisms of deformations like the Multimechanism Deformation Constitutive Model [104,105] and the composite model [52]. The Multimechanism Deformation Constitutive Model (MDCM) was initially elaborated for the secondary creep stage and later extended for the primary creep stage [106]. The model describes a relationship between strain, temperature and load on the basis of microstructural mechanisms. Moreover, Munson [48,106] indicated that inner rock salt structure influence the creep curve. The dislocations and other defects are generated in rock salt as the result of the creep process to form a submicroscopic internal structure. Five deformation mechanisms for secondary creep stage acting in different stress and temperature conditions [104] were indicated: dislocation climb, dislocation glide, undefined mechanism, diffusional creep and defect-less flow. The Composite Model developed for the transient and steady-state creep by Hunsche & Hampel [52] was based on dislocations micromechanisms. Creep by dislocations is a general deformation controlling process in crystalline materials like rock salt in temperature from 20° to 200°C. The temperature rise causes a change in the dominant mechanism of creep deformation from dislocation slip to dislocation climb [107] Each constitutive model mentioned above requires the determination of different parameters in laboratory creep tests.

The creep deformation process of rock salt is controlled by many factors, mainly by stress and temperature, which activate different mechanisms (Fig. 11). In a vast majority of cases in a natural environment is controlled by several parallel mechanisms [10]. The fabrics of natural rock salt are the final result of deformation, recrystallisation and fluid migration processes such as pressure solution, dislocation creep, grain boundary migration, microcracking [60]. Moreover, the creep deformation is influenced by impurities present in rock salt [68,69,108,109].

Hansen et al. [108] noticed that the amount of clay matter and anhydrite in the rock salt has no statistical correlation with a rate of steady-state creep and total strain. The creep tests performed on "milky" salt, which was fine-grained, rich in fluid inclusions and coarse-grained salt with clay and carbonate impurities located around the halite crystals, showed that the strains of "milky" salt were two times higher than coarse-grained salt after one month [111]. The independence of creep rate from halite grain size was reported by Ślizowski et al. [112]. The highest strain was observed in medium-grained salt than in coarse and fine-grained halite. However, the analysed samples were rich in fluid inclusions. The fluid inclusions at grain boundaries that may enhance deformation mechanisms as a solution–precipitation creep and fluid-assisted grain boundary migration [40,41,60]. On the contrary, fine-grained rock salt with elongated and uniformly oriented grains may retard creep by the climb and glide of dislocations as there is a higher density of grain boundaries and accelerate creep by fluid assisted grain boundary mechanisms (pressure solution). This occurs when there is a minor amounts of water present [41,67]. Creep dependence from a density of grain boundaries indicates grains size impact on creep rate. Moreover, this type of rock salt is considered anomalous salt [9,30].

Munson [109] indicated that for rock salt with impurity content of 5-6%, creeps slower than pure rock salt. The author also noticed that rock salt containing the anhydrite at grain boundaries crept slower than salt in which anhydrite is dispersed inside the grains [109]. One of the variables in the MDCM model was the structural factor in which was elaborated for rock salt from WIPP (Waste Isolation Pilot Plant). This factor was compared with rock salts from several American

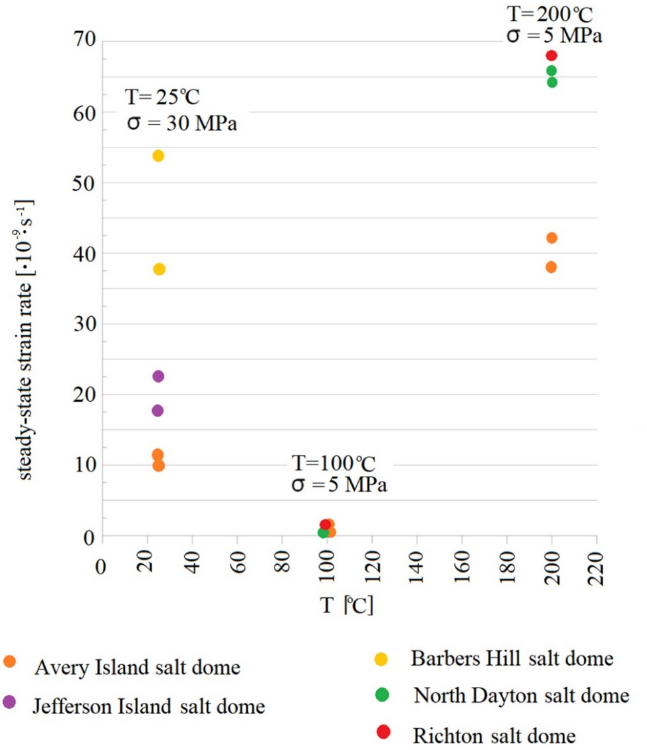

Fig. 11. The steady state creep rates for rock salt from different salt domes in USA [110]

salt domes and its value was determined. The rock salt from Weeks Island salt dome is characterised by an anhydrite content of 1-2%, and coarse grains have the a structural factor of 0,59. For coarse and very coarse-grained rock salt from Bryan Mound salt dome containing 6.0% of anhydrite in a form of bands, the factor is 0,17. Another example is medium to very coarse-grained rock salt with an anhydrite content of 1,7% from the Big Hill salt dome, for which the structural factor is 1,29 [109]. However, the detailed petrological description of samples and the impact of petrological features on the deformation mechanism were not presented.

In the papers by Hunshe et al. [66] and Hunshe [113] authors pointed out that different types of rock salt exhibit rather different creep behaviour. These differences result from a different distribution of microscopic impurities within grains but not from the total amount of the impurity mass. During the creep process, impurities act like a barrier for dislocation migration through the halite grains and a larger load is necessary to maintain the creep. These results were confirmed by studies of rock salt formation from the Chinese [10,114]. Moreover, it was found that the small grains are related to more boundaries between them. Consequently, this salt creeps slower. Moreover, when the boundaries between the grains are irregular, then more dislocation movements occur and accumulate at grain boundaries and as a result, the creep is slower [10,114,115].

An admixture of sylvinite and carnallite in rock salt is considered as an unfavourable impurity in the context of salt caverns. The impact of both minerals on rock salt solubility is known in engineering practice. However, their influence on creep behaviour was not fully elaborated. Based on creep tests of salt samples from Saskatchewan, Canada, it was noticed [47,116] that an increase in the steady-state creep rate corresponds to an increase of sylvite and carnallite content. Based on laboratory creep tests results it was predicted that the carnallite admixture (max. 13.0%) causes 20 times faster steady-state strain rates than the steady-state strain rate for halite at the same conditions. During the 25% admixture of sylvite it was only ten times faster. The creep tests results for Maha Sarakham rock salt confirmed that the higher is the carnallite content, the larger creep strains are registered [13]. These probable results were connected with water content in carnallite, which may increase the strain rate via water release [116]. However, a detailed description of sylvite and carnallite occurrence forms was not reported in these papers.

