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ORIGINAL ARTICLE

An investigation on karst development in gypsum and limestone (case study; Zagros folded zone, southwest of Iran)

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Abstract
Karstification is a phenomenon that is more common in limestone and gypsum than in other rocks. Despite their equal geological conditions such as tectonics and hydrology, karstification in limestone and gypsum is different in the Ramhormoz area in Zagros folded zone in the southwest of Iran. This study aims to evaluate the lithological, physical, and mechanical properties of gypsum and limestone from Gachsaran and Asmari formations in the Ramhormoz area as well as their relationship with karstification features. This investigation involves two main parts: a morphological study and laboratory tests. First, morphological features of karsts were measured in gypsum and limestone. Then lithological, physical, and mechanical properties of the two were measured using laboratory tests such as SEM and XRD analyses, a calcimeter test, dry density, saturated density, porosity, solubility, durability, Uniaxial Compressive Strength (UCS), and the Brazilian tensile tests. In the next step, the relationship between laboratory properties and karstification phenomena in these types of rocks was obtained. In this study, limestones were divided into four types based on calcite content, and gypsums were divided into two types based on texture: alabaster gypsum and porphyritic gypsum. Karst morphology studies show a higher frequency and larger dimensions of caves and karrens in limestone types 1 and 2, and collapse and cap rock sinkholes in porphyritic gypsum. The results of laboratory tests show that, compared to gypsum, limestone has higher compressive strength and slake durability and low dissolution potential. Because of their high strength and durability, karst features such as cave and karren are more stable in limestone compared to gypsum which has low strength and durability and high dissolution and is also unstable. According to this research, the karst in limestone is stable while in gypsum it is unstable.

Keywords Zagros folded zone · Karstification · Stable karst · Unstable karst

Introduction

Karsts are defined areas with different and particular hydrology and geomorphology developed in rocks with high dissolution and secondary porosity (Ford and Williams 1989). On a world scale, the dissolution of limestone and gypsum by natural waters creates extensive karst landforms that can be very difficult ground for civil engineers (Waltham and Fookes 2003). Limestone and gypsum dissolution has so far been investigated by many researchers, and their studies have introduced parameters such as the chemical composition of water and jointing as some of the effective factors involved (Milanovich 1981; Waele et al. 2009; Klimchouk and Aksem 2005; Boroujeni et al. 2019; Barmaki et al. 2019; Calligaris et al. 2019). However, limited studies have been conducted on the relationship between Karstification and the physical–mechanical properties of the limestone and gypsum rocks. In this regard, Adamo et al. (2018) compared gypsum and limestone karstification in the Mosul and Haditha dams in Iraq. The foundation geology of any dam plays the most important role in the selection of the type and details of foundations' treatments. While both Mosul and Haditha Dams sites suffered from the presence of karsts. These karsts have different origins, types, shapes, sizes and depths. In the Mosul Dam site, it was of dissolution type (type of foundations' treatments), which was formed as a result of the high dissolution rates of gypsum beds within the foundations. In the Haditha Dam site, it occurred in varying degrees in the limestone beds of the Euphrates and Ana formations in the shape of fissures, cracks and nearly isolated collapsed sinkholes. Sinkholes in the Mosul Dam site

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are of the dangerous dissolution type which could develop quickly and appear suddenly without enough prior notice, whereas sinkholes in the Haditha Dam site are not of the collapse type, but are of the stable closed type which can take a very long time to develop, and are there for less dangerous (the type of sinkholes in the Mosul Dam site are solution sinkholes and the type of sinkholes in the Haditha Dam site are collapse sinkholes). This is attributed to the fact that limestone is generally less soluble than gypsum. The thickness of the karstified rocks in the Mosul Dam site is about 300 m, whereas at the Haditha Dam site is about 50 m. This large difference in the thickness of the karstified succession of rocks played also a big role in causing more difficulties in the grouting process in the Mosul Dam.

Azizi et al. (2014) assessed the karst sinkhole stability in the Cheria Area, NE Algeria and reported that under imposed loading, the stability of the karst cavities depends on the geo-mechanical parameters (RMR, Rock Mass Rating; GSI, Geological Strength Index; E, Young modulus) of the host rock as well as the depth and dimensions of the gallery. Yilmaz and Karakan (2005) studied durability and its relationship with sinkhole development in gypsum and concluded that rock texture, particularly grain size and effective porosity are among the most important controlling parameters on slake durability and sinkhole development in gypsum. Ahmed and Masoud (2017) evaluated the impact of karsts phenomena on engineering properties of limestone foundation bed at the Ar Riyadh in Saudi Arabia. Results of petrographical analyses and XED of limestone samples show that the strength parameters of samples are mostly composed of micrite (mudstone/wackestone) and dolomite in hard limestone of the Hittin district. In the Al Aziziyah district, the samples mostly consist of foraminifera and a high amount of calcite as in karst limestone (wackestone/packstone). Rock mechanical tests with a combination of fabric analyses have shown that strength parameters depend on the amount of karst. Major geomechanical differences between the two types of limestone provide the proper base for prioritizing areas to alleviate future risks and sustainable urban planning for decision makers. The studied karst limestones are generally poor foundation materials in their natural state especially for high and infrastructures due to weak mechanical strength and heterogeneity of their both physical and mechanical aspects. The construction problems of karst come from sudden and unpredictable occurrences such as earth subsidence and earth collapse led to swallowing parts of highways and houses reported during the last decades.

Tony et al. (2005) explained the sinkhole development mechanism and mentioned that for limestone the majority of cavities and karst features are developed in rocks with Uniaxial Compressive Strength (UCS) higher than 60 MPa, unit weight of 2.6 KN/m^3, and initial permeability less than 2%. Parise and Lollino (2011) studied failure mechanism in karsts for southern Italy and concluded the need for a comprehensive study on rock mass geomechanical properties for analysis of sinkhole development risk, which in turn needs study of strength and deformation properties of the jointed rocks (rock mass) and rock material (intact rock). Ghabezloo and Pouya (2006) proposed a numerical model for the effect of weathering on failure development in limestone, where they show that physical and chemical weathering processes lead to the reduction of strength parameters of rock and failure of underground limestone mines. Parise and Triscuzzi (2007) investigated geomechanical characteristics of karst carbonate rock masses in the Castellana-Grotte, Italy, using the ISRM standards and concluded that characterization of geomechanical properties of rock masses is necessary for rock stability. Note that this characterization is critical for karst areas. Integration of rock mass geomechanical data and field observations of the cavity failures are of great importance for further understanding of failure mechanism and detection of areas more prone to failure. Waltham and Fookes (2003) proposed an engineering classification for karst areas in which diversity and frequency of sinkholes and size of underground cavities are described. The other types of karst phenomena have less importance in this classification. Besides, rock strength is not incorporated in it. Gutierrez et al. (2008) proposed a classification for sinkhole developed in evaporates, where they mentioned that gypsum collapses faster than limestone due to its lower compressive and tensile strengths. Furthermore, evaporates might be subject to mechanical strength reduction due to the severe erosion along the joints. The distribution of the karst features appears to be controlled by a combination of lithologic, stratigraphic and tectonic structure factors (Torabi-Kavehet al. 2012). This study aimed to investigate the relationship between karst development and lithological, physical, and mechanical properties of gypsum and limestone in the Ramhormoz area located in the southwest of Iran (Fig. 1). Moradi et al. (2016) are used Geographic Information Systems (GIS) and Remote Sensing (RS) to create karstification potential map in the northeast of Khuzestan province of Iran. The extraction of this map is based on the study of input data such as lithology, lineament density, elevation, slope, rainfall, temperature, drainage density and vegetation cover. The study area in the present paper is part of the area studied by Moradi et al. (2016). The results of their research show that since factors, weight of input data (such as lithology, lineament density, elevation, slope, rainfall, temperature, drainage density) in our study area are similar, karstification is almost similar in all Asmari limestone and so is it for the Gachsaran gypsum. But field study shows that karst development in some limestone types is more than in other types, and for gypsum too. So other effective parameters in karst

