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Geotechnical characteristics and empirical geo-engineering relations of the South Pars Zone marls, Iran

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Abstract. This paper evaluates the geotechnical and geo-engineering properties of the South Pars Zone (SPZ) marls in Assalouyeh, Iran. These marly beds mostly belong to the Aghajari and Mishan formations which entail the gray, cream, black, green, dark red and pink types. Marls can be observed as rock (soft rock) or soil. Marlstone outcrops show a relatively rapid change to soils in the presence of weathering. To geotechnically characterise the marls, field and laboratory experiments such as particle-size distribution, hydrometer, Atterberg limits, uniaxial compression, laboratory direct-shear, durability and carbonate content tests have been performed on soil and rock samples to investigate the physico-mechanical properties and behaviour of the SPZ marls in order to establish empirical relations between the geo-engineering features of the marls. Based on the experiments conducted on marly soils, the USCS classes of the marls is CL to CH which has a LL ranging from 32 to 57% and PL ranging from 18 to 27%. Mineralogical analyses of the samples revealed that the major clay minerals of the marls belong to the smectite or illite groups with low to moderate swelling activities. The geomechanical investigations revealed that the SPZ marls are classified as argillaceous lime, calcareous marl and marlstone (based on the carbonate content) which show variations in the geomechanical properties (i.e., with a cohesion ranging from 97 to 320 kPa and a friction angle ranging from 16 to 35 degrees). The results of the durability tests revealed that the degradation potential showed a wide variation from none to fully disintegrated. According to the results of the experiments, the studied marls have been classified as calcareous marl, marlstone and argillaceous lime due to the variations in the carbonate and clay contents. The results have shown that an increase in the carbonate content leads to a decrease in the degradation potential and an increase in the density and strength parameters such as durability and compressive strength. A comparison of the empirical relationships obtained from the regression analyses with similar studies revealed that the results obtained herein are reasonably reliable.

Keywords: Assalouyeh; marl; physio-mechanical properties; carbonate content; South Pars Zone

1. Introduction

In general, marls and marlstones consist of clay minerals and calcium carbonate in different ratios (Lamas *et al.* 2002) whereas the constituent parts of these geological formations are classified as weak materials. The index properties of the marls depend on the carbonate content and on the type and content of minerals in the clay fraction (El-Amrani Paaza *et al.* 1998, Jalali-Milani *et al.* 2017, Angin and İkizler 2018, Mebarki *et al.* 2019, Asghari-Kaljahi *et al.* 2019). These geo-materials show different behaviour under different saturation conditions (Athmania *et al.* 2010, Lei *et al.* 2018) which causes complications in the analyses of their engineering properties (Azarafza *et al.* 2015, 2018a). Due to the unpredictable and variable behaviour of marls, many foundations that were located on these geo-materials have faced diverse damages. Thus, a large volume of research has been carried out so far on the characterisation of marls in the different parts of the world (e.g., Ouhadi 1997, Mohamed 2000, Ouhadi and Yong 2003, Lamas *et al.* 2005, Athmania *et al.* 2010, Hooshmand *et al.* 2012). The main objectives of this study are to evaluate the physio-mechanical characteristics and to assess the relations between engineering attributes such as marl identification, marl behaviour, marl stability and the effect of the marl clay-carbonate content on the strength properties. Pettijohn (1983) mentioned that marl is a type of geo-material (soil or rock) which is generally composed of clay minerals and carbonate with various proportions that normally vary between 35% and 65%. Fookes and Higginbottom (1980) stated that marl is a simple binary mixture of true clay and calcium carbonate, while marlite or marlstone is an indurate equivalent. Akili (1981, 2008) defined marl as a binary mixture of calcium carbonate and clay minerals and commented that the characteristics of clays or marls depend on the percentage of the calcium carbonate and on the type and amount of clay minerals. Yong *et al.* (1996), Alber and Heiland (2001), Ayalew *et al.* (2009) and Azarafza *et al.* (2018a) mentioned that the geotechnical properties of these geo-materials vary with the amount and type of clay minerals which influence many of