The laboratory creep experiment of rock salt samples with interbeds reported by Chinese authors showed that their creep properties are worse than pure rock salt and creep strains are between the value of rock salt and interlayers e.g. mudstone [10,117-119]. The long-term creep tests on rock salt with interlayers showed [120] that shear stress is generated at the contact between rock salt and interlayers (Fig. 12). When the creep of rock sat increases in time and the shear stress accelerates. They are exceeding of the shear strength in a contact results in creep failure.

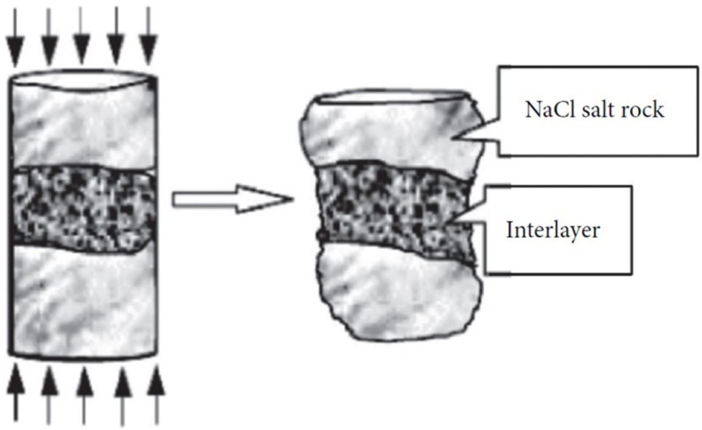

Fig. 12. Creep failure sketch map of bedded rock salt ([10] after [121])

5. Discussion

The research results described in the previous sections showed both the positive and negative influence of impurities and fabrics on the long- and short-term mechanical properties of rock salt. All these results were summarised below (Tab. 1). This summary includes only several types of fabrics and impurities registered in rock salt. These features are visible in samples by the naked eye (mesoscale) e.g. laminae, size of halite grains, interlayers and the following are visible under the microscope (microscale) e.g. fluid inclusions, anhydrite crystals in halite grains and at halite grain boundaries. The deformation mechanism of rock salt with interlayers and laminae in short-term laboratory tests was explained based on macroscopic observations of cracks, their geometry,

TABLE 1

Influence of petrological features on short- and long-term mechanical properties of rock salt – summary

Type of rock salt	Petrological feature characteristic	Short-term properties			Long-term properties
		Uniaxial compressive strength	Young's modulus	Poisson's ratio	Creep rate
1	2	3	4	5	6
Mesostructural features					
Laminated rock salt (insoluble laminae up to 2 mm thick) [43]	Laminae inclined perpendicular to loading direction	Greater than pure salt	Greater than pure salt	Lower than pure salt	Probably lower than pure salt (based on [106])
	Laminae inclined parallel to loading direction	Similar to rock salt with horizontal lamination	Lower than rock salt with horizontal lamination	Greater that rock salt with horizontal lamination	Probably lower than pure salt (based on [106])
	Laminae inclined oblique to loading direction	Lower than rock salt with horizontal lamination	Lower than rock salt with horizontal lamination	Greater than rock salt with horizontal lamination	Probably lower than pure salt (based on [106])
Rock salt with insoluble interlayers (10-40 mm thick) [10,44,45,121]	Interlayers inclined perpendicular to loading direction	Greater than pure salt	Greater than pure salt	Lower than pure salt	Lower than pure salt
	Interlayers inclined oblique to loading direction	Greater than pure salt	Greater than pure salt	Lower than pure salt	Lower than pure salt
Rock salt with interlayers of different mineralogy [10,45,105,120]	Anhydrite interlayers	Greater than pure salt	Greater than pure salt	Lower than pure salt	Lower than pure salt
	Mudstone or claystone interlayers	Greater than pure salt	Greater than pure salt	Lower than pure salt	Lower than pure salt

1	2	3	4	5	6
Rock salt with grains or aggregates (mudstone, claystone) dispersed within halite grains [58, 77, 113]	Banded rock salt	Slightly greater than pure salt	Slightly greater than pure salt	Slightly lower than pure salt	Not determined
	Grey rock salt	Greater than pure salt	Greater than pure salt	Lower than pure salt	Lower than pure salt
Rock salt with K-Mg minerals [13,47,116]	Admixture of sylvinite	Not determined	The same as pure salt	The same as pure salt	Greater than pure salt
	Admixture of carnallite	Lower than pure salt	Lower than pure salt	Greater than pure salt	Greater than pure salt
Rock salt of various grain size [10,60,85]	Fine-grained rock salt	Greater than middle and coarse-grained rock salt	Greater than middle and coarse-grained rock salt	Not determined	Probably lower than coarse-grained rock salt (based [10])
	Coarse-grained rock salt	Lower than middle and fine-grained halite	Lower than middle and fine-grained halite	Not determined	Probably larger than fine-grained rock salt (based on [10])
Microstructural features					
Rock salt with fluid inclusions [49,60,73]	Fluid inclusions at grain boundaries	Lower than other types of rock salt	Lower than other types of rock salt	Greater than other types of rock salt	Greater than other types of rock salt
Rock salt with insolubles [49,73,108,109]	Anhydrite crystals located at grain boundaries	Greater than pure salt	Greater than pure salt	Lower than pure salt	Lower than pure salt
	Anhydrite crystals dispersed within halite grains	Lower than rock salt with anhydrite crystals at grain boundaries	Lower than rock salt with anhydrite crystals at grain boundaries	Greater than rock salt with anhydrite crystals at grain boundaries	Not determined

and analytical equations [42-44]. However, the mechanical behaviour of rocks is controlled by their microstructure consequently, the macro-mechanical behaviour results from mechanisms acting at the grain scale [122-124]. The creep deformations of pure rock salt were explained by microstructural mechanisms involving dislocations movements [52,104,105]. The mechanism of rock salt deformation which contains impurities in a different form, fluid inclusions and rock salt samples characterised by the admixture of different minerals as well as empirical relationships between these factors were not elaborated. Empirical determination of these factors role in the deformation process is crucial for understanding the physical mechanisms of this process both in the short and long term for use in engineering purposes. Qualitative and empirical description of these mechanisms will be useful not only for theoretical consideration of natural phenomenon but also for engineering purposes e.g. numerical evaluation of cavern stability, long term operation and cavern shape design.