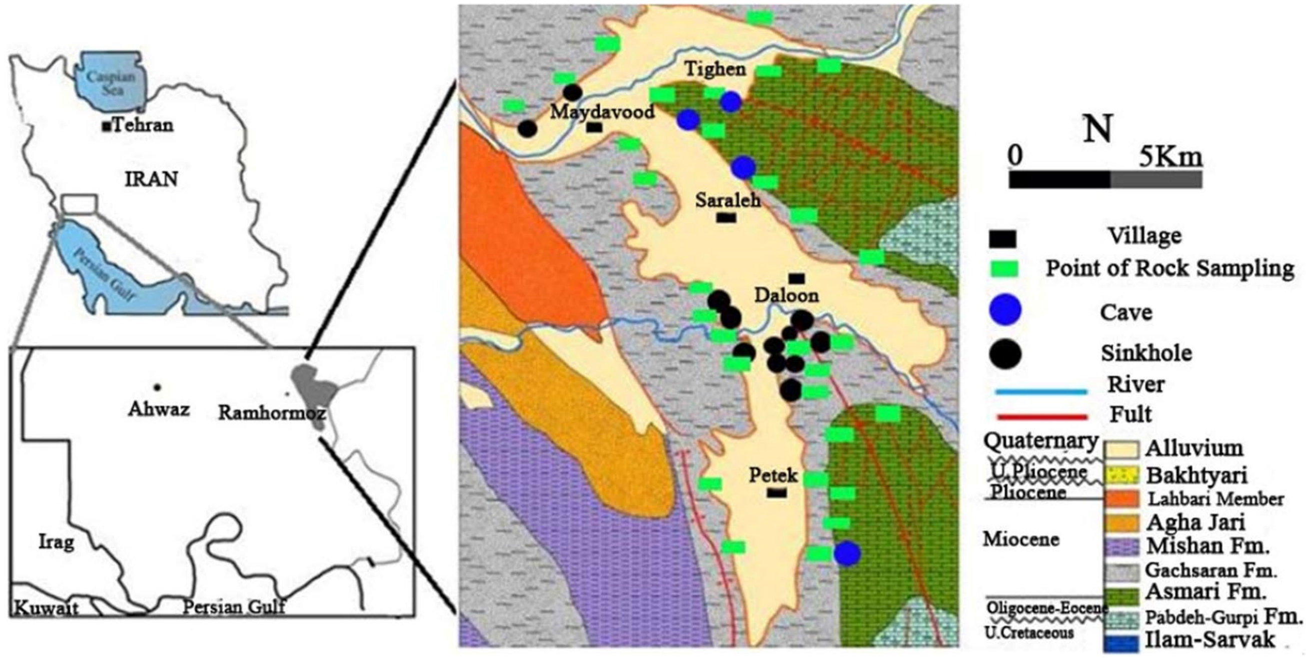
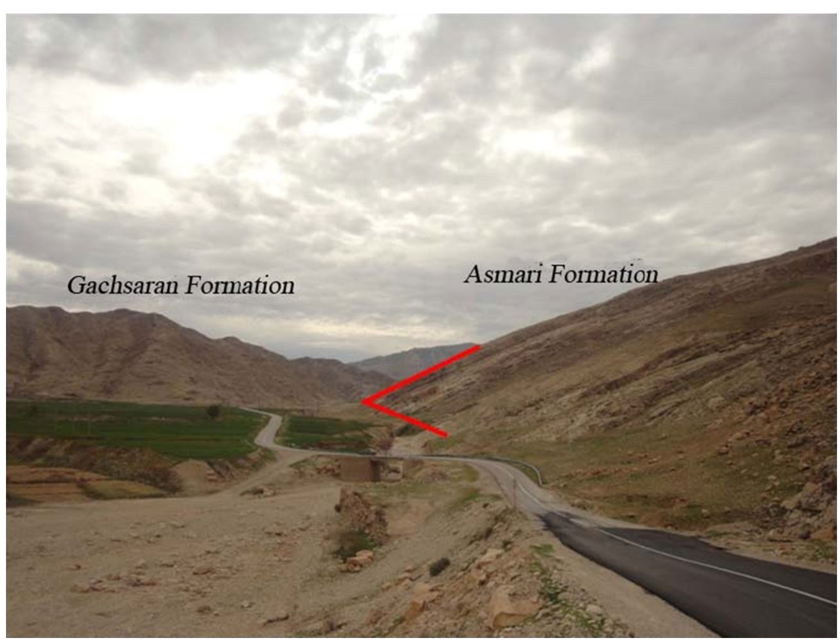


Fig. 1 Geological map and location of study area

development such as lithological, physical, and mechanical properties and solubility of rocks must be investigated. In the study area, there are many residential areas and engineering projects such as Ramhormoz-Baghmalek-Izeh road, oil pipeline, electric power transmission, Jareh and Abolfares dams. The karst phenomenon of limestone and gypsum poses danger for residential areas and engineering projects. In this study, we compared the gypsum and limestone karst phenomenon to determine which karstic phenomenon is more unstable and can lead to more considerable dangers. The most important hydrology features of the area are Alah and Talkh rivers, Barme-Jamal spring, Poto spring, Sarelah spring and sorok spring. The climate of the area is warm and humid. The maximum and minimum temperature is + 50 °C and − 4 °C, respectively. The average annual rainfall of the area is 410 mm.

