

Article

Strength Anisotropy in Stylolitic Limestone

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Abstract

A stylolite is a common sedimentary feature acting as a weakness plane in sedimentary rocks, especially carbonates. This sedimentary feature can cause anisotropic behaviors in some inherent properties of rock. The present study investigated the effect of a stylolite plane containing clay mineral as the filling material, in both the dry and saturated states, on the behavior of uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) of limestone widely used in building applications. Specimens at different angles of the stylolite plane (β), namely, 0° , 30° , 45° , 60° , and 90° (β is the angle between the stylolite plane and loading axis), taken from limestone under both dry and saturated conditions, were subjected to UCS and BTS tests. The findings indicate anisotropic behaviors of the UCS and BTS of the sample as a function of β . Moreover, the values of UCS and BTS are strongly affected by water effects, such that the sample suffers significant reductions in these properties after being saturated. Overall, the results show that β , the type of filling material, and test specimen state (i.e., dry or saturated) should be considered for a more accurate assessment of limestone quality. When taking these factors into account, the limestone used in a building is expected to have a longer service life.

Keywords: anisotropy; clay mineral; limestone; strength; stylolite plane; water effect

1. Introduction

Building stones have played a pivotal role in human civilization, serving as essential materials for construction from prehistoric times to the present. Their significance spans cultural, historical, architectural, scientific, and environmental dimensions, influencing the durability, esthetics, and sustainability of structures worldwide. For these reasons, many researchers around the world have conducted studies on various aspects of building stones, and these studies are still ongoing [1–4].

Among the types of building stones with igneous, sedimentary, and metamorphic origins, limestone, as a sedimentary rock, is one of the most commonly used stones in historical monuments and modern buildings due to its abundance, acceptable technical parameters and esthetic aspects [5–8]. In addition to being used as a restoration material in historical monuments, limestone is also widely used in various parts of modern buildings for cladding, paving, flooring, stairs, and curbs [9,10].

During the service life of limestone used in a building, natural deterioration processes [e.g., freezing–thawing (FT), salt crystallization (SC), heating–cooling (HC), and wetting–drying (WD)] and external influences causing artificial decay (e.g., traffic due to people and vehicles) can lead to a loss in the durability of the stone, thereby causing a negative effect on its performance. Any loss in the durability of the limestone, in addition to esthetic



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damage to the building, may also cause structural problems. Therefore, utmost care must be taken in selecting a durable limestone.

According to previous studies, the durability of a building stone against deterioration processes is highly dependent on the inherent properties of the stone, including mineralogical, textural, physical, mechanical, and thermal properties [11–14]. Uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) are among the key mechanical properties that have been frequently used to assess the durability of stone subjected to deterioration processes such as FT, SC, HC, and WD. In the studies conducted by Altindag et al. [15], Bayram [16], Ghobadi et al. [17], and, recently, Shahrokhi et al. [18] on the various building stones, overall, findings showed that samples with higher UCS and BTS were more durable during the adverse effects of deterioration processes.

The presence of weakness planes, such as lamination and foliation, in some building stones is one of the factors affecting UCS and BTS. These weakness planes cause the stone to lose its integrity in a given orientation, resulting in anisotropic behavior of UCS and BTS and affecting the stone's durability when subjected to deterioration processes. Some researchers have studied the effects of anisotropy due to lamination and foliation on the UCS and BTS of sandstone, slate, shist and gneiss, such as Zalooli et al. [14], Ramamurthy et al. [19], Tavallali and Vervoort [20], Khanlari et al. [21], and Kong et al. [22]. Their findings indicated a loss of UCS and BTS depending on the orientation of the weakness planes with respect to the loading axis.

A stylolite is an irregular, suture-like dissolution plane found in carbonate stones such as limestone [23–25], and it can affect the behavior of the inherent properties of limestone. While the UCS and BTS behaviors of building stones in relation to lamination and foliation orientation have been widely studied, there have been few investigations into the effect of stylolites on these mechanical properties. For example, the UCS and BTS of limestone containing stylolites were examined by Baud et al. [26], Aly et al. [27], Torabi-Kaveh et al. [28], and Pluymakers et al. [29]. These researchers found that stylolite planes have significant effects on the UCS and BTS of the samples. Therefore, it is necessary to investigate the effect of stylolites on the UCS and BTS of a stone before selecting it for use in a building. Based on the data analysis, the most appropriate stone can be selected to ensure better durability, consequently increasing the building's service life.

To improve understanding and add new information to findings reported in the literature, the present study investigated the UCS and BTS behaviors of a stylolitic limestone as a function of stylolite plane orientation, stylolite plane filling material type, and test specimen state (i.e., dry or saturated).

2. Materials and Methods

A number of block samples were collected from a stylolitic limestone outcrop around Khorramabad city (Lorestan Province, western Iran). Figure 1 shows the geographical location of the study area and some of the limestone block samples. These samples were collected from a single, spatially restricted limestone outcrop. Within this exposure, the limestone exclusively contains clay-filled stylolites, and no other types of stylolite fillings were observed. Due to its cheapness, abundance, and availability, limestone is a common building stone widely used in civil structures under construction and the restoration projects of historical monuments in Khorramabad city (Figure 2).