The post sedimentary processes like folding, stretching, shearing, and flowing result in recrystallisation, overprinting and the creation of new fabrics and structural features in rock salt [8,9], all can lead to the deformation of the crystal lattice. Polarised light microscopy observations revealed optical anisotropy (birefringence) of blue halite crystals from the Kłodawa salt dome (central Poland) and rock salt from the Pembina salt deposit (Alberta, Canada) resulting from the crystals' deformation at the atomic level [125-127]. In blue halite crystals, a deviation from cubic symmetry was indicated [128,129]. Moreover, a variability of microhardness (HV) value and the distortion of an imprint's shape were indicated in these crystals [125,126]. These microstructural features may have an impact on the macro-mechanical behaviour of rock salt but this issue requires further studies.

In addition, in the literature relevant to salt mechanics, including the journals, conference papers and reports, information about mineral composition, impurities distribution, structure and texture of the tested salt samples are rarely included. As a result, comparison of mechanical properties with different types of rock salt, fabrics and mineral composition is impossible. An increase in the availability of this information may contribute to the elaboration of the mathematical relationship between these features. As an example., three aforementioned papers [13,47,116] describing creep parameters of rock salt with the admixture of carnallite and sylvite are presented. In these papers, the only chemical composition of samples was tested without the description of rock salt fabrics and form of impurity occurrence. Moreover, the correlation of mineralogical, structural, and textural characteristics with mechanical and rheological parameters of rock salt could be useful in grading and classifying different types of rock salt for engineering purposes. This kind of correlations was performed for other rocks, e.g. granitic rocks [130,131] and sandstones [132].

6. Conclusion

A comprehensive review of the short- and long-term mechanical properties of rock salt and their dependence on impurity content, mineral composition, and fabrics is presented in this paper. From this study, the following conclusions can be drawn. The admixture of anhydrite, claystone or mudstone improve uniaxial compressive strength, Young's modulus and decrease creep rate. The sylvite and carnallite admixture in rock salt increases its creep rate. Sylvite content has no impact on the short-term mechanical properties of rock salt but an admixture of carnallite decreases these properties. However, there are some differences in the mechanical behaviour of rock salt related to the form of impurity occurrence. For instance, anhydrite crystals located at the halite grain boundaries strengthen and increase the stiffness of the halite grains. Anhydrite crystals dispersed in the halite grains contribute to the initiation and propagation of microcracks. Thus, anhydrite crystals dispersed within the halite grains decrease uniaxial compressive strength but located at halite grain boundaries improve this parameter. On the contrary, fluid inclusions at the halite grain boundaries contribute to decreasing the mechanical parameters and accelerating creep rate. Moreover, the grain size, grain shape and preferred orientation have an impact on the mechanical properties of rock salt, e.g. fine-grained rock salt with elongated uniformly oriented grains is stronger during uniaxial deformation. The Young's modulus is directly proportional to the average grain area, grain shape and uniformity. The creep rate in this type of rock salt is lower because of the large number of grain boundaries that retard creep.

The review presented in this paper shows that elaboration of the relationship between impurities, fabrics and mechanical behaviour of rock salt requires further study. Annual growth in energy consumption resulted in increasing demand on storage caverns and utilisation of salt beds with higher impurity content and consideration of these parts of salt domes that are close to their edges. In addition, cavern stability at the designing, completion, and operation stage, as well as risk assessment, are mostly evaluated by numerical modelling that relies on mechanical properties of rock salt and material models. Thus, qualitative understanding of impurities and fabrics influence on rock salt mechanical behaviour as well as the elaboration of the empirical relationship between these factors and formulation of constitutive models will contribute to the improvement of accuracy and the precisions in prediction and evaluation of cavern stability by numerical modelling including addressing the atypical, local features like shear zones and anomalous rock salt.

References

[1] F. Crotogino, *Compressed Air Energy Storage in Underground Formations*. Letcher T.M. (ed.), Storing Energy, Elsevier, 391-409 (2016).

[2] S. Donadei, G.S. Schneider, *Compressed Air Energy Storage in Underground Formations*. Letcher T.M. (ed.), Storing Energy, Elsevier, 113-133 (2016).

[3] J.G. Speight, *Recovery, storage, and transportation*. Speight J.G. (ed.) Natural Gas (Second Edition), Gulf Professional Publishing, 149-186 (2019).

[4] J. Chen, D. Lu, W. Liu, J. Fan et al., *Stability study and optimization design of small-spacing two-well (SSTW) salt caverns for natural gas storages*. Journal of Energy Storage **27**, 101131 (2020). DOI: https://doi.org/10.1016/j.est.2019.101131

[5] S. Mokhatab, W.A. Poe, J.Y. Mak, *Natural gas fundamentals*. In: Mokhatab S., Poe W.A., Mak J.Y. (eds.), Handbook of natural gas transmission and processing (Fourth Edition), Gulf Professional Publishing, 1-35 (2019).

[6] H. Yin, C. Yang, H. Ma, *Study on damage and repair mechanical characteristics of rock salt under uniaxial compression*. Rock Mech. Rock Eng. **52**, 659-671 (2019). DOI: https://doi.org/10.1007/s00603-018-1604-0

[7] Q. Zhang, J. Liu, L. Wang, M. Luo et al., *Impurity efects on the mechanical properties and permeability characteristics of salt rock*. Energies **13**, 1366 (2020). DOI: https://doi.org/10.3390/en13061366

[8] K.M. Looff, K.M. Looff, C.A. Rautman, *Salt spines, boundary shear zones and anomalous salts: their characteristics, detection and influence on salt dome storage caverns.* SMRI Spring Technical Conference, April 26-27, 2010, Grand Junction, Colorado, (2010).

[9] K.M. Looff, K.M. Looff, C.A. Rautman, *Inferring the geologic significance and potential imapact of salt fabric and anomalous salt on the development and long-term operation of salt storage caverns on gulf coast salt domes*. SMRI Spring Technical Conference, 26-27 April 2010, Grand Junction, Colorado (2010).