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Fig. 1 A view of the marls of the Aghajari formation in the study area

their engineering properties. Geotechnical laboratory experiments are frequently used for marl behaviour characterisation. Experiments for the determination of the physical properties (ASTM C830), particle-size distribution (ASTM D422 and ASTM D1140), Atterberg limits (ASTM D4318), uniaxial compressive strength (ASTM D2166), shear strength (ASTM D3080), durability (ASTM D3744) and carbonate content determination (ASTM D4373) have appropriate results on the physio-mechanical characteristics of marls under different environmental conditions (Acar *et al.* 2007). In this regard, application of these geotechnical experiments helps to achieve the correct description regarding marl behaviour.

Marls or marly geo-materials are present in many parts of Iran, especially in southwest Iran. The South Pars Zone (SPZ), which is located in southwest Iran contains extensive marl outcrops that are substantially affected by the geo-engineering properties of the geological units and are involved with various construction activities and developments. For this reason, the study presented herein focuses on the physio-mechanical characteristics of the SPZ marls and on establishing relations between the characteristics and geo-engineering features of marls by mainly using geotechnical in-situ and laboratory experiments. According to the results of the field surveys, the SPZ marls are highly weathered and mostly belong to the Aghajari and Mishan formations which are the gray, cream, black, dark greeen and pink coloured types. Fig. 1 presents a view of an outcrop of the marls of the Aghajari formation in the study area.

2. Geological setting

The SPZ is located in southwest Iran and lies about 300 kilometres southeast of Bushehr City and in the narrow region of the foothills in the northern coast of the Persian Gulf (Fig. 2). This region has an approximate area of over 10,000 hectares, which is covered by different geological units from late Neo-Proterozoic (Hormuz series) to Quaternary deposits (recent alluviums). The formations older than Cenozoic (Asmari formation) are exposed in the core of Assalouyeh anticline where the SPZ region is mostly covered by the post-Asmari (Eocene-Oligocene) Mishan, Aghajari, Bakhtiari formations and alluvial deposits (Quaternary sediments). The studied units are related to the marly materials which represent parts of the Mishan formation (molasses, carbonate and siliciclastic facies deposited in a carbonate rimmed shelf and of gray marl and marlstone with clay layers, olive green to gray and sometimes red marls), Aghajari formation (fine, medium and coarse grained sediments, usually interpreted as channel deposits and alternating gray to brown calcareous sandstone, gray, dark green and pink to red marl with veins of gypsum, gray marls, green siltstone) with an age attributed to Miocene and Pliocene and alluvial deposits (Azarafza *et al.* 2017a,b). The geological map and a stratigraphical column of the SPZ area are presented in Figs. 3 and 4. As could be observed in Fig. 4, the Mishan and Aghajari formations are the main sources of the marls in the region. By field investigations performed on the SPZ marls, it is most likely that the tectonic movements have caused the displacement, folding and faulting of these geo-units and the SPZ is highly active in terms of seismic activities (Azarafza *et al.* 2018b). These tectonic and seismic activities have led to increased exposure to weathering that have directly affected the strength parameters due to the transformation of the marlstone (soft/weak rock) to marly soil in the region.

3. Geotechnical and geomechanical characterisation of the marls

Marl is one of the most complicated geo-materials with a complex geotechnical and geomechanical behaviour which is classified as weak rock or hard soil. In this study, the authors have determined the geotechnical and geomechanical characteristics of the SPZ marls at three stations. These stations are situated towards the beginning, middle and end of the Assalouyeh-Kangan highway (Fig. 5) where a total of 45 rock samples and 15 soil samples have been collected from the stations and transferred to the laboratory for relevant testing. Geotechnical assessments have been performed to determine the SPZ marl geotechnical characteristics and the physical and mechanical tests that have been conducted led to the identification and classification of the marls (rock and soil samples). These studies have been discussed separately as “Geotechnical soil (marl) testing” and “Geomechanical rock (marlstone) testing”, respectively. These conducted experiments led to evaluate the index and mechanical properties of the SPZ marls as illustrated in Table 1. Marl classification was performed according to the instructions recommended by Pettijohn (1983) to categorise carbonate sediments such as marls as presented in Table 2.