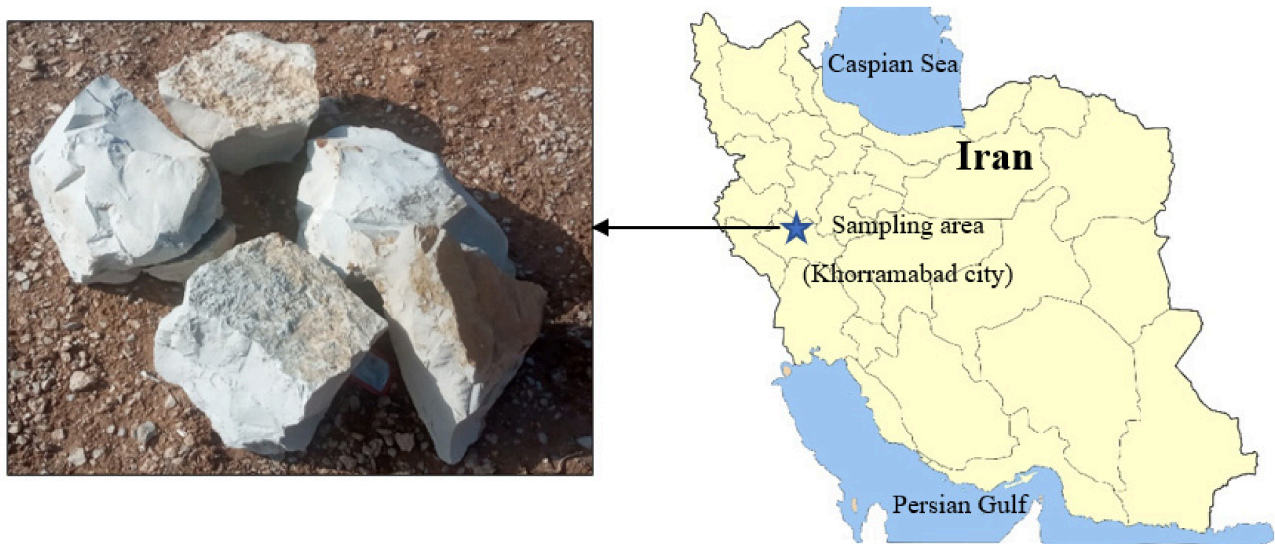


Figure 1. Sampling area and some block samples collected from a limestone containing stylolites.

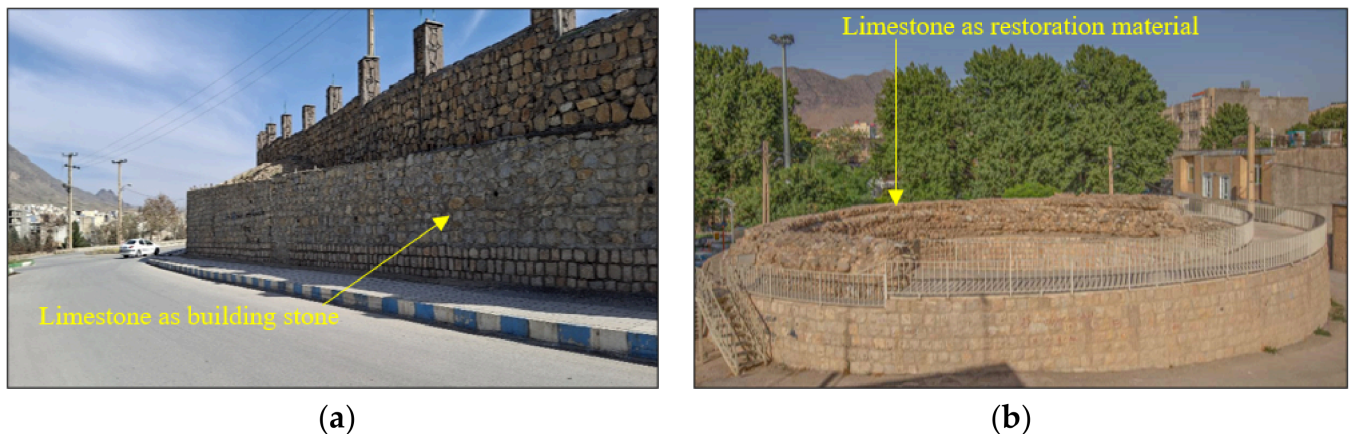


Figure 2. Uses of limestone in the civil and restoration projects located in Khorramabad city (Lorestan Province, Western Iran). (a) Retaining wall and (b) historical monuments.

Polarized light microscopy and scanning electron microscopy (SEM) were used to identify the stylolite plane and the type of material in it. Next, cylindrical core specimens with a diameter of 44 mm were prepared for UCS and BTS tests using a coring machine. The specimens were divided into five sets according to the angle (β) between the stylolite plane and the loading axis, including 0° , 30° , 45° , 60° , and 90° . Figure 3 shows schematic images of the specimens at different β angles for the UCS and BTS tests. Finally, the data obtained from the various tests were analyzed to investigate the effects of β , the type of filling material and the state of the specimen (i.e., dry or saturated) on the UCS and BTS of limestone. Figure 4 summarizes the methodology of the present study.