[10] Q. Zhang, Z. Song, J. Wang, Y. Zhang et al., *Creep properties and constitutive model of salt rock.* Advances in Civil Engineering 8867673 (2021). DOI: https://doi.org/10.1155/2021/8867673

[11] J.K. Warren, *Evaporites: sediments, resources and hydrocarbons*. Springer Springer-Verlag Berlin Heidelberg (2006).

[12] J.K. Warren, *Salt usually seals, but sometimes leaks: Implications for mine and cavern stabilities in the short and long term*. Earth-Science Reviews **165**, 302-341 (2017). DOI: https://doi.org/10.1016/j.earscirev.2016.11.008

[13] A. Luangthip, N. Wilalak, T. Thongprapha, K. Fuenkajorn, *Effects of carnallite content on mechanical properties of Maha Sarakham rock salt.* Arab. J. Geosc. **10**, 149, (2017).

[14] R.C.M. Franssen, C.J. Spiers, *Deformation of polycrystalline salt in compression and in shear at 250-350°C*. In: R.J. Knipe, E.H. Rutter (eds), Deformation mechanisms, rheology and tectonics. Geological Society, London, Special Publications **54**, 201-213 (1990,).

[15] S.V. Raj, G.M. Pharr, *Effect of temperature on the formation of creep substructure in sodium chloride single crystal*. J. Amer. Cer. Soc. **75**, 347-352 (1992).

[16] P.E. Senseny, J.W. Handin, F.D. Hansen, J.E. Russell, *Mechanical behavior of rock salt: phenomenology and micro-mechanisms*. Int. J. Rock Mech. Min. Sc. **29**, 363-378 (1992).

[17] M.S. Bruno, *Geomechanical analysis and design considerations for thin-bedded salt caverns: final report*. Arcadia, CA: Terralog Technologies USA (2005).

[18] M.S. Bruno, L. Dorfmann, G. Han K, Lao. Et al., *3D geomechanical analysis of multiple caverns in bedded salt.* SMRI Fall Technical Conference, 1-5 October 2005, Nancy, France, 1-25 (2005).

[19] K.L. De Vries, K.D. Mellegard, G.D. Callahan, W.M. Goodman, *Cavern roof stability for natural gas storage in bedded salt.* RESPEC final report 26 September 2002 – 31 March 2005 for United States Department of Energy National Energy Technology Laboratory (2005).

[20] C. Jie, L. Dan, L. Wei, F. Jinyang et al., *Stability study and optimization design of smallspacing two-well (SSTW) salt caverns for natural gas storage*. J. Ener. Stor. **27**, 101131 (2020). DOI: https://doi.org/10.1016/j.est.2019.101131

[21] J.L. Li, Y. Tang, X.L. Shi, W. Xu et al., *Modelling the construction of energy storage salt caverns in bedded salt.* Appl. Energ. **255**, 113866 (2019). DOI: https://doi.org/10.1016/j.apenergy.2019.113866

[22] T. Wang, X. Yan, H. Yang, X. Yang et al., *A new shape design method of salt cavern used as underground gas storage.* Appl. Energ. **104**, 50-61 (2013). DOI: https://doi.org/10.1016/j.apenergy.2012.11.037

[23] T.T. Wang, C.H. Yang, X.L. Shi, H.L. Ma, Y.P. et al., *Failure analysis of thick interlayer from leaching of bedded salt caverns.* Int. J. Rock Mech. Min. Sci. **73**, 175-183 (2015). DOI: https://doi.org/10.1016/j.ijrmms.2014.11.003

[24] T. Wang, C. Yang, H. Ma, Y. Li et al., *Safety evaluation of salt cavern gas storage close to an old cavern.* Int. J. Rock Mech. Min. Sci. **83**, 95-106 (2016). DOI: https://doi.org/10.1016/j.ijrmms.2016.01.005

[25] Y. Wang, J. Liu, *Critical length and collapse of interlayer in rock salt natural gas storage.* Adv. Civ. Eng., Article ID 8658501 (2018). DOI: https://doi.org/10.1155/2018/8658501

[26] H. Yin, C. Yang, H. Ma, X. Shi et al., *Stability evaluation of underground gas storage salt caverns with micro-leakage interlayer in bedded rock salt of Jintan, China.* Acta Geotech. **15**, 549-563 (2020). DOI: https://doi.org/10.1007/s11440-019-00901-y

[27] G. Zhang, Y. Li, J.J.K. Daemen, C. Yang et al., *Geotechnical feasibility analysis of compressed air energy storage (CAES) in bedded salt formations: a case study in Huai'an City, China.* Rock Mech. Rock Eng. **48**, 5, 2111-2127 (2015). DOI: https://doi.org/10.1007/s00603-014-0672-z

[28] N. Zhang, X.L. Shi, T.T. Wang, C. Yang et al., *Stability and availability evaluation of underground strategic petroleum reserve (SPR) caverns in bedded rock salt of Jintan, China.* Energy **134**, 504-514 (2017). DOI: https://doi.org/10.1016/j.energy.2017.06.073

[29] J.L. Li, X. Shi, C. Yang, Y. Li et al., *Repair of irregularly shaped salt cavern gas storage by re-leaching under gas blanket*. J. Nat. Gas Sci. Eng. **45**, 848-859 (2017). DOI: https://doi.org/10.1016/j.jngse.2017.07.004

[30] K.M. Looff, *The Impact of Anomalous Salt and Boundary Shear Zones on Salt Cavern Geometry, Cavern Operations, and Cavern Integrity*. American Gas Association Operations Conference 2-5 May 2017, Orlando, Florida (2017).

[31] J. Li, X. Shi, C. Yang, Y. Li et al., *Mathematical model of salt cavern leaching for gas storage in high insoluble salt formations*. Sci. Rep. **8**, 372, 1-12 (2018). DOI: https://doi.org/10.1038/s41598-017-18546-w

[32] Y. Charnavel, J. O'Donnell, T. Ryckelynck, *Solution Mining at Stublach*. SMRI Spring Technical Conference 27-28 April 2015 Rochester, New York, USA (2015).

[33] K. Looff, J. Duffield, K. Looff, *Edge of Salt Definition for Salt Domes and Other Deformed Salt Structures – Geologic and Geophysical Considerations*. SMRI Spring Technical Conference 27-30 April 2003, Houston, Texas, USA (2003).

[34] L.H. Gevantman (ed.), *Physical properties data for rock salt*. Monograph 161, U.S. Deptartment of the Commerce, National Bureau of Standards, Government Printing Office, Washington D.C. (1981).

[35] A. Garlicki, *Salt Mines at Bochnia and Wieliczka*. Przegląd Geologiczny **56**, 8/1, 663-669 (2008).