3.1 Geotechnical soil (marl) testing

In order to evaluate the geotechnical properties of the marly soils, 15 samples were taken from the SPZ region. Soil mechanics tests including particle-size distribution tests (ASTM D422 and ASTM D1140) and Atterberg limit (ASTM D4318) determinations were performed on these 15 samples.

The results of the particle-size distribution tests are presented in Fig. 6. According to these results, the fine

Fig. 2 Location of Assalouyeh and the study area on the satellite image (Google Earth)

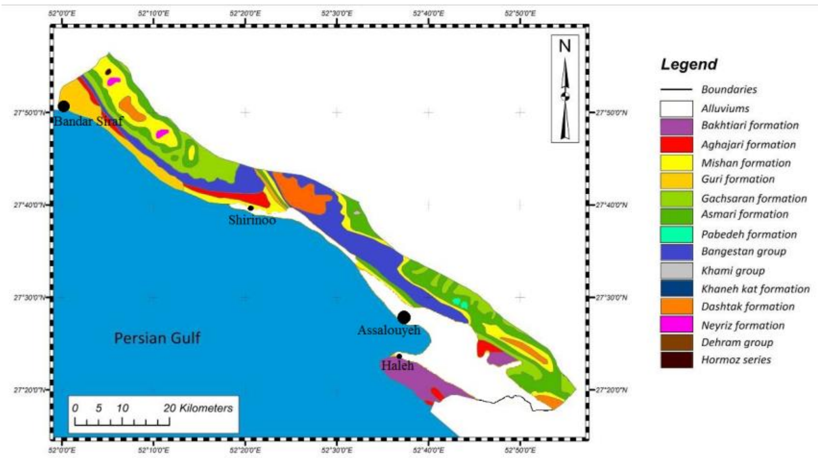


Fig. 3 Geological map of SPZ (Adapted from the Geological Survey of Iran 2009a)

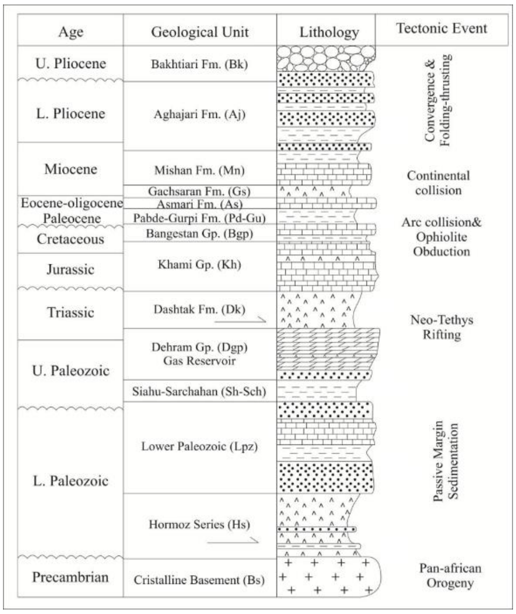


Fig. 4 Stratigraphical column of the SPZ region (Adapted from the Geological Survey of Iran 2009b)

material content (passing sieve #200) which is presented as clay content is 15 to 32% with a mean value of 23%. Since the behaviour of clay could greatly affect the geotechnical