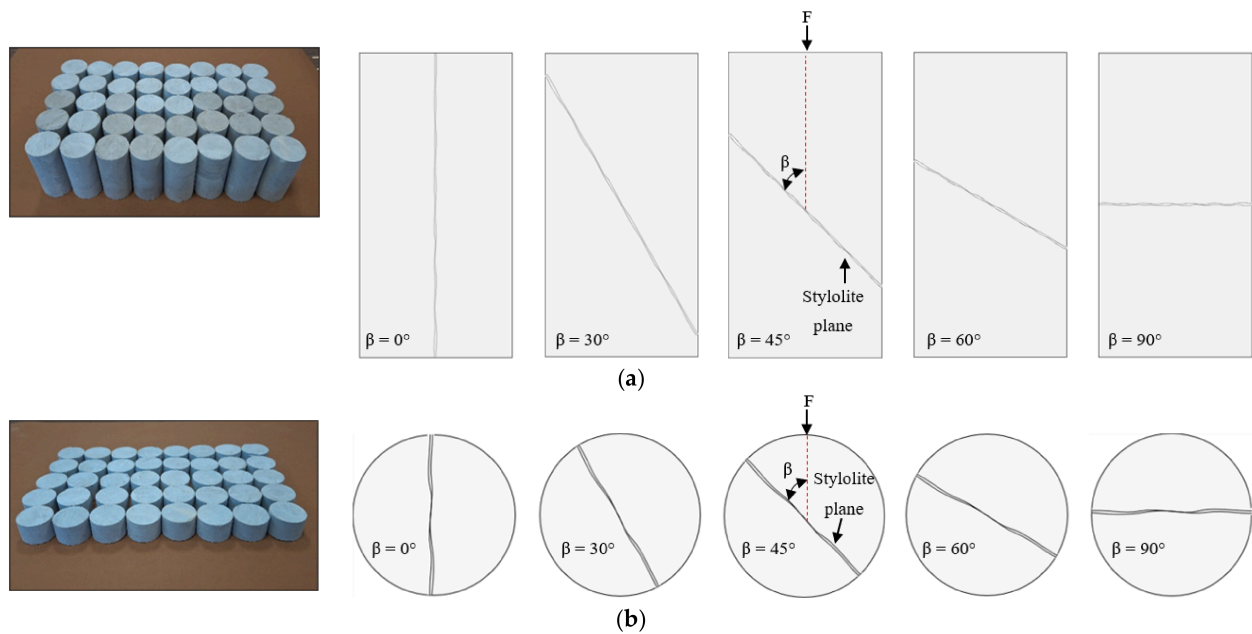


Figure 3. The schematic views of cylindrical core specimens prepared at different β angles for tests: (a) UCS and (b) BTS. Note: β is the angle between the stylolite plane and loading axis (F).

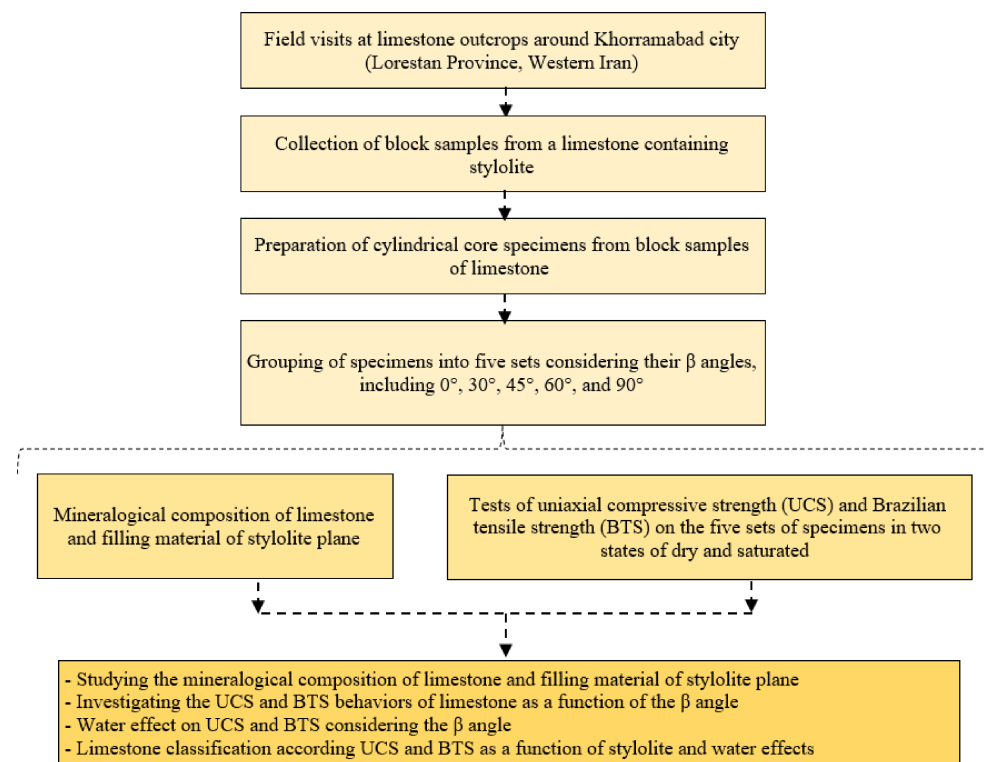


Figure 4. Methodology of the present study.

3. Test Procedures

3.1. Mineralogical Composition of Limestone and Filling Material of the Stylolite Plane

Thin sections of the limestone sample were prepared in two directions: parallel and perpendicular to the stylolite plane. Next, the thin sections were studied under a Zeiss Olympus BX51 polarized light microscope to determine the mineralogical composition of the sample and the filling material of the stylolite plane. Furthermore, to specify the

mineralogical composition more precisely, X-ray diffraction (XRD) was carried out on the powdered specimen using a “STOE model” diffractometer with a copper (Cu) anode tube.

As a complementary tool commonly used in the study of the mineralogical composition and structure of rock materials, a specimen perpendicular to the stylolite plane was taken from the limestone and studied using scanning electron microscopy (SEM; MIRA3-LMU model) and energy-dispersive spectrometry (EDS), the latter of which was equipped with a wolfram filament in order to identify the type of filling material in the stylolite plane. Before the measurements were taken, the surfaces of the specimens were coated with gold (Au) to make them electronically conductive.

3.2. Uniaxial Compressive Strength (UCS)

UCS is a fundamental strength parameter in the design of engineering structures such as slopes, dams, tunnels, and power plants [30–32]. Furthermore, UCS is a key technical parameter for assessing the quality of building stones for use in cladding, paving, flooring, load-bearing walls, stairs, etc. [16,18,33,34].

In the present study, UCS tests were carried out according to a method suggested by the International Society for Rock Mechanics [35]. To this end, ten specimens with a diameter of 44 mm and a length-to-diameter ratio were prepared for each β angle (i.e., 0° , 30° , 45° , 60° and 90°) from limestone blocks. The ends of the core specimens were flattened to within 0.02 mm and kept perpendicular to within 0.05 mm. Five of these specimens were placed in an oven at a temperature of 105°C for 48 h to achieve a moisture-free specimen, i.e., a dry state. The remaining five specimens were submerged in a distilled water bath for 48 h to reach a saturated state. Table 1 provides details of the materials used for the UCS tests. The specimen was loaded using a UCS device at a constant rate until failure. Figure 5 shows the UCS device and a representative test specimen. The UCS of a specimen was determined using Equation (1):

$$UCS = \frac{P}{A} \quad (1)$$

where P is the failure load of the specimen and A is the cross-sectional area of the specimen.