[36] J. Wachowiak, *Poziomy mineralne w solach cechsztyńskich wysadu solnego Kłodawa jako narzędzie korelacji litostratygraficznej*. Kwartalnik AGH – Geologia **36**, 2, 367-393 (2010).

[37] D.H. Kupfer, *Problems associated with anomalous zones in Louisiana salt stocks, USA*. In: A.H. Coogan and L. Hauber, eds., Fifth Symposium of Salt, Hamburg Germany, June 1978, Northern Ohio Geological Society, Cleveland **1**, 119-134 (1980).

[38] D.H. Kupfer, *Anomalous features in the Five Island Salt Stocks, Louisiana*. Gulf Coast Association of Geological Societies Transactions **40**, 425-437 (1990).

[39] Z. Schléder, J.L. Urai, *Microstructural evolution of deformation-modified primary halite from the Middle Triassic Röt Formation at Hengelo, The Netherlands.* Int. J. Earth Sci. (Geol Rundsch) **94**, 5-6, 941-955 (2005). DOI: https://doi.org/10.1007/s00531-005-0503-2

[40] J.L. Urai, Z. Schléder, C.J. Spiers, P.A. Kukla, *Flow and transport properties of saltrocks.* In: R. Littke, U. Bayer, D. Gajewski, S. Nelskamp (eds.) Dynamics of complex intracontinental basins: The Central European Basin System. Berlin: Springer, 277-90 (2008).

[41] J.L. Urai, C.J. Spiers, *The effect of grain boundary water on deformation mechanisms and rheology of rocksalt during long-term deformation.* In: M. Wallner, K. Lux, W. Minkley, H. Hardy (eds.), Proceedings of the 6th conference on the mechanical behavior of salt, Hannover, Germany (2007).

[42] M. Azabou, A. Rouabhi, L. Blanco-Martìn, *Effect of insoluble materials on the volumetric behavior of rock salt.* J. Rock Mech. Geotech. Eng. **13**, 1, 84-97 (2021). DOI: https://doi.org/10.1016/j.jrmge.2020.06.007

[43] R.K. Dubey, *Bearing of structural anisotropy on deformation and mechanical response of rocks: an experimental example of rocksalt deformation under variable compression rates.* J. Geol. Soc. India **91**, 109-114 (2018). DOI: https://doi.org/10.1007/s12594-018-0826-9.

[44] Y. Li, W. Liu, C. Yang, J.J.K. Daemen, *Experimental investigation of mechanical behavior of bedded rock salt containing inclined interlayer.* Int. J. Rock Mech. Min. Sci. **69**, 39-49 (2014). DOI: https://doi.org/10.1016/j.ijrmms.2014.03.006

[45] W. Liang, C. Yang, Y. Zhao, M.B. Dusseault, J. Liu, *Experimental investigation of mechanical properties of bedded salt rock.* Int. J. Rock Mech. Min. Sci. **44**, 3, 400-411 (2007). DOI: https://doi.org/10.1016/j.ijrmms.2006.09.007

[46] W. Liu, Z. Zhang, J. Fan, D. Jiang, J.J.K. Daemen, *Research on the Stability and Treatments of Natural Gas Storage Caverns with Different Shapes in Bedded Salt Rocks.* IEEE Access, 8, 18995-19007 (2020). DOI: https://doi.org/10.1109/ACCESS.2020.2967078

[47] K.D. Mellegard, L.A. Roberts, G.D. Callahan, *Effect of sylvite content on mechanical properties of potash*. Pierre Bérest, Mehdi Ghoreychi, Faouzi Hadj-Hassen, Michel Tijani (eds.) Mechanical Behaviour of Salt VII Edition 1st Edition, Imprint CRC Press (2012).

[48] D.E. Munson, *Constitutive model of creep in rock salt applied to underground room closure.* Int. J. Rock Mech. Min. Sci. **34**, 233-247 (1997). DOI: https://doi.org/10.1016/S0148-9062(96)00047-2

[49] A. Pouya, *Correlation between mechanical behaviour and petrological properties of rock salt.* Proceedings of the 32nd US Symposium on Rock Mechanics, USRMS (1991).

[50] H. Alkan, Y. Cinarb, G. Pusch, *Rock salt dilatancy boundary from combined acoustic emission and triaxial compression tests*. Int. J. Rock Mech. Min. Sci. **44**, 108-119 (2007). DOI: https://doi.org/10.1016/j.ijrmms.2006.05.003

[51] Von Sambeek L., Ratigan J.L., Hansen F.D., *Dilatancy of Rock Salt in Laboratory Tests*. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. **30**, **7**, 735-738 (1993). DOI: https://doi.org/10.1016/0148-9062(93)90015-6

[52] U. Hunsche, A. Hampel, *Rock salt – The mechanical properties of the host rock material for a radioactive waste repository*. Eng. Geol. **52**, 271-291 (1999). DOI: https://doi.org/10.1016/S0013-7952(99)00011-3

[53] O. Schulze, T. Popp, H. Kern, *Development of damage and permeability in deforming rock salt.* Eng. Geol. **61**, 163-180 (2001). DOI: https://doi.org/10.1016/S0013-7952(01)00051-5

[54] H. Moriya, T. Fujita, H. Niitsum, *Analysis of fracture propagation behavior using hydraulically induced acoustic emissions in the Bernburg salt mine, Germany.* Int. J. Rock Mech. Min. Sci. **43**, 49-57 (2006). DOI: https://doi.org/10.1016/j.ijrmms.2005.04.003

[55] W. Liang, C. Zhang, H. Gao, X. Yang et al., *Experiments on mechanical properties of salt rocks under cycling loading.* J. Rock Mech. Geotech. Eng. **4**, 1, 54-61 (2012). DOI: https://doi.org/10.3724/SP.J.1235.2012.00054

[56] C. Jie, J. Zhang, S. Ren, L. Li, L. Yin, *Determination of damage constitutive behaviour for rock salt under uniaxial compress ion condition with acoustic emission.* The Open Civil Engineering Journal **9**, 75-81 (2015). DOI: https://doi.org/10.2174/1874149501509010075

[57] H. Mansouri, R. Ajalloeian, *Mechanical behavior of salt rock under uniaxial compression and creep tests.* Int. J. Rock Mech. Min. Sci. **110**, 19-27 (2018). DOI: https://doi.org/10.1016/j.ijrmms.2018.07.006

[58] D. Flisiak, *Laboratory testing of geomechanical properties for selected Permian rock salt deposits.* Miner. Resour. Manag. **24**, 121-140 (2008).