Table 1 Index and mechanical properties of the SPZ marls

Parameter	Mean	Std. Dev.	Number of tests
Water content (%)	6.123	3.061	45
Specific gravity (G_s)	2.759	1.107	45
γ_t (kN/m^3)	22.97	1.130	45
γ_d (kN/m^3)	21.67	1.386	45
Porosity (%)	13.82	6.060	45
Liquid limit (%)	40.93	7.045	15
Plasticity limit (%)	17.73	4.527	15
Plasticity index (%)	23.20	4.723	15
Consistency index (%)	1.81	1.104	15
Activity number	0.73	1.037	15

Table 2 Classification of marls according to Pettijohn (1983)

Categories	Classification	Main ingredients (%)	
		Carbonate	Clay
Carbonate	Lime/Limestone	95-100	0-5
	Slightly argillaceous lime	85-95	5-15
	Argillaceous lime	75-85	15-25
Marl	Calcareous marl	65-75	25-35

Table 2 Continued

Categories	Classification	Main ingredients (%)	
		Carbonate	Clay
Marl	Marl/marlstone	35-65	35-65
	Argillaceous marl	25-35	65-75
Clay	Calcareous mud	15-25	75-85
	Slightly argillaceous mud	5-15	85-95
	Mudstone	0-5	95-100

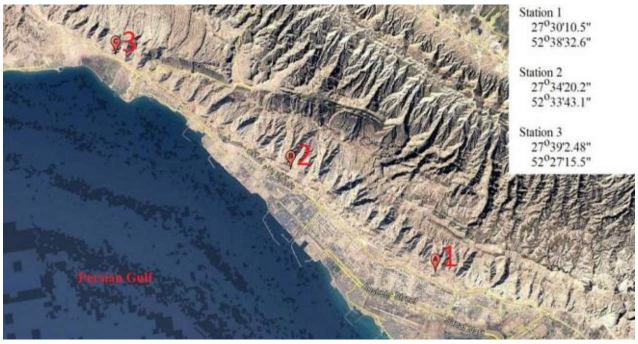


Fig. 5 Location of the sampling stations on the satellite image (Google Earth)

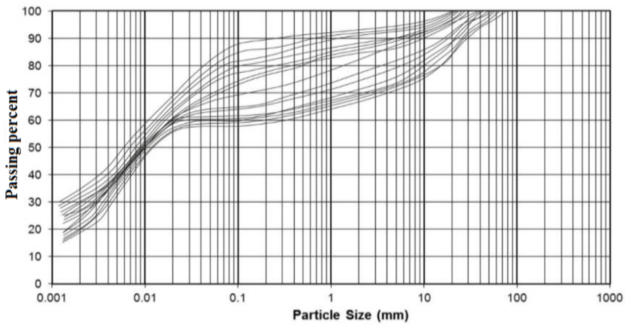


Fig. 6 The particle-size distribution and hydrometer test results of the SPZ marls

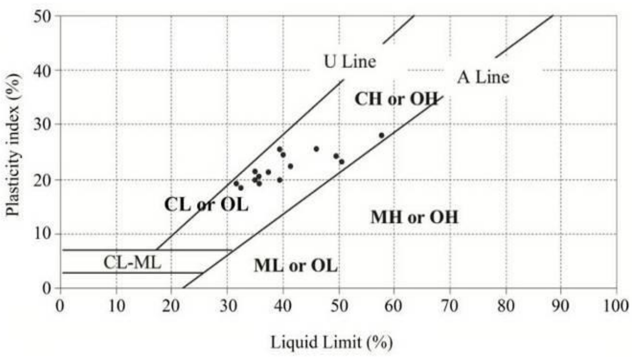


Fig. 7 The plasticity of the samples on the Casagrande chart

features of marls (Hunt 2006), geotechnical characterisation of the clay content is important. The Atterberg limit tests are presented in Fig. 7. According to these results, the marl classification falls in the CL to CH groups by the Unified Soil Classification System (USCS) where CL is clay with low plasticity and CH is clay with high plasticity. For the