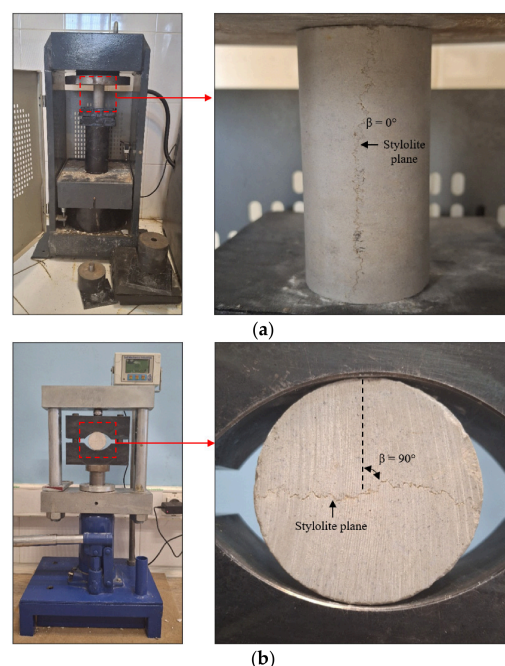


Figure 5. Devices used in the present study and test specimen for a given β angle: (a) UCS and (b) BTS.

Table 1. Materials used to determine the UCS and BTS of limestone [35].

Characteristic Type	Specimen Shape	Specimen Size	Specimen State	β Angle				
		Diameter/Length (mm)		$\beta = 0^\circ$	$\beta = 30^\circ$	$\beta = 45^\circ$	$\beta = 60^\circ$	$\beta = 90^\circ$
UCS	Cylindrical core	44/88	Dry	5	5	5	5	5
			Saturated	5	5	5	5	5
BTS	Cylindrical core	44/30	Dry	5	5	5	5	5
			Saturated	5	5	5	5	5

3.3. Brazilian Tensile Strength (BTS)

Tensile strength is one of the critical inherent characteristics widely used to select a suitable building stone. The BTS test is a well-known and common indirect procedure for evaluating the tensile strength of stones [36–39].

In the BTS test, two sets of specimens were prepared for each β angle (0° , 30° , 45° , 60° , and 90°): one set in a dry state and one in a saturated state. Each set included five specimens with a diameter (D) of 44 mm and a length (L) of 30 mm. Details of the materials used in the BTS tests are presented in Table 1. According to ISRM [35], each specimen was placed between two loading jaws embedded in the BTS device (see Figure 5). The specimen was subjected to loading at a constant rate of 0.01 MPa/s until failure occurred.

The BTS value of a specimen was calculated using the following equation, knowing the failure load (P), D and L:

$$BTS = \frac{2P}{\pi DL} \quad (2)$$

where $\pi = 3.14$.

4. Results and Discussion

4.1. Mineralogical Composition and Specification of the Stylolite Plane

Figure 6 shows close-up and microscopic thin-section images obtained from the sample. The wavy appearance of the stylolite plane, which has resulted in a loss of specimen integrity, is clearly visible in these images. The aperture of the stylolite planes varies from 0.05 to 0.3 mm. The space between the stylolite planes is occupied by filling material. While studying microscopic thin sections is a suitable way to obtain rough information about mineralogical composition, XRD provides more precise results. Figure 6 depicts the XRD pattern of the limestone sample. It can be seen that the sample is composed of calcite, quartz, and types of clay minerals, including montmorillonite, chlorite, and kaolinite. Figure 6 shows the results of the SEM-EDX that was used to identify the filling material of the stylolite plane. According to the SEM-EDX spectrum taken from a point on the stylolite plane, the elements Si, Al, Fe, Ca, and O were detected, indicating that the type of filling material is a clay mineral.

4.2. Anisotropic Behavior of the UCS and BTS

Figure 7 presents the UCS data of the sample at β angles of 0° , 30° , 45° , 60° , and 90° . The results revealed that the lowest and highest UCS values (for both dry and saturated states) correspond to the β angles of 30° and 90° , respectively. As depicted in Figure 7, an “asymmetrical shoulder-type curve” was obtained for UCS changes as a function of the β angle. UCS is lowest at a β angle of 30° , corresponding to 30.1 and 41.4 MPa for the dry and saturated states, respectively. This can be attributed to the geometric alignment between the loading direction and the stylolite plane. At $\beta = 30^\circ$, the stylolite is optimally oriented for shear slip, meaning that the resolved shear stress acting on the stylolite plane is maximized relative to the applied axial load. This facilitates sliding-type failure along

the stylolite plane, resulting in the lowest UCS value at $\beta = 30^\circ$ compared to β angles of 0° , 45° , 60° , and 90° . The UCS results for the sample are consistent with the findings of Zhang et al. [40], Khanlari et al. [41], and Jamshidi et al. [42] on sedimentary rocks containing a lamination plane, and Nasserli et al. [43], Karakul et al. [44], Zhang et al. [45], and Gholami and Rasouli [46] for foliation-bearing metamorphic rocks. These researchers investigated the effect of lamination/foliation on the UCS of various rocks and found that UCS is the lowest when the β angle varies from 20° to 40° and highest when the β angle equals 0° or 90° .