[59] C. Yang, T. Wang, Y. Li, H. Yang et al., *Feasibility analysis of using abandoned salt caverns for large-scale underground energy storage in China*. Appl. Energ. **137**, 467-481 (2015). DOI: https://doi.org/10.1016/j.apenergy.2014.07.048

[60] G. Speranza, A. Vona, S. Vinciguerra, C. Romano, *Relating natural heterogeneities and rheological properties of rocksalt: New insights from microstructural observations and petrophyisical parameters on Messinian halites from the Italian Peninsula.* Tectonophysics **666**, 103-120 (2016). DOI: https://doi.org/10.1016/j.tecto.2015.10.018

[61] Y.-L. Zhao, W. Wan, *Mechanical properties of bedded rock salt.* Electron. J. Geotech. Eng. **19**, 9347-9353 (2014).

[62] M. Kolano, D. Flisiak, *Comparison of geo-mechanical properties of white rock salt and pink rock salt in Kłodawa salt diaper.* Studia Geotechnica et Mechanica **35**, 1, 119-127 (2013). DOI: https://doi.org/10.2478/sgem-2013-0010

[63] K. Cyran, *Tectonics of Miocene salt series in Poland.* PhD thesis, AGH University of Science and Technology, Cracow (2008).

[64] D. Flisiak, K. Cyran, *Właściwości geomechaniczne mioceńskich soli kamiennych.* Biuletyn Państwowego Instytutu Geologicznego **429**, 43-49 (2008).

[65] J. Chen, C. Du, D. Jiang, J. Fan, J. He, *The mechanical properties of rock salt under cyclic loading-unloading experiments.* Geomechanics and Engineering **10**, 3, 325-334 (2016). DOI: https://doi.org/10.12989/gae.2016.10.3.325

[66] U. Hunsche, *Determination of the dilatancy boundary and damage up to failure for four types of rock salt at different stress geometries.* In: M. Aubertin, H.R. Hardy (eds.), Proceedings of the fourth conference on the mechanical behaviour of salt, 17-18 June, Montreal. Clausthal, Trans Tech. Publications; 163-7 (1996).

[67] C.J. Spiers, N.L. Carter, *Microphysics of rocksalt flow in nature*. In: Aubertin M, Hardy HR, editors. The mechanical behavior of salt proceedings of the 4th conference, Trans Tech. Publ. Series on Rock and Soil Mechanics, **22**, 15-128 (1998).

[68] J.L. Ratigan, L.L. von Sambeek, K.L. DeVries, *The influence of seal design on the development of the disturbed rock zone in the WIPP alcove seal tests*. RSI-0400, Sandia National Laboratories, Albuquerque, USA (1991).

[69] U.E. Hunsche, *Failure behaviour of rock salt around underground cavities*. In: H. Kakihana (ed.), Proceedings of the Seventh Symposium on Salt, Kyoto, Elsevier Science Publisher, Amsterdam, 1, 59-65 (1993).

[70] Z. Zhang, D. Jiang, W. Liu, J. Chen et al., *Study on the mechanism of roof collapse and leakage of horizontal cavern in thinly bedded salt rocks*. Environ. Earth. Sci. **78**, 10, 292 (2019). DOI: https://doi.org/10.1007/s12665-019-8292-2

[71] R. Dadlez, W. Jaroszewski, *Tektonika*. Wydawnictwo Naukowe PWN Warszawa (1994).

[72] R.D. Lama, V.S. Vutukuri, *Handbook on mechanical properties of rocks*. Trans. Tech. Publ. III, Zurich, Switzeland (1978).

[73] K. Cyran, T. Toboła, P. Kamiński, *Wpływ cech petrologicznych na właściwości mechaniczne soli kamiennej z LGOM (Legnicko-Głogowskiego Okręgu Miedziowego).* Biuletyn Państwowego Instytutu Geologicznego **466**, 51-63 (2016).

[74] A. Łaszkiewicz, *Minerały i skały solne*. Prace Muzeum Ziemi **11**, 101-188 (1967).

[75] W. Liu, Y.P. Li, Y.S. Huo, X.L. Shi et al., *Analysis on deformation and fracture characteristics of wall rock interface of underground storage caverns in salt rock formation*. Rock and Soil Mechanics **34**, 6, 1621-1628 (2013).

[76] J. Poborski, K. Skoczylas-Ciszewska, *O miocenie w strefie nasunięcia karpackiego w okolicy Wieliczki i Bochni*. Rocznik Polskiego Towarzystwa Geologicznego **33**, 3, 340-347 (1963).

[77] L. Wei, L. Yinping, Y. Chunhe, H. Shuai, W. Bingwu, *Analysis of Physical and Mechanical Properties of Impure Salt Rock.* 47th U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, California, June 2013, ARMA-2013-336 (2013).

[78] C.J. Peach, C.J. Spiers, *Influence of crystal plastic deformation on dilatancy and permeability development in synthetic salt rock.* Tectonophysics **256** (1-4), 101-128 (1996). DOI: https://doi.org/10.1016/0040-1951(95)00170-0

[79] G.M. Pennock, M.R. Drury, C.J. Spiers, *The development of subgrain misorientations with strain in dry synthetic NaCl measured using EBSD*. J. Struct. Geol. **27**, 12, 2159-2170 (2005). DOI: https://doi.org/10.1016/j.jsg.2005.06.013

[80] G.M. Pennock, M.R. Drury, C.J. Peach, C.J. Spiers, *The influence of water on deformation microstructures and textures in synthetic NaCl measured using EBSD*. J. Struct. Geol. **28**, 4, 588-601 (2006). DOI: https://doi.org/10.1016/j.jsg.2006.01.014

[81] J.H. Ter Heege, J.H.P. De Bresser, C.J. Spiers, *Rheological behaviour of synthetic rock salt: the interplay between water, dynamic recrystallisation and deformation mechanisms.* J. Struct. Geol. **27**, 948-963 (2005). DOI: https://doi.org/10.1016/j.jsg.2005.04.008

[82] J.H. Ter Heege, J.H.P. De Bresser, C.J. Spiers, *Dynamic recrystallisation of wet synthetic polycrystalline halite: dependence of grain size distribution on flow stress, temperature and strain.* Tectonophysics **396**, 1-2, 35-57 (2005). DOI: https://doi.org/10.1016/j.tecto.2004.10.002