Fig. 2 Contact of Asmari formation and Gachsaran formation (north of Ramhormoz)



Geological setting

Asmari Formation is the most important carbonate formation of Iran belonging to Oligo-Miocene and covers a wide area extending from west to southwest Iran; it is an oil and gas reservoir of this area. This formation is divided into three sections of Lower, Middle, and Upper Asmari. The Upper Asmari section of the study area is in contact with the Gachsaran Formation. In terms of stratigraphy, the Upper Asmari contains 50 m of limestone with vuggy dolomite interlayers, 55 m of massive dolomite, and 60 m of massive limestone (James and Wynd 1965). Upper Asmari, which contains solution cavities, indicates also more karstification as compared to the middle and lower parts. Gachsaran Formation, which indicates wide outcrops in the southwest of Iran, is the caprock for a large number of oil fields. This formation indicates a large temporal variation, as it belongs to Oligocene to Miocene. This formation includes seven members as follows: (1) the oldest member, alternation of thick anhydrite, limestone and shale; (2) thick salt layer, anhydrite with thin layers of limestone; (3) thick anhydrite with salt; (4) thick salt layer with gray marl, limestone and anhydrite; (5) red and gray marl with alternation of gypsum; (6) alternation of anhydrite (or gypsum), salt, red marl and limestone layers; (7) the youngest member, alternation of gypsum, gray marl and limestone (James and Wynd 1965). According to the field observations, members 1, 2, 5, 6 and 7 of the Gachsaran Formation are outcrops in the study area. The study area is in the Zagros folded zone or External Zagros (Stocklin 1968) and Simply Folded Belt (Berberian 1995) of Zagros system. This system is composed of elongated whaleback or box-shaped anticline mountains (Bosak et al. 1999). Tectonics forces caused by the Zagros compressive folding have caused the formation of the faults and thrust faults with a northwest-southeast trend in the study area. As shown in Fig. 2, the Asmari and Gachsaran formations are adjacent in the study area, but karstification developments in the limestone of the Asmari Formation and gypsum of the Gachsaran Formation are quite difference.

Method

To compare karst development (engineering and environmental aspects of karst) in Asmari Formation limestones and Gachsaran Formation gypsums, field studies were carried out by identification of karst features, measurement of joint properties, and sampling. Karst features such as caves, sinkholes, and karrens were identified in the field studies. The number and dimensions of the caves were then measured. Subsequently, the sinkhole type was determined (base on the classification of sinkhole by Waltham and Fookes (2003)) and the number and dimensions of sinkholes were measured. Karren dimensions were measured as well. The criteria for the collection of the sample included: from karstic area (close to karstic phenomena such as caves, sinkholes, karrens), and from nonkarstic area. In the next stage, thin sections of the collected samples were prepared for microscopic studies after which petrographic studies were carried out. To detect constituting minerals of the rock samples, SEM and XRD analyses and calcimeter tests were used. To perform rock mechanic tests, from 80 blocks with dimensions of about 30 cm × 30 cm × 30 cm, cores were prepared. The porosity of the samples was measured according to ASTM D2216, while their unit weight was determined based on the procedure proposed by Brown (1981). To study the dissolution rate of samples, a circulation-based dissolution test was applied (Ghobadi1997). A durability test was then carried out based on the ASTM D4644 standard using 15 cycles for four types of limestone and two types of gypsum. To compare the mechanical strength of the rocks, unconfined compressive strength (σ_C), Young's modulus (E), and tensile strength (σ_t) were carried out based on ASTM (1996) and ISRM. Furthermore, the stress–strain curve was plotted for the rocks, their Young's modulus was determined, and the rocks were then classified based on the method proposed by Deere and Miller (1966). Eventually, the differences in lithological, physical, and mechanical properties of gypsum and limestone samples and their relationship with karst development were investigated.

Results

Lithology

Petrological, lithological, and structural features greatly influence all aspects of karst genesis. Lithological properties that effected upon karst development are rock purity, grain size and texture, fabric porosity and mechanical strength (Ford and Williams 2007). The lithological properties of limestone and gypsum have been studied in the present research. SEM and XRD analyses were carried out on 12 collected samples to determine the mineral content (Fig. 3a–d). The analysis results show that Gachsaran Formation gypsum content includes about 100% of gypsum mineral with calcite and clay mineral traces. The calcite content of the Asmari Formation limestones is variable and other minerals such as dolomite and clay minerals also exist in them. The carbonate mineralogy of a limestone can be investigated using a chemical staining technique (Dickson 1966). This involves a reaction which produces a coloured precipitate on a mineral surface, making the mineral more