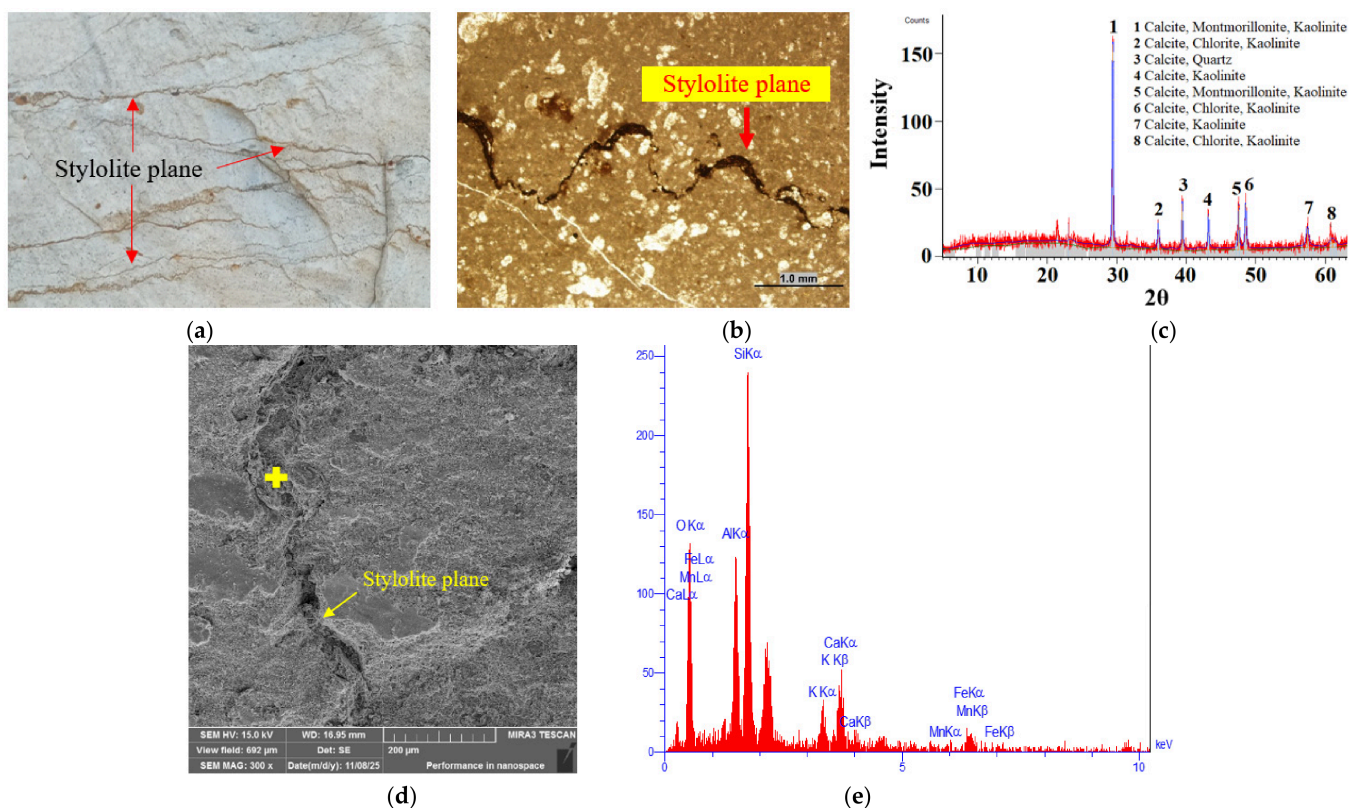


Figure 6. Typical images of a representative specimen: (a) close-up, (b) polarized light microscopy, (c) XRD pattern, (d) SEM micrographs, and (e) SEM–EDS spectrum taken on the stylolite plane [point marked by + on (d)].

Figure 7 shows how the sample BTS changes as a function of the β angle. An increasing trend in BTS was observed in the dry sample as β increased from 0° (BTS = 4.93 MPa) to 90° (BTS = 6.77 MPa). A similar pattern was observed for BTS changes in the saturated sample as a function of the β angle. According to Figure 7, the lowest (3.86 MPa) and highest (6.50 MPa) BTS values for the saturated sample were obtained at β angles of 0° and 90° , respectively. As β increases, the stylolite plane becomes progressively less favorable for sliding. The component of shear stress acting along the stylolite decreases, and the normal stress acting perpendicular to the plane increases. This change in stress orientation reduces the likelihood of shear-dominated failure, instead promoting opening-mode deformation. Consequently, the BTS of the sample gradually increases as β increases from 0° to 90° . The results of the present study are consistent with the findings reported in the literature. Khanlari et al. [21], Chen et al. [47], Abdi [48], and, more recently, Kong et al. [22] all conducted experimental studies on the BTS of foliated metamorphic rocks and laminated sandstones. Their results showed that BTS increases with an increase in the β angle.

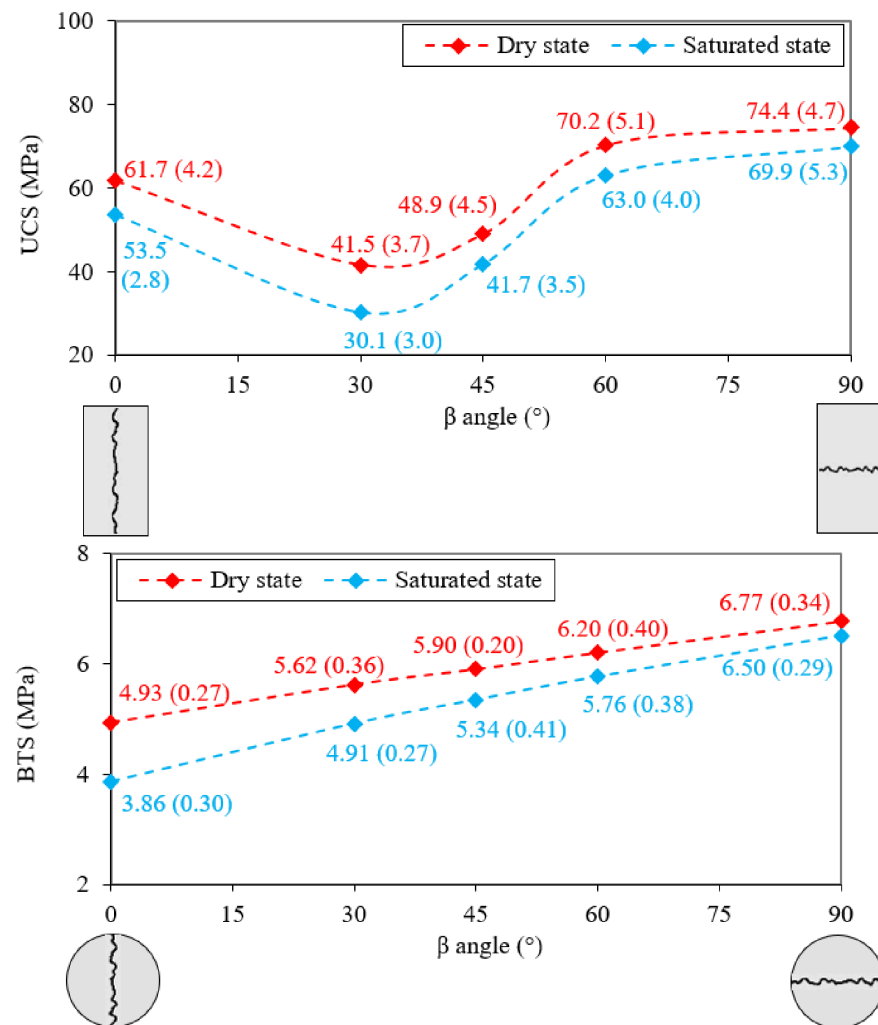


Figure 7. The changes in the UCS and BTS of the sample as a function of the β angle (the values in the brackets are standard deviations).