[83] N.L. Carter, F.D. Hansen, *Creep of rock salt*. Tectonophysics **92**, 275-333 (1983). DOI: https://doi.org/10.1016/0191-8141(93)90168-A

[84] S.J. Bauer, B. Song, B. Sanborn, *Dynamic compressive strength of rock salts*. Int. J. Rock Mech. Min. Sci. **113**, 112-120 (2019). DOI: https://doi.org/10.1016/j.ijrmms.2018.11.004

[85] K. Liang, L.Z. Xie, B. He, P. Zhao et al., *Effects of grain size distributions on the macro-mechanical behavior of rock salt using micro-based multiscale methods*. Int. J. Rock Mech. Min. Sci. **138**, 104592 (2021). DOI: https://doi.org/10.1016/j.ijrmms.2020.104592

[86] S.Y. Li, J.L. Urai, *Rheology of rock salt for salt tectonics modelling*. Petrol. Sci. **13**, 712-724 (2016). DOI: https://doi.org/10.1007/s12182-016-0121-6

[87] Z. Schléder, J.L. Urai, *Deformation and recrystallisation mechanisms in mylonitic shear zones in naturally deformed extrusive Eocene-Oligocene rocksalt from Eyvanekey plateau and Garmsar hills (central Iran).* J. Struct. Geol. **29**, 241-255 (2007). DOI: https://doi.org/10.1016/j.jsg.2006.08.014

[88] C.J. Spiers, PM.T.M. Schutjens, R.H. Brzesowsky, C.J. Peach et al., *Experimental determination of constitutive parameters governing creep of rocksalt by pressure solution.* In: R.J. Knipe, E.H. Rutter (eds.) Deformation mechanisms, rheology and tectonics. Geological Society, London, Special Publications **54**, 1, 215-27 (1990).

[89] J.L. Urai, C.J. Spiers, H.J. Zwart, G.S. Lister, *Weakening of rock salt by water during long-term creep.* Nature **324**, 554-557 (1986). DOI: https://doi.org/10.1038/324554a0

[90] J.L. Urai, C.J. Spiers, C.J. Peach, R.C.M.W. Franssen, J.L. Liezenberg, *Deformation mechanisms operating in naturally deformed halite rocks as deduced from microstructural investigations*. Geology en Mijnbouw **66**, 165-176 (1987).

[91] R.K. Dubey, V.K. Gairola, *Influence of structural anisotropy on the uniaxial compressive strength of pre-fatigued rocksalt from Himachal Pradesh, India*. Int. J. Rock Mech. Min. Sci. **37**, 993-999 (2000). DOI: https://doi.org/10.1016/S1365-1609(00)00020-4

[92] R.K. Dubey, V.K. Gairola, *Influence of structural anisotropy on creep of rocksalt from Simla Himalaya, India: an experimental approach*. J. Struct. Geol. **30**, 6, 710-718 (2008). DOI: https://doi.org/10.1016/j.jsg.2008.01.007

[93] R.A. Lebensohn, P.R. Dawson, H.M. Kern, H.R. Wenk, *Heterogeneous deformation and texture development in halite polycrystals: comparison of different modelling approaches and experimental data*. Tectonophysics **370** (1-4), 287-311 (2003). DOI: https://doi.org/10.1016/S0040-1951(03)00192-6

[94] J.R. Hirth, L. Kubin (Eds), *Dislocations in solids*. The 30th anniversary volume. Elsevier (2009).

[95] M.P.A. Jakson, M.R. Hudec, *Salt tectonics principles and practice*. Cambridge University Press (2017).

[96] D.R. Askeland, P.P. Fulay, W.J. Wright, *The Science and Engineering of Materials*. Cengage Learning Inc. (2010).

[97] J. Wichert, H. Konietzky, C. Jakob, *Salt Mechanics*. TU Bergakademie Freiberg, Institut für Geotechnik, Freiberg (2018).

[98] G. Wang, *A new constitutive creep-damage model for salt rock and its characteristics.* Int. J. Rock Mech. Min. Sci. **41**, 61-67 (2004). DOI: https://doi.org/10.1016/j.ijrmms.2004.03.020

[99] Z. Hou, *Untersuchungen zum Nachweis der Standsicherheit für Untertagedeponien im Salzgebirge*. Technische Universität Clausthal, Professur für Deponietechnik und Geomechanik. Papierflieger (1997).

[100] U. Hunsche, O. Schulze, *Das Kriechverhalten von Steinsalz*. Kali und Steinsalz, **11**, 238-255 (1994).

[101] K.H. Lux, *Gebirgsmechanischer Entwurf und Felderfahrungen im Salzkavernenbau: ein Beitrag zur Entwicklung von Prognosemodellen für den Hohlraumbau im duktilen Salzgebirge*. F. Enke Verlag (1984).

[102] R.M. Günther, *Erweiterter Dehnungs-Verfestigungs-Ansatz: phänomenologisches Stoffmodell für duktile Salzgesteine zur Beschreibung primären, sekundären und tertiären Kriechens*. Ph.D. dissertation, Institut für Geotechnik, Technische Universität Bergakademie Freiberg (2009).

[103] C. Missal, A. Gährken, J. Stahlmann, *Vergleich aktueller Stoffgesetze und Vorgehensweisen anhand von Modellberechnungen zum thermo-mechanischen Verhalten und zur Verheilung von Steinsalz*. BMBF-Verbundvorhaben, Einzelbericht zum Teilvorhaben (2016).

[104] D.E. Munson, *Preliminary deformation mechanism map for salt (with application to WIPP).* Sandia Rep. SAND 79-0076 (1979).

[105] D.E. Munson, P.R. Dawson, *Constitutive model for the low temperature creep of salt (with application to WIPP).* Sandia Rep. SAND 79-1853 (1979).

[106] D.E. Munson, *Constitutive model of creep in polycrystalline halite based on workhardening and recovery*. International Symposium on Plasticity and its Current Applications. Baltimore, MD (United States) (1993).

[107] N.L. Carter, S.T. Horseman, J.E. Russell, J. Handin, *Rheology of rock salt*. J. Struct. Geol. **15**, 9, 1257-1271 (1993). DOI: https://doi.org/10.1016/0191-8141(93)90168-A

[108] F.D. Hansen, P. E. Senseny, T.W. Pfeifle, T.J. Vogt, *Influence of impurities on the creep of salt from the Palo Duro basin.* 29th U.S. Symposium on Rock Mechanics (USRMS), June 1988, Minneapolis, Minnesota (1988).