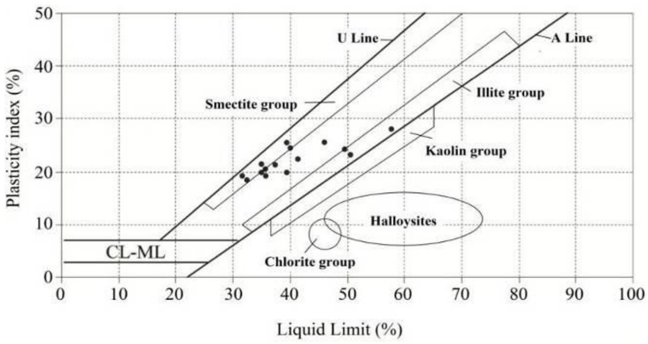


Fig. 8 Distribution of the marly soils and the clay minerals on the Holtz and Kovacs (1981) chart

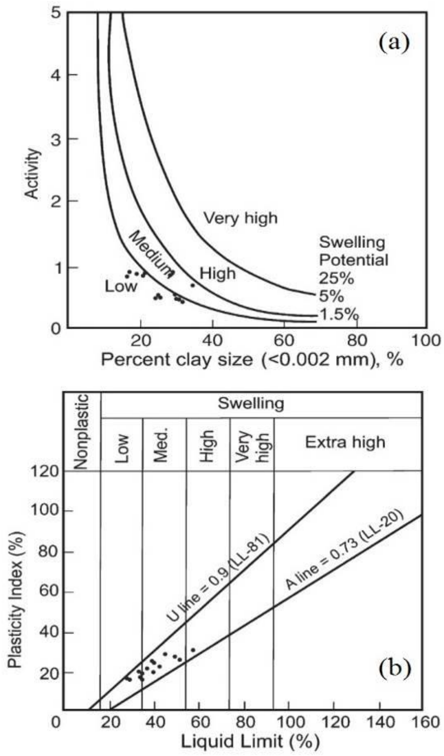


Fig. 9 SPZ marl activity according to: (a) Skempton chart and (b) Seed *et al.* chart (from Yilmaz 2006)

SPZ marls, the liquid limit (LL) ranged from 32 to 57%, and the plasticity limit (PL) ranged from 18 to 27%, depending on the silt and clay content of the samples. The results of the sieve analysis indicated that the samples were well sorted with considerable amount of fine grained soil which is expected to affect their geo-engineering properties. According to USCS, the clay is classified to range from CL to CH. Holtz and Kovacs (1981) have prepared a plasticity diagram and clay identification by the Atterberg limit range chart based on the clay group as presented in Fig. 8. By plotting the Atterberg limit results in Fig. 8, it can be observed that the major clay minerals of the studied marls belong to either the smectite (montmorillonite) or illite groups. The smectite group is classified as a soft phyllosilicate that precipitates from water solution as microscopic crystals. Since the individual crystals of the montmorillonite clay are not tightly bound, water can intervene and cause marly soils to swell. On the other hand,