Overall, the variations in UCS and BTS reported by different researchers as a function of the β angle indicate that these strength parameters vary over a wide range. As the rock types examined in both the present study and in previous studies originate from different geological settings, the conditions of their formation and diagenesis are inherently distinct. These differences lead to variations in mineralogical composition, texture, and porosity, which, in turn, control the mechanical response of the rocks and result in different UCS and BTS values at various β angles.

As a quantitative–qualitative measure for evaluating the strength anisotropy behavior of a rock, Ramamurthy [49] introduced the concept of the anisotropy ratio (Ar). The Ar is defined as the ratio of the highest to the lowest UCS/BTS as follows:

$$Ar_{UCS} = \frac{UCS_{\beta=90^\circ}}{UCS_{\beta=30^\circ}} \quad (3)$$

where Ar_{UCS} is the anisotropy ratio of UCS, and $UCS_{\beta=90^\circ}$ and $UCS_{\beta=30^\circ}$ are the UCS values at β angles of 90° and 30° , respectively.

$$Ar_{BTS} = \frac{BTS_{\beta=90^\circ}}{BTS_{\beta=0^\circ}} \quad (4)$$

where Ar_{BTS} is the anisotropy ratio of BTS, and $BTS_{\beta=90^\circ}$ and $BTS_{\beta=0^\circ}$ are the BTS values at β angles of 90° and 0° , respectively.

Rocks are categorized into five anisotropy classes based on the Ar value: isotropic ($Ar \leq 1.1$), low anisotropy ($1.1 < Ar \leq 2.0$), medium anisotropy ($2.0 < Ar \leq 4.0$), high anisotropy ($4.0 < Ar \leq 6.0$), and very high anisotropy ($Ar > 6.0$). Figure 8 shows a schematic classification of sample anisotropy for dry and saturated states based on Ar_{UCS} and Ar_{BTS} . Overall, the results obtained from UCS and BTS at β angles of 0° , 30° , 45° , 60° , and 90° indicate different anisotropy behaviors of the limestone under study in both the dry and saturated states. The sample is classified as a rock with low anisotropy ($Ar = 1.79$) with respect to its UCS in the dry state, whereas in the saturated state, it falls into a rock class with medium anisotropy ($Ar = 2.32$). The anisotropy behavior of the sample under study was compared with that obtained by Zhang et al. [40], Khanlari et al. [41], and Jamshidi et al. [42]. These researchers found Ar_{UCS} values of 1.50, 1.51, and 1.87 for laminated sandstones. The comparison of these results shows reasonable agreement between the Ar_{UCS} values of the present study and the previous studies. Figure 8 shows that the Ar_{BTS} values of the sample in the dry and saturated states are equal to 1.37 and 1.68, respectively. According to the anisotropy classification suggested by Ramamurthy [49], these values imply that the sample is a rock with low anisotropy ($1.1 < Ar \leq 2.0$). However, these results differ from those reported by Abdi [48]. This researcher examined the BTS of two different laminated limestones, and the results show Ar_{BTS} values of 2.42 and 3.24 for the samples, indicating a medium anisotropy behavior ($2.0 < Ar \leq 4.0$).

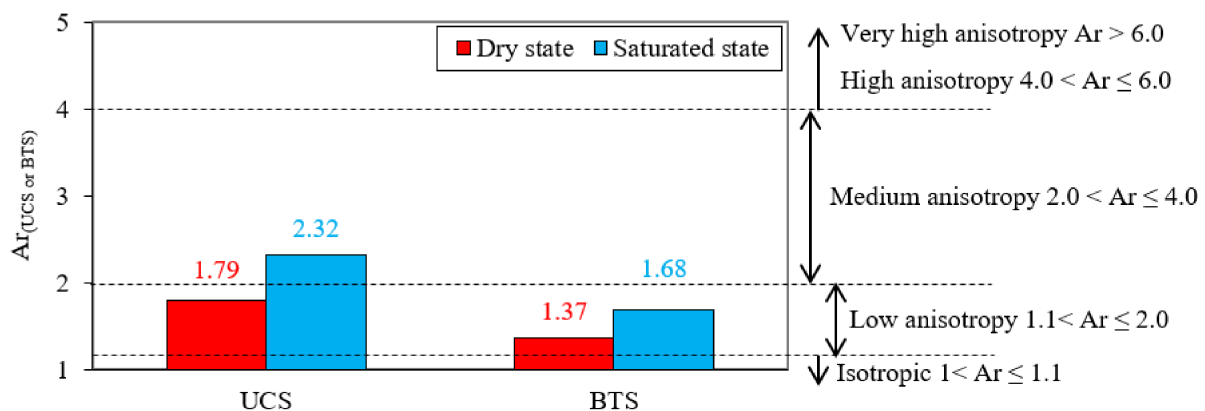


Figure 8. Anisotropy classification of the sample based on Ar_{UCS} and Ar_{BTS} values [49].

In general, the similarities and differences observed between the Ar_{UCS} and Ar_{BTS} values of the limestone investigated in the present study and those reported in the literature for various rock types can be attributed to several geological and mechanical factors. These include the mineralogical composition and texture of the host rock, the type of inherent weakness planes (e.g., lamination, foliation, or stylolite), and the geometric and physical characteristics of these planes, such as roughness, aperture, spacing, and the nature of the infilling materials. These features determine the extent of mechanical contrast between the host rock matrix and the weakness planes and therefore play a significant role in governing the anisotropic response of the rock under compressive and tensile loadings.