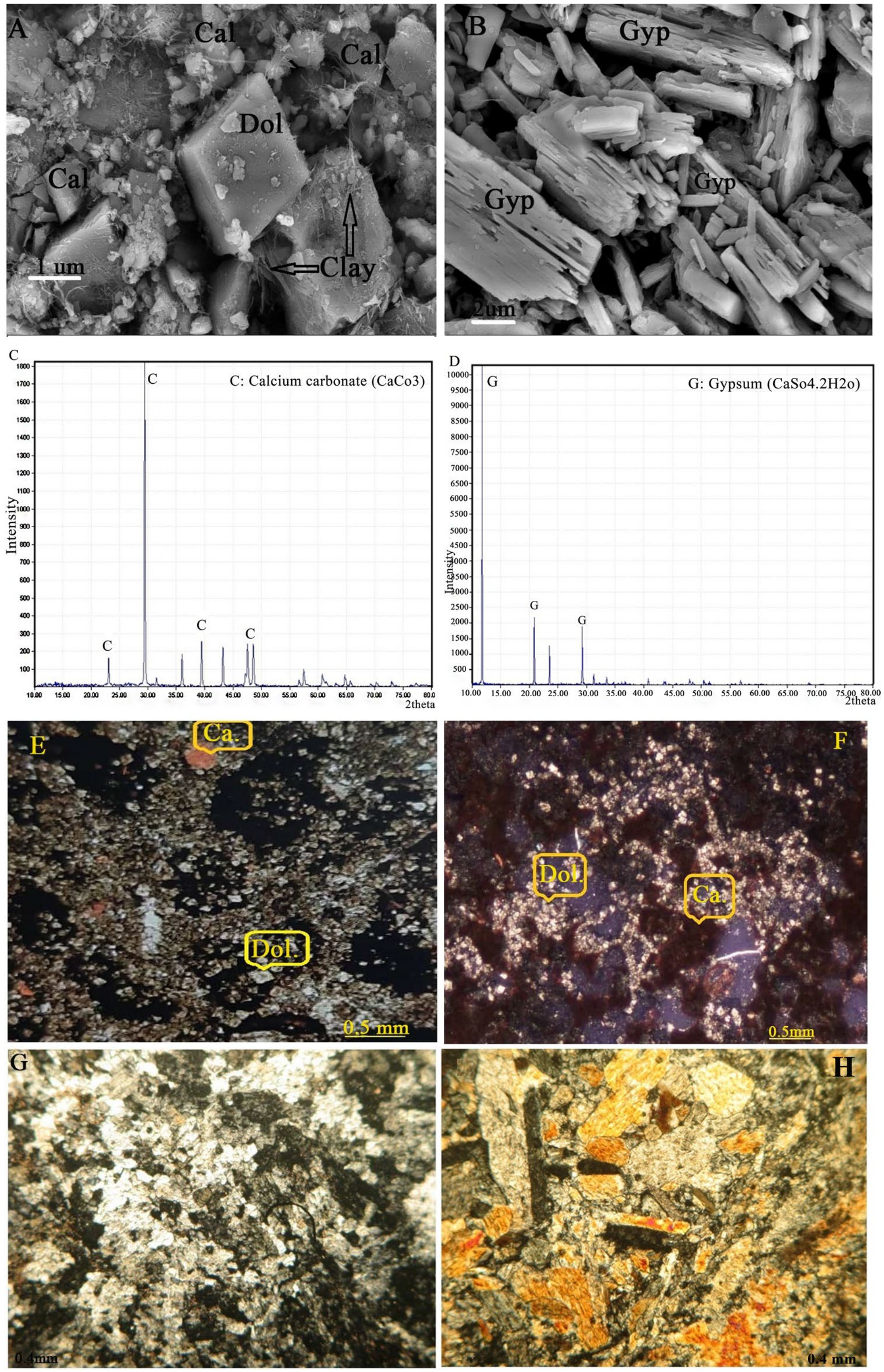


Fig. 3 **a** SEM of Asmari formation limestone (Cal: calcite, Dol: dolomite, Clay: clay mineral), **b** SEM of Gachsaran formation gypsum (Gyp: Gypsum), **c** XRD of Asmari formation limestone, **d** XRD of Gachsaran formation gypsum, **e** and **f**: mineralogy of limestone by chemical staining technique, **g** photomicrographs of Alabastrine gypsum, **h** Photomicrographs of Porphyritic gypsum

easily recognised. In this study, it was used to determine the presence of dolomite in the samples. Thin sections were prepared from the collected limestone and gypsum samples. Based on the thin section studies, limestone in this research included mudstone, wackestone and packstone. For baste classification, calcimetri tests were prepared from the limestone. The results show that calcite content is maximum in the karstic area and minimum in the nonkarstic area. In each area, an average of the calcite content was taken and four types of limestone were obtained (Table 1). Based on the thin section studies, two texture types of gypsum were obtained: alabaster and porphyritic (Fig. 3e, f). Alabaster is secondary gypsum very fine-grained and formed by replacement of anhydrite (Yilmaz and Karakan 2005). Porphyritic was observed as larger gypsum crystal (phenocrysts) sets in a finer-grained secondary gypsum groundmass. Concerning the field study, porphyritic gypsum is outcropped in the south and east of the study area while alabaster gypsum is outcropped in the west.

Laboratory characteristics of limestone and gypsum

To investigate karst development in limestone and gypsum, the properties of these rocks were measured in a laboratory according to the available standards. Slake durability is among the engineering properties of rocks that indicate their resistance to weathering agents and is closely related to karst development (Yilmaz and Karakan 2005). Slake durability was measured through a durability test in 15 cycles for four types of limestone and two types of gypsum (Fig. 4). The formation of karstic features such as caves and sinkholes is highly related to the unconfined compressive strength (σ_C), Young's modulus (E), and tensile strength (σ_t). Using the unconfined compressive strength test, the stress–strain curve was prepared and Young's modulus (E) was measured from this curve (Fig. 5). The failure shape of rocks in unconfined compressive strength test is shown in Fig. 5. The Deere and Miller classification was also used to compare the unconfined compressive strength (σ_C) and Young's modulus (E) of the samples (Fig. 6). The results of physical, mechanical and dissolution properties of the samples are shown in Table 1.

Discussion

Dolomitization has widely affected the limestones in the middle and upper sections of the Asmari Formation. The rate of dolomttization increases from the lower to upper units of this formation (Mahboubi et al. 2020). Results show that type 1 limestone has lower porosity while type 4 has higher porosity as compared to other types. This is, due to the dolomitization process and conversion of calcite to dolomite (dolomitization increased the porosity of the rock). Type 4 has maximum dolomite content whereas type 1 has minimum content. The unit weight (dry density and saturated density) of type 1 is higher than that of other types due to lower porosity. From another aspect, water absorption of type 4 is higher than other types due to higher porosity. The dissolution test results show that the dissolution rate of type 1 of limestone is higher than other types due to higher calcite content. The slake durability index after 15 wet and dry cycles for type 1 was lower than in other types due to the higher calcite content. The strength properties such as compressive and tensile strengths and Young's modulus of type 1 were higher than in other types due to lower porosity and dolomite content. The compressive strength and Young's modulus were related to the carbonate percent (Lashkaripour et al. 2018) and the conversion of limestone to dolomite (increase dolomite content) resulted in decrease in compressive strength (Williams and Namara 1992). Based on unconfined compressive strength (σ_C) and the stress–strain curve, all types of limestone indicate the elastic–plastic behaviors under the applied loads. Moreover, using Deere and Miller's (1966) classification, types 1 and 2 were categorized as rocks with medium strength and high modulus ration (class CH), while types 3 and 4 of limestone were categorized as rocks with poor strength and high modulus ration (class DH).

Table 1 The range of geotechnical properties of the gypsum and limestone

	Limestone (base on calcite content)				Gypsum (base on texture)	
	Type 1 (> 98%)	Type 2 (95–98%)	Type 3 (90–95%)	Type 4 (< 90%)	Alabaster	Porphyritic
Number of sample	16	13	8	8	20	15
Dry density (gr/cm^3)	2.63–2.68	2.53–2.56	2.46–2.48	2.4–2.42	2.3–2.33	2.2–2.23
Saturated density (gr/cm^3)	2.7–2.72	2.63–2.66	2.54–2.57	2.41–2.44	2.4–2.42	2.3–2.32
Porosity (%)	1.5–1.8	3.2–3.5	5.1–5.5	7.4–7.8	0.5–0.53	1.2–1.3
Water absorption (%)	0.43–0.52	1.21–1.25	2.65–2.68	3.41–3.44	0.6–0.62	0.8–0.85
Solubility (gr/l)	0.007	0.006	0.0054	0.0048	2.6–2.8	2.4–2.5
Slake durability index I_{d15} (%)	95–96	97–97.4	98–98.4	99–99.2	80 -81	84–85
σ_C (MPa)	85–89	70–74	56–59	40–43	31–33	21–23
σ_t (MPa)	8.3–8.6	6.5–6.8	5.3–5.5	4.1–4.4	3.2–3.4	2.2–2.3
E (GPa)	28–28.6	19.2–19.5	14.2–14.5	9.6–9.8	5.9–6.2	2.4–2.5