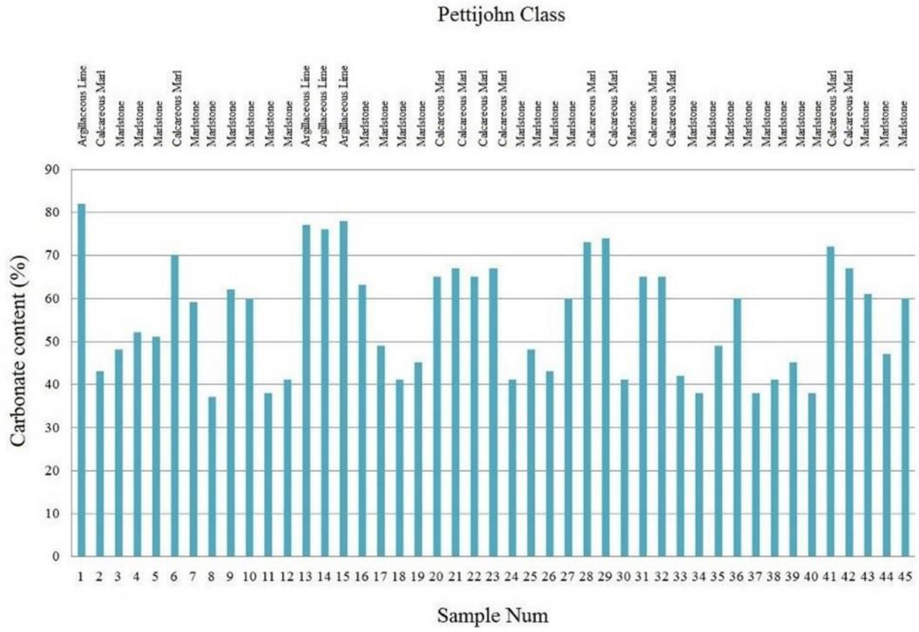
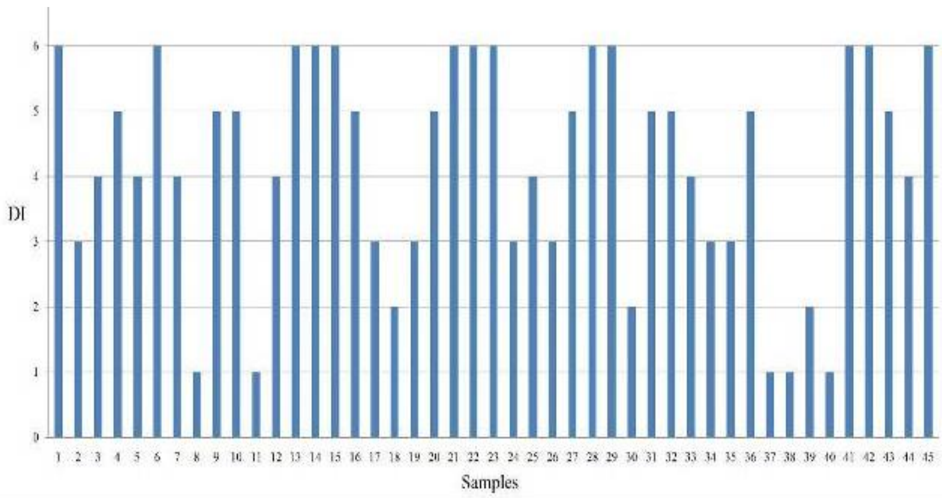


Fig. 10 Classification of the SPZ marls according to Pettijohn (1983)



Description	Turned into mud	Severe deterioration	High deterioration	Moderate deterioration	Low deterioration	No change
Deterioration index (DI)	I	II	III	IV	V	VI

Fig. 11 Durability test results and deterioration index (DI) of the SPZ marls

the water absorption activity of the illite group is much lower than that of the smectite group. However, when the clay type in the marls belongs to the smectite group, the clay mineral activity is very important to evaluate (Yilmaz 2006). Skempton (1953) has stated that the clay particles in soil have a direct impact on plasticity which linearly increases with the content of the clay-size fraction and is accounted for by the activity number (A_N) in an attempt to explain the importance of the clay fraction on the plasticity index. A_N is expressed as

$$A_N = \frac{PI}{\text{Percentage of clay, by weight}} \quad (1)$$

Consideration of the activity of the SPZ marls (Yilmaz 2006) reveals that marls show low to high activity which implies that the SPZ marls possess a wide range of sensitivity that ranges from sensitive to insensitive behavior (Fig. 9). According to these results, the SPZ marls are determined to possess low to moderate swelling activity. Table 4 presents the geotechnical properties of the marly soils which are geologically classified in 3 classes, namely, silty clay, stiff and hard marls. To estimate the mechanical properties of the marly soils, soil mechanics tests including uniaxial compression (ASTM D2166) and laboratory direct-shear (ASTM D3080) tests were conducted. As observed in Fig. 8, although most of the marly soil specimens belong to the smectite clay group with low plasticity that leads to low to moderate swelling potential, several cases show high swelling potential. This fact is confirmed by the Skempton