4.3. Sample Classification Based on UCS and BTS as a Function of β and Water Effect

One of the key criteria for assessing the quality of a stone for use in building is the quantitative–qualitative classification based on UCS and BTS values, as established by researchers and institutions. In the present study, the limestone sample was classified according to its UCS and BTS values at various β angles, considering both dry and saturated

states. Based on the UCS-based classification established by IAEG [50], the same pattern was observed for both the dry and saturated samples. As can be seen in Table 2, at β angles of 30° and 45° , the sample is categorized as moderately weak strength (UCS = 15–50 MPa), whereas at β angles of 0° , 60° , and 90° , it falls into the strong class (UCS = 50–120 MPa). These results showed that the quantitative–qualitative class of the sample based on its UCS is strongly affected by the value of the β angle. However, it was found that, for a given β angle, the sample falls into the same UCS class in both the dry and saturated states. According to the BTS-based classification proposed by Jamshidi and Akbay [51] (Table 2), the dry sample is classified as a rock with strong strength (BTS > 4.3 MPa) at all β angles (i.e., 0° , 30° , 45° , 60° , and 90°). Although the saturated sample showed a BTS class similar to that of the dry sample (i.e., strong strength; BTS > 4.3 MPa), at β angles of 30° , 45° , 60° , and 90° , a loss in BTS class to medium strength (BTS = 2.2–4.3 MPa) was observed at $\beta = 0^\circ$. Overall, the results of the UCS- and BTS-based rock classifications show that, to more accurately assess the quality of stylolite-containing limestone, the effects of the β angle and the state of the test specimen (i.e., dry or saturated) should be considered as the critical parameters in determining the UCS and BTS classes of the sample.

The results of the UCS- and BTS-based rock classifications, based on the IAEG [50] and Jamshidi and Akbay [51], respectively, also have important practical implications for engineering applications. The observed transition in strength classes with changes in the β angle and moisture conditions indicates that the mechanical performance of stylolite-bearing limestone depends strongly on stress orientation and environmental exposure. In practical terms, this suggests that when selecting stone blocks for architectural or structural design, the orientation of stylolite planes relative to the principal stress direction should be carefully considered. If the stylolite plane is expected to be oriented near the critical angle range where failure activation is most likely (i.e., $\beta = 30^\circ$ and 0° for UCS and BTS, respectively), the effective strength of the material may correspond to a lower classification class than that obtained from standard laboratory tests on randomly oriented specimens. Additionally, the reduction in UCS and BTS under water-saturated conditions implies that structures exposed to moisture, rainfall, or groundwater may deteriorate further. Therefore, conservative safety factors or stricter material selection criteria should be adopted in moisture-prone environments. These findings emphasize that rock strength classifications should not be interpreted as intrinsic constants of the material, but rather as parameters influenced by structural anisotropy and environmental conditions. These factors must be explicitly considered in engineering design, stone selection, and durability assessment.

Table 2. The limestone classification according to UCS and BTS as a function of β angle and specimen state.

β Angle ($^\circ$)	¹ UCS Classification		² BTS Classification	
	Dry State	Saturated State	Dry State	Saturated State
0	S	S	S	M
30	MW	MW	S	S
45	MW	MW	S	S
60	S	S	S	S
90	S	S	S	S

¹ According to IAEG [50]: **W**—weak (UCS < 15 MPa), **MW**—moderately weak (UCS = 15–50 MPa), **S**—strong (UCS = 50–120 MPa), **VS**—very strong (UCS = 120–230 MPa), and **ES**—extremely strong (UCS > 230 MPa).

² According to Jamshidi and Akbay [51]: **W**—weak (BTS < 2.2 MPa), **M**—medium (BTS = 2.2–4.3 MPa), and **S**—strong (BTS > 4.3 MPa).

4.4. Durability Classification of the Sample as a Function of β and Water Effect

According to the data presented in Figure 7, there was a loss in UCS and BTS as the sample became saturated. These results suggest that water has an adverse effect on the UCS and BTS of the sample. To evaluate the effect of water on the UCS and BTS of rock, Cobanoglu and Celik [52] introduced a durability classification based on the ratio of saturated to dry strength (SDr) of test specimens. The SDr values for the UCS and BTS of the sample were calculated using Equations (5) and (6), respectively:

$$SDr_{UCS} = \frac{UCS_{saturated}}{UCS_{dry}} \quad (5)$$

$$SDr_{BTS} = \frac{BTS_{saturated}}{BTS_{dry}} \quad (6)$$

Using the data reported in Figure 7, the SDr_{UCS} and SDr_{BTS} values were determined using Equations (5) and (6), respectively. The results of these determinations are presented in Figure 9.