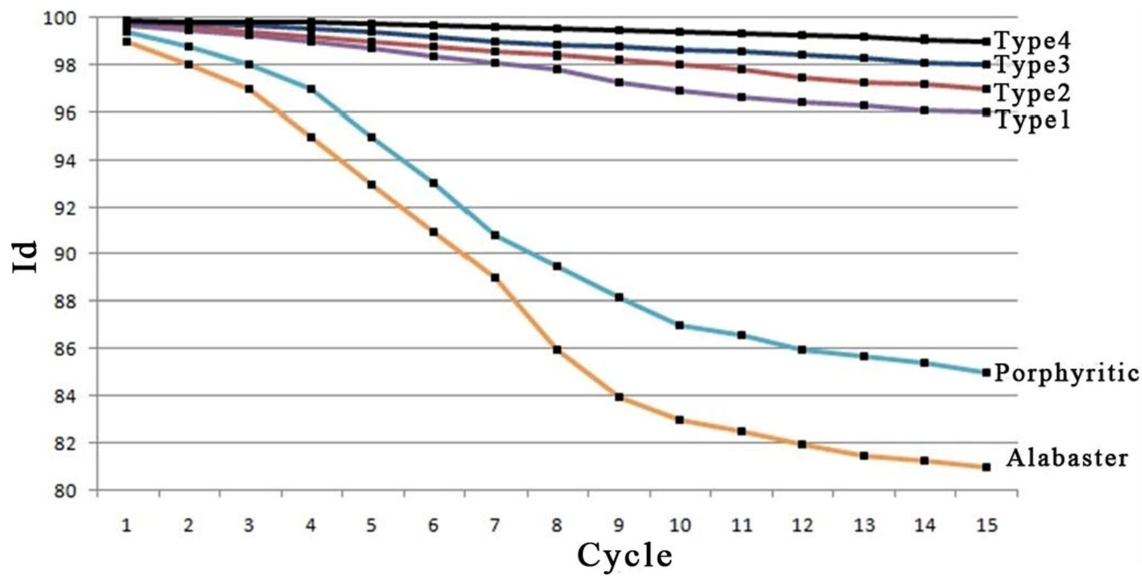
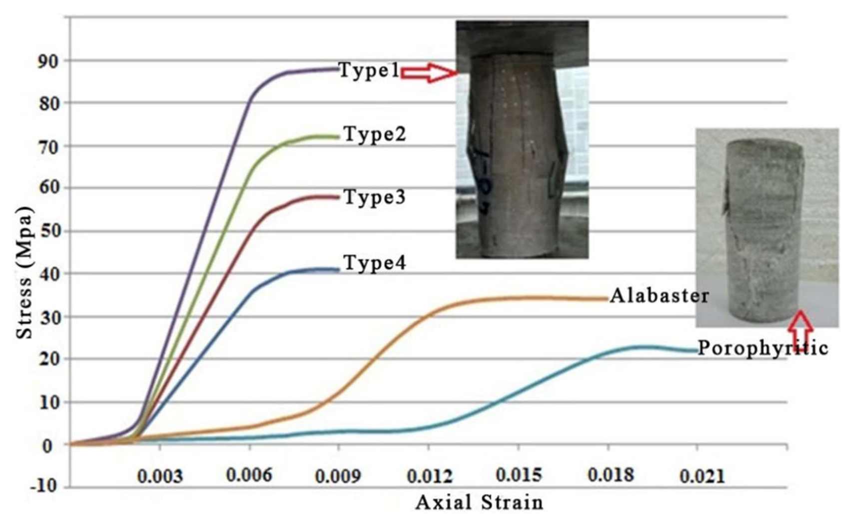


Fig. 4 Slake durability index versus the number of cycles

Fig. 5 Typical stress–strain curves of the gypsum and limestone



The results for gypsum show that alabaster (fine-grained gypsum) has lower porosity while that of porphyritic (coarse-grained gypsum) is higher. The unit weight (dry density and saturated density) of alabaster gypsum is higher than porphyritic gypsum as a result of lower porosity. Water absorption of porphyritic gypsum is higher than alabaster gypsum because of higher porosity. The dissolution test results show that the dissolution rate of alabaster gypsum is higher than porphyritic gypsum as a result of its fine-grain texture and high specific surface area. The results of the slake durability index after 15 wet and dry cycles show that the slaking behavior characteristically depends on texture type. Alabaster gypsum has lower durability than in porphyritic gypsum. Due to the high specific surface area, inter-granular bonds are weakened by the action of water in alabaster gypsum than porphyritic gypsum. When the drying and wetting cycles are increased, the weakening of intergranular bonds becomes easier, indicating the influence of the number of cycles in the slake durability tests. The strength properties of the studied gypsum are closely related to the texture and grain size. The fine-grained alabastrine gypsum gave a higher unconfined compressive strength (σ_C), Young's modulus (E) and tensile strength (σ_t) than the coarse-grained porphyritic gypsum. Based on unconfined compressive strength (σ_C) and the stress–strain curve, two types of gypsum indicate the plastic-elastic–plastic

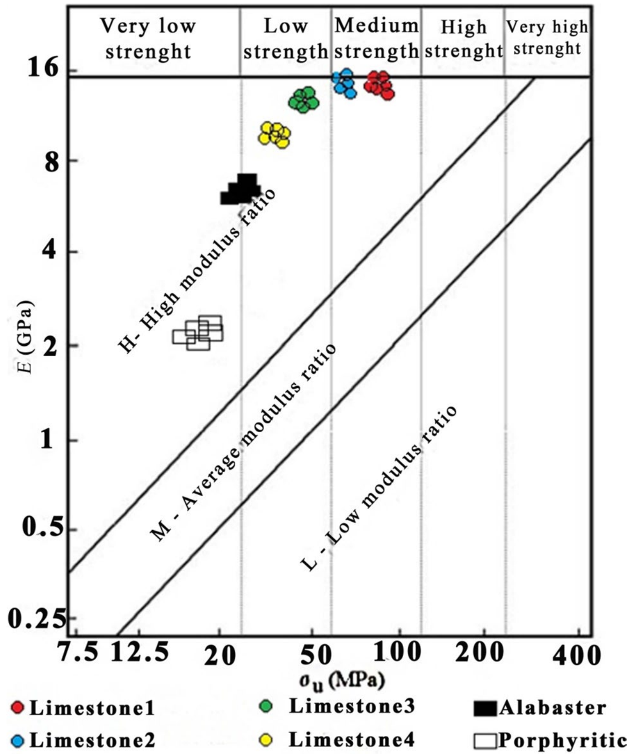


Fig. 6 Distributions of the gypsum and limestone samples on the *E*–σ_C chart (after Deere and Miller 1966)