[109] D.E. Munson, *Analysis of Multistage and other creep data from domal salts*. SANDIA report 98-2276 (1998).

[110] T.W. Pfeifle, T.J. Vogt, G.A. Brekken, *Correlation of Chemical, Mineralogic, and Physical Characteristics of Gulf Coast Dome Salt to Deformation and Strength Properties*. Solution Mining Research Institute Report no. 94-0004-5 (1995).

[111] A. Pouya, *Correlation Between Mechanical Behaviour And Petrological Properties of Rock Salt*. In: J.C. Roegiers (ed.), Proceedings of 32nd US symposium on rock mechanics 385-92. Balkema, Rotterdam, ARMA-91-385 (1991).

[112] J. Ślizowski, S. Nagy, S. Burliga, K. Serbin, K. Polański, *Laboratory investigations of geotechnical properties of rock salt in Polish salt deposits*. In: R.L., Mellegard K., Hansen F. (eds.) Mechanical behavior of salt VIII: Proceedings of the Conference on Mechanical Behavior of Salt, SALTMECH VIII : Rapid City, USA, 26-28 May 2015, CRC Press Taylor & Francis Group, 33-38 (2015).

[113] U. Hunsche, *Determination of the dilatancy boundary and damage up to failure for four types of rock salt at different stress geometries*. In: Aubertin, M., Hardy Jr., H.R. (Eds.), The Mechanical Behavior of Salt IV; Proc. of the Fourth Conf., (MECASALT IV), Montreal 1996. TTP Trans Tech Publications, Clausthal, 163-174 (1998).

[114] C. Du, C.H. Yang, H.L. Ma, X.L. Shi, J. Chen, *Study of creep characteristics of deep rock salt.* Rock and Soil Mechanics **33**, 8, 2451-2520 (2012).

[115] X.D. Qui, Y. Jiang, Z.L. Yan, Q.C. Zhuang, *Creep damage failure of rock salt*. Journal of Chongqing University **26**, 3,106-109 (2003).

[116] J.W. Hustoft, R.D. Arnold, L.A. Roberts, *Effects of sylvite and carnallite content on creep behavior of potash*. SMRI Spring Technical Conference 23-24 April 2012, Regina, Saskatchewan, Canada (2012).

[117] L.J. Ma, H.F. Xu, M.Y. Wang, E.B. Li, *Numerical study of gas storage stability in bedded rock salt during the complete process of operating pressure runaway.* Chinese Journal of Rock Mechanics and Engineering **34**, S2, 4108-4115 (2015).

[118] M.M. Tang, Z.Y. Wang, G.S. Ding, Z.N. Ran, *Creep property experiment and constitutive relation of salt-mudstone interlayer.* Journal of China Coal Society **35**, 1, 42-45 (2010).

[119] Z.W. Zhou, J.F. Liu, F. Wu, L. Wang et al., *Experimental study on creep properties of salt rock and mudstone from bedded salt rock gas storage*. Journal of Sichuan University (Engineering Science Edition) **48**, S1, 100-106 (2016).

[120] W.G. Liang, C.H. Yang, Y.S. Zhao, *Physico-mechanical properties and limit operation pressure of gas deposit in bedded salt rock*. Chinese Journal of Rock Mechanics and Engineering **27**, 1, 22-27 (2008).

[121] Y.L. Zhao, Y. Zhang, W. Wan, *Mechanical properties of bedded rock salt and creep failure model.* Mineral Engineering Research **25**, 1, 6-20 (2010).

[122] C.H. Yang, H.J. Mao, X.C. Wang, X.H. Li, J.W. Chen, *Study on variation of microstructure and mechanical properties of water-weakening slates*. Rock and Soil Mechanics **27**, 6, 2090-2098 (2006). DOI: https://doi.org/10.1201/9781439833469.ch24

[123] J.E. Lindqvist, U. Åkesson, K. Malaga, *Microstructure and functional properties of rock materials*. Mat. Charact. **58**, 1183-1188 (2007). DOI: https://doi.org/10.1016/j.matchar.2007.04.012

[124] X. Shi, Y.F. Cheng, S. Jiang, D.S. Cai, T. Zhang, *Experimental study of microstructure and rock properties of shale samples.* Chinese Journal of Rock Mechanics and Engineering **33**, 3439-3445 (2014).

[125] T. Toboła, K. Cyran, M. Rembiś, *Petrological and Microhardness Study on Blue Halite from Kłodawa Salt Dome (central Poland).* 9th Conference on the Mechanical Behavior of Salt (SaltMech IX), September 12-14, 2018, Hannover, Germany, (2018).

[126] T. Toboła, K. Cyran, M. Rembiś, *Microhardness analysis of halite from different salt-bearing formations.* Geol. Quart. **63**, 4, 771-785 (2019). DOI: https://doi.org/ 10.7306/gq.1499

[127] T. Toboła, P. Kukiałka, *The Lotsberg Salt formation in Central Alberta (Canada) – petrology, geochemistry and fluid inclusions*. Minerals **10**, 868 (2020). DOI: https://doi.org/10.3390/min10100868

[128] S. Zelek, K. Stadnicka, J. Szklarzewicz, L. Natkaniec-Nowak, T. Toboła, *Halite from Kłodawa: the attempt of correlation between lattice defor mation and spectroscopic properties in UV-VIS*. Gospodarka Surowcami Mineralnymi PAN **3**, 159-172 (2008).

[129] S. Zelek, K. Stadnicka, T. Toboła, L. Natkaniec-Nowak, *Lattice deformation of blue halite from Zechstein evaporite basin: Kłodawa Salt Mine, Central Poland*. Mineral. Petrol. **108**, 619-631 (2014). DOI: https://doi.org/10.1007/s00710-014-0323-9

[130] A. Tuğrul, I.H. Zarif, *Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey*. Eng. Geol. **51**, 4, 303-317 (1999). DOI: https://doi.org/10.1016/S0013-7952(98)00071-4

[131] A.A. Momeni, G.R. Khanlari, M. Heidari, A.A. Sepahi, E. Bazvand, *New engineering geological weathering classifications for granitoid rocks.* Eng. Geol. **185**, 43-51 (2015). DOI: https://doi.org/10.1016/j.enggeo.2014.11.012

[132] E. Cantisani, C.A. Garzonio, M. Ricci, S. Vettori, *Relationships between the petrographical, physical and mechanical properties of some Italian sandstones*. Int. J. Rock Mech. Min. Sci. **60**, 321-332 (2013). DOI: https://doi.org/10.1016/j.ijrmms.2012.12.042