Rocks fall into one of the five durability classes based on the SDr value: extremely poor durability ($SDr < 0.5$), poor durability ($SDr 0.5\text{--}0.6$), medium-to-poor durability ($SDr 0.6\text{--}0.7$), good-to-very good durability ($SDr 0.7\text{--}0.8$), and excellent durability ($SDr 0.8\text{--}1.0$). As can be seen in Figure 9, the SDr_{UCS} values of the sample range from 0.73 to 0.94. The lowest and highest SDr_{UCS} values belong to samples with β angles of 30° and 90° , respectively. According to the SDr_{UCS} values, the sample at $\beta = 30^\circ$ is classified as a rock with good-to-very good durability. In contrast, at $\beta = 0^\circ, 45^\circ, 60^\circ$, and 90° , the sample falls into the excellent durability class. Moreover, it was found that the samples at $\beta = 0^\circ$ and $\beta = 90^\circ$ had the lowest and highest SDr_{BTS} values of 0.78 and 0.96, respectively. As can be seen in Figure 9, the sample is classified as a rock with good-to-very good durability when $\beta = 0^\circ$, whereas it is classified as a rock with excellent durability at $\beta = 30^\circ, 45^\circ, 60^\circ$, and 90° . These results show that water has an adverse effect on the sample, resulting in a reduction in UCS and BTS and a loss of durability. A higher reduction in UCS and BTS indicates a lower durability of the sample under the adverse effects of water. Overall, the results show that the durability behavior of the sample under water exposure depends on the β angle. Previous studies have revealed that water can have a negative effect on rocks containing clay minerals. Clay minerals are highly susceptible to the softening effects of water due to their sheet structure and the presence of negative charges on their surfaces [53–55]. Based on the SEM-EDX analysis of the sample (Figure 6), the stylolite plane contains clay minerals. When the sample is in a saturated state, a rupture in the stylolite plane can be facilitated during UCS and BTS tests. The pronounced reduction in UCS and BTS values when the samples are saturated with water is interpreted in terms of clay-related softening processes acting along the stylolite planes. Beyond the simple “softening” of clay minerals, several coupled micro-mechanisms are likely to be involved. Firstly, the adsorption of water onto clay surfaces and into interlayer sites promotes the swelling of expandable clay phases and a partial breakdown of the interparticle fabric. This reduces the effective interlocking between grains and weakens grain–stylolite and grain–matrix contacts, lowering the apparent cohesion of the stylolite plane. Secondly, the hydration of clay minerals decreases interlayer bonding forces and van der Waals attractions at mineral contacts. Consequently, both cohesion and frictional resistance are affected. As a result, the shear strength envelope of the stylolite plane shifts towards lower cohesion values and, in some cases, a reduced friction angle. This is consistent with the observed drop in UCS and BTS under saturated conditions. Therefore, the presence of clay minerals as a filling material of the stylolite plane is a critical factor in the loss of UCS

and BTS in the saturated sample and thus in its durability against the effects of water. As a result, when assessing the durability of a rock containing a stylolite plane, the type of filling material needs to be accurately identified, as it affects the strength loss of the sample when exposed to water.

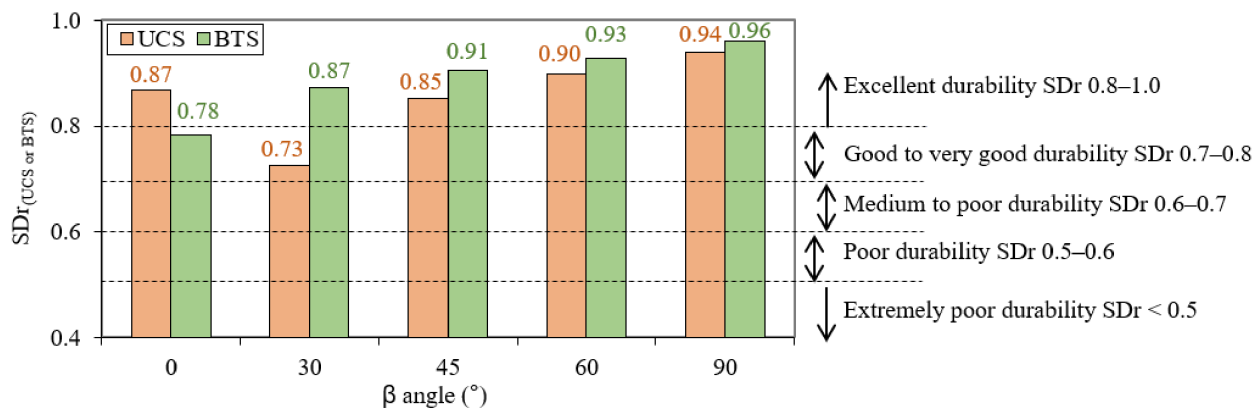


Figure 9. Durability classification of the sample based on SDr_{UCS} and SDr_{BTS} at different β angles [52].

5. Conclusions

The present research investigates the effects of the angle between the stylolite plane and the loading axis (β), the material filling the stylolite plane and the presence of water on the uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) behaviors of a stylolitic limestone. To this end, dry and saturated limestone specimens containing a clayey stylolite plane at the β angles of 0°, 30°, 45°, 60°, and 90° were subjected to UCS and BTS tests. Based on the data analysis, the results were as follows:

- The results of microscopic thin sections and X-ray diffraction (XRD) patterns showed that the limestone contained calcite, quartz, and clay. Furthermore, micrographs and spectra obtained using scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS) revealed that clay was the filling material in the stylolite plane.
- The UCS and BTS behaviors of the limestone are strongly affected by the β angle. An “asymmetrical shoulder-type curve” was obtained for UCS as a function of the β angle, with the lowest and highest UCS values occurring at β angles of 30° and 90°, respectively. However, the BTS of the sample exhibited different behavior from the UCS. An increasing trend in the BTS of the limestone was observed as the β angle increased from 0° to 90°.
- Water significantly reduces the UCS and BTS of the limestone. This was attributed to the softening effect of water on the clay minerals as a filling material in the stylolite plane. The weakening of the stylolite plane caused by the softening of the clay facilitated the failure of the specimens subjected to the loading during UCS and BTS tests.
- Based on the UCS- and BTS-based rock classifications, the limestone falls into different classes depending on the β angle and water effect. Since UCS and BTS are key technical parameters for evaluating the quality of building stones, the effects of the β angle and water on UCS and BTS must be considered.
- It was found that the limestone exhibits different durability behaviors in response to the adverse effects of water. Based on the ratio of saturated to dry UCS and BTS (SDr_{UCS} and SDr_{BTS} , respectively), limestone shows good-to-very good and excellent durability, considering several values of the β angle.

- As a practical result, using limestone containing clayey stylolite as load-bearing components may lead to structural problems during a building's service life when limestone is subjected to water/moisture.
- In the present study, the UCS and BTS of a limestone containing a single stylolite plane were examined under dry and saturated conditions. Future studies could extend this work by investigating rocks with multiple stylolite planes to clarify how their arrangement, intersection, and spacing influence macroscopic strength anisotropy. Furthermore, incorporating non-destructive methods, such as ultrasonic wave velocity, could help to establish a quantitative link between ultrasonic anisotropy and mechanical strength anisotropy. This would provide a more comprehensive understanding of stylolite-bearing limestones.

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