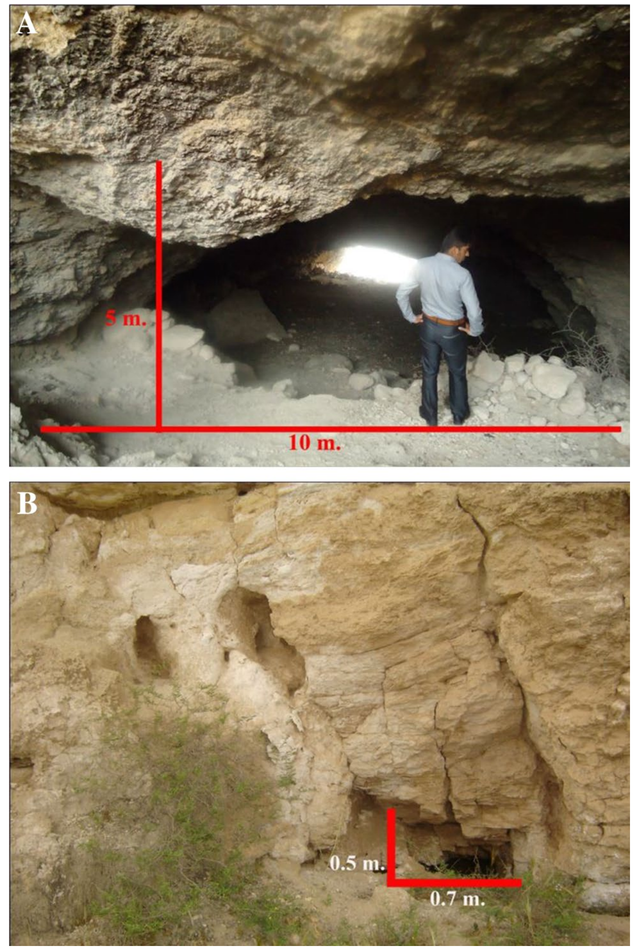


Fig. 7 **a** Cave in limestone of Asmari formation, **b** dissolution vuggyin gypsum of Gachsaran formation

behaviors under the applied loads. Also, using the Deere and Miller's (1966) classification, alabaster gypsum was categorized as a stone with poor strength and high modulus ration (class DH), while porphyritic gypsum was categorized as a stone with very poor strength and high modulus ration (class EH).

Karstic features

Karst development is controlled by many parameters such as tectonics, climatic conditions, lithology and hydrology (Milanovich 1981). Although the Asmari and Gachsaran formations are adjacent in the Ramhormoz area and have similar tectonics and hydrology conditions, the limestone of the Asmari Formation and the gypsum of the Gachsaran Formation indicate different karstifications. Different rocks show different behaviors against the karstification process because of their different properties. Physical properties, dissolution rate, and mechanical properties of gypsum and limestone can be among the main parameters leading to karstification in these rocks. Sinkholes, caves, and karrens are among the frequently observed karst features in the study area. According to the field observations, the morphology and frequency of these phenomena are different in limestone and gypsum. Caves are among the karst phenomena whose development is different in these two types of rocks. Where many caves with different lengths and widths can be observed in limestone (Fig. 7a), few are observed in gypsum and are limited to dissolution vuggy (Fig. 7b). In the field studies, a lot of caves were found in the Asmari Formation limestone types 1 and 2.

Cavity aperture, jointing intensity, orientation, and shear strength of joints and UCS of intact rock are among the mechanical factors controlling the stability of karst caves (Yossef et al. 2010). When the width of an opening is small, the cavity roof tends to propagate upwards by progressive failure. The deflection of gravitational stresses around the cavity creates a tension zone over the roof that is overlain by an arched compression zone. This tension zone determines the development of cupola-shaped failure planes and the generation of arched roofs. The function of the cave roof can be considered as a beam, which, when the beam is compressed, tensile stress is developed in the arched section (Tony et al. 2005) (Fig. 8).

In rocks with high tensile strength, the cave remains stable without any roof collapse. The Brazilian test simulates the conditions where rocks stretch and rupture under a linear load. In this study, the cave roof was simulated with the Brazilian test. Based on the results of the Brazilian test, the limestone has higher tensile strength as compared to gypsum, and thus the caves created in the limestone are stable due to the high tensile strength of the cave roof, but the caves created in gypsum are unstable due to the cave roof's low tensile strength. Caves are often formed along with the fractures. The results of the tests show that limestone has elastic and brittle behavior, and field observations also show that limestone has many fractures. Besides, tests results indicate that gypsum has plastic-elastic–plastic and ductility behavior. The brittle behavior of limestone and its frequent fractures is another factor that causes cave development in limestone. But if fractures are developed in gypsum, they are closed due to the plastic behavior. Another important factor in the stability of the cave roof is the diameter of the cave. As the diameter of the cave increases, the probability of the creation of fracture and collapse of the cave roof will increase as a result of the concentration of tension on the cave roof. In the present study, to investigate the effect of the cave diameter on its tensile strength, holes with 5, 10, and 20 mm diameter were created in test samples the tensile strength of which was measured using the Brazilian test (Fig. 9). To eliminate the effect of porosity on the results, this test was performed on more samples after which the average was taken. The results show that the tensile strength of the rock decreases with holes size increase. But the amount of tensile strength reduction is different in limestone and gypsum. The tensile strength of limestone type 1 with a 5 mm hole decreased about 10%, while with a 10 mm hole it decreased about 30%, and with a 20 mm hole the decrease was about 50%.

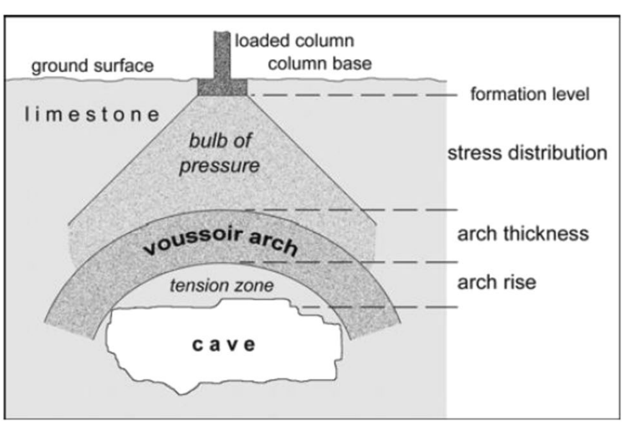


Fig. 8 Cave development mechanism (Tony et al. 2005)

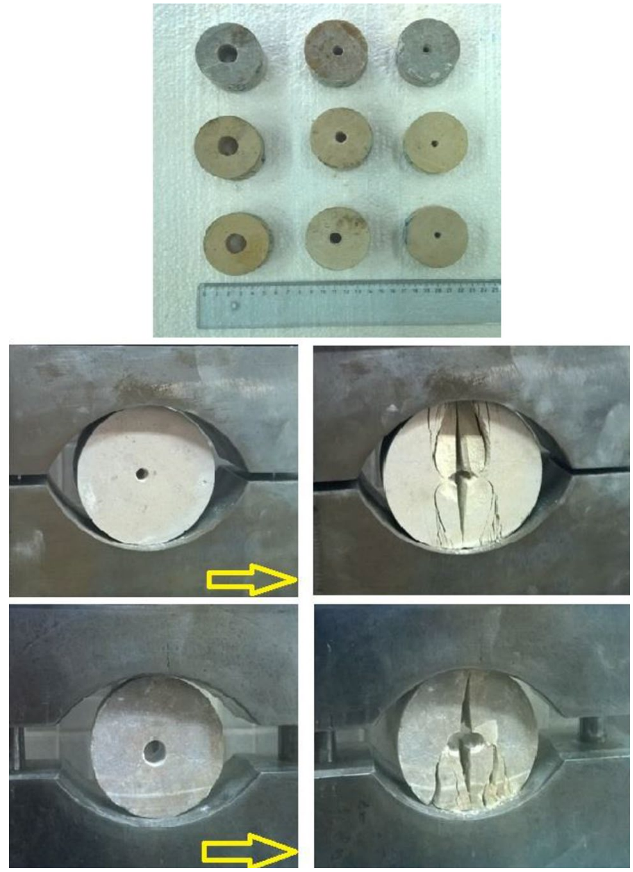


Fig. 9 Effect of the hole diameter on tensile strength in Brazilian test

Comparably, the tensile strength of porphyritic gypsum with a 5 mm hole also decreased about 20%, while with a 10 mm hole it decreased about 50%, and with a 20 mm hole the decrease was about 80%.

The sinkhole is another karst phenomenon with different development mechanism in limestone and gypsum. In the field study, more than 80 sinkholes were identified, the characteristics of which are shown in Table 2. Field observations show that collapse and cap rock sinkholes are formed in porphyritic gypsum, where some of them are 30 m in depth and 20 m in diameter (Fig. 10). In alabaster gypsum, sinkholes are found, while no-sinkhole were observed in limestone.

Sinkholes, particularly the collapse sinkholes and caprock collapse sinkholes, are often caused by failures occurring in underground caves (Parise and Lollino 2011). Collapse sinkhole occurs to a greater extent and at higher rates in gypsum than it does in limestone. This difference is primarily related to the greater solubility and lower mechanical strength of gypsum. These sinkholes, which have typically ellipsoid or circular aperture and vertical walls, are formed in planes and the vicinity of aquifers. The water existing in these aquifers leads to the dissolution of gypsum and dissolution cavity development in it. As time goes by and the

Table 2 The characteristics of some sinkholes in study area

UTM-N	UTM-E	Sinkhole type	Depth (m)	Diameter (m)
3497342	391780	Solution	2	4
3505885	387656	Cap rock	3	3
3496726	386028	Collapse	10	3
3499750	394146	Collapse	3	5
3504217	388086	Solution	2	4
3505732	387549	Solution	1.5	4
3509318	386325	Solution	3	7
3483474	405064	Solution	2	5
3477893	391102	Collapse	0.5	3
3468575	386513	Collapse	1	2
3473291	372722	Collapse	5	10
3474268	373447	Cap rock	2.5	6
3474178	372722	Collapse	0.5	2
3464330	383321	Collapse	1	3
3465934	383074	Cap rock	1	3
3474713	372263	Collapse	10	15
3465875	388440	Collapse	0.5	3
3469399	391845	Collapse	30	5
3469416	391834	Collapse	25	3
3465784	391938	Cap rock	5	12
3464990	392465	Cap rock	4	7

dissolution process prolongs, the cavities grow and create underground caves. Due to its lower compressive and tensile strength, gypsum cannot bear the overload of the upper layers and therefore collapses (Fig. 11a). These collapses, which are usually sudden, can be very dangerous. In comparison, because of its low dissolution, limestone dissolves at a slower rate than gypsum and does not collapse because of its higher strength, so it can serve as an underground cave (Fig. 11b). Hence, gypsum is unstable because of its low strength and higher dissolution, meaning that a larger number of sinkholes develop in them, whereas in limestone a larger number of caves develop due to their higher strength and, as a result, higher stability.

Karrens are small-scale dissolution cavities with a groove or channel-form geometry that are developed on the surface of limestone and gypsum (Waele et al. 2009). Karrens are the result of the chemical activity of water on rock (Milanovich 1981) and are the most frequent karst features in the karst area. The field studies show that karrens have a large variety in the Asmari Formation limestone types 1 and 2 as they are found in the pit, vuggy, groove, and channel forms (Fig. 12a, b). The width and length of some of these karrens are up to 20 cm and 100 cm, respectively. These features are very common on the surface of limestone and this is why they have developed a karren field in the study area. In comparison, karrens are also frequently on the surface of gypsum, but they are typically found as small cavities or grooves (Fig. 12c, d).

Karren is one of the karst phenomena with a development mechanism related to rock durability. The formation of karrens in the field implies rock durability against the weathering agents. As the slake durability results show, the durability of limestone is considerably higher than gypsum. After 15 wet and dry cycles of slake durability tests, slight variations were observed in limestone samples, while gypsum samples showed a change in their size and morphology. Due to its low durability, gypsum is easily eroded by rainfall water as a result of which karrens are developed on its surface. Due to this low durability, gypsum is easily washed out and the developed karrens are shallow. On the other hand, limestone is stable against the weathering agents and has higher durability meaning that the karrens developed on its surface are not eroded and are available as different morphologies.

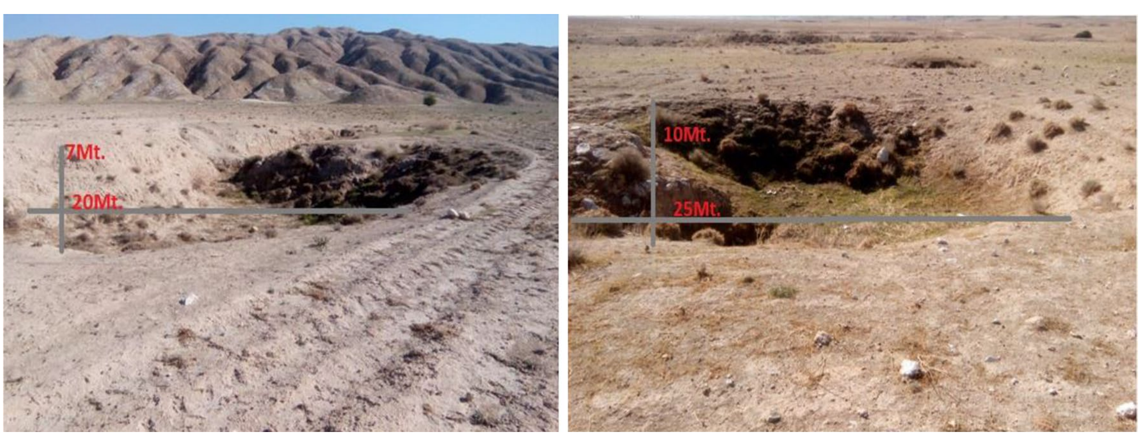


Fig. 10 Examples of sinkhole in gypsum of Gachsaran Formation (Mohammadian et al. (2019))

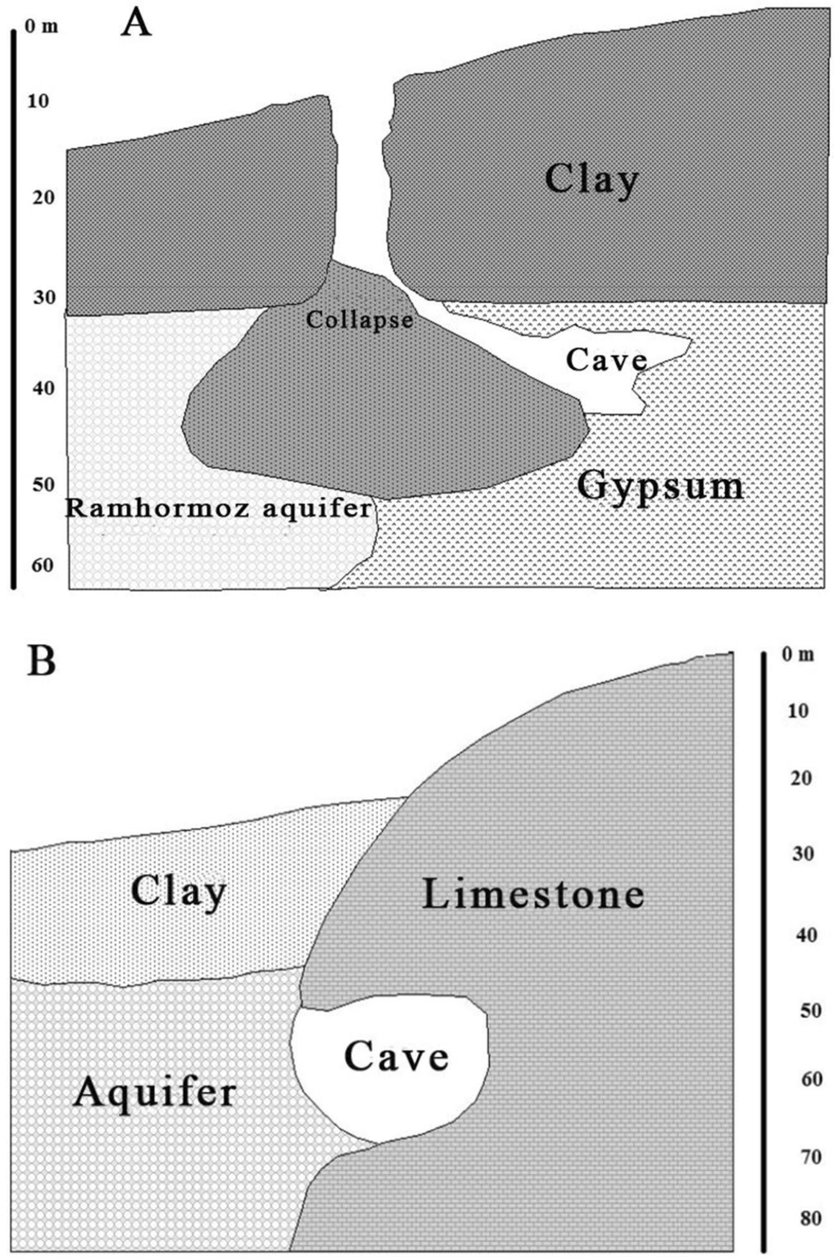


Fig. 11 **a** Formation mechanism of the sinkhole in gypsum of Gachsaran formation, **b** cave in limestone of Asmari formation

Conclusions

Despite the equal performance of the structural factors (such as faults and joints), climate, and the hydrology conditions of the study area, the development of karst features is different in the gypsums of the Gachsaran Formation and the limestone of the Asmari Formation. This difference is induced by the physical, chemical, and mechanical properties of these rocks. Based on the thin section studies, two texture types of gypsum were obtained: alabaster (fine-grain gypsum) and porphyritic (coarse-grain gypsum). Alabaster gypsums are outcrop in the west, while porphyritic gypsums are in the south and east of the study area, respectively. Based on the calcimetri test, four types of limestone were obtained based on calcite content. The field observation shows that type 1 and 2 are outcrop in the area where karstification has developed more and karstic phenomenon such as cave and karren is observed, while type 3 and 4 are outcrop in areas where karstification has developed less and karstic phenomenon is not observed. The results of tests revealed that gypsum has higher dissolution as compared to limestone. Moreover, slake durability of limestone after 15 wet and dry cycles are higher than gypsum.

Fig. 12 **a**, **b** Karrens in Asmari formation limestone (as large pit, vuggy, groove), **c**, **d** karrens in Gachsaran formation gypsum (as small cavity or groove)

The test results also show that the mechanical properties such as compressive and tensile strengths of limestone are higher as compared to the gypsum. The stress–strain curves for limestone and gypsum indicate elastic–plastic and plastic-elastic–plastic behaviors, respectively. The field and laboratory studies show that karst features such as cave and karren are abundant in types 1 and 2 limestone due to higher solubility, lower durability and higher strength than other types of limestone while collapse and cap rock sinkholes are abundant in porphyritic gypsum due to lower strength than alabaster gypsum.

Cavities are more stable in limestone than in gypsum due to higher compressive and tensile strengths and the lower level of dissolution in limestone. As a result, karst features are developed in the form of large caves in limestone. In comparison, the cavities are less stable and collapsed and create collapse and cap rock sinkholes with 30 m depth and 20 m diameter in gypsum because of its lower compressive and tensile strengths and higher dissolution. The elastic behavior of limestone results in the development of many joints in this rock that make it prone to cave formation. But gypsum is less jointed because of its plastic-elastic-plastic behavior. Based on the results of the slake durability test, limestone involves higher durability than gypsum. This higher durability results in its higher resistance to the weathering agent and, consequently, the development of stable karrens in it with various morphologies. In comparison, karrens developed on the gypsum surface are less stable and washed out due to their lower level of durability. The results of this study indicate that the main reason for the difference between the karst developed in limestone and gypsum in a specified area is the difference in their physical, dissolution, and mechanical properties. Based on the findings of this study, limestone and gypsum karst can be called “stable karst” and “unstable karst”, respectively.

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