Table 3 The physical properties of the SPZ marls

Sample No.	Water abs. (%)	Porosity (%)	γ_d (kN/m^3)	γ_t (kN/m^3)	G_s	Carbonate content (%)
P1	0.79	2.01	25.25	25.45	2.63	82
P2	8.29	18.58	22.07	23.90	2.76	43
P3	7.97	17.23	21.22	22.91	2.61	48
P4	6.85	15.42	22.05	23.56	2.66	52
P5	10.23	21.27	20.43	22.52	2.65	51
P6	2.02	4.83	23.71	24.19	2.54	70
P7	9.89	20.87	20.71	22.76	2.67	59
P8	11.50	23.44	20.00	22.30	2.66	37
P9	6.85	15.11	22.04	23.55	2.65	62
P10	4.07	9.57	23.05	23.99	2.60	60
P11	11.00	23.16	20.67	22.94	2.94	38
P12	10.93	23.38	20.98	23.24	2.79	41
P13	1.87	4.76	25.10	25.57	2.69	77
P14	3.81	8.77	22.62	23.48	2.53	76
P15	3.33	7.62	22.39	23.14	2.47	78
P16	6.05	12.81	20.81	22.07	2.43	63
P17	4.80	10.59	21.69	22.73	2.47	49
P18	4.58	10.08	21.61	22.60	2.45	41
P19	4.75	10.53	21.45	22.47	2.44	45
P20	6.53	13.40	20.21	21.53	2.38	65
P21	4.14	23.44	21.25	22.13	2.45	67
P22	8.95	15.11	20.21	22.02	2.73	65
P23	3.60	9.57	23.04	23.87	2.65	67
P24	3.34	23.16	22.71	23.47	2.52	41
P25	8.56	23.38	22.06	23.95	2.22	48
P26	7.89	4.76	20.55	22.17	9.95	43
P27	5.19	8.77	21.23	22.33	2.39	60
P28	4.68	17.23	20.05	20.99	2.76	73
P29	2.20	15.42	25.11	25.66	2.85	74
P30	9.36	21.27	23.27	25.45	2.63	41
P31	4.17	10.58	21.78	22.69	2.66	65
P32	3.93	10.08	22.12	22.99	2.59	65
P33	9.67	10.53	20.98	23.01	2.41	42
P34	9.10	22.11	20.21	22.05	2.35	38
P35	7.88	15.52	20.05	21.63	2.55	49
P36	2.55	12.21	21.59	22.11	2.49	60
P37	6.14	12.12	20.66	21.93	2.92	38
P38	7.23	10.58	20.47	21.95	2.81	41
P39	6.27	10.08	20.39	21.67	2.67	45
P40	10.35	10.53	21.25	23.45	2.65	38
P41	2.33	7.43	23.51	24.06	2.85	72
P42	2.44	8.83	22.89	23.45	2.63	67
P43	3.97	15.36	20.40	21.21	2.35	61
P44	12.37	22.11	20.21	22.71	2.49	47
P45	3.12	8.56	21.44	22.11	2.58	60

Table 4 Geotechnical and geomechanical properties of the SPZ marls

Rock properties				*Soil properties*			
Sample No.	Description	c (kPa)	ϕ (deg.)	Sample No.	Description	c (kPa)	ϕ deg.)
P1	Argillaceous lime	320	35	S1	Silty clay (marly soil)	25	18
P2	Calcareous marl	100	25	S2	Silty clay (marly soil)	25	18
P3	Marlstone	130	30	S3	Silty clay (marly soil)	27	22
P4	Marlstone	150	32	S4	Silty clay (marly soil)	27	22
P5	Marlstone	130	19	S5	Stiff marl	45	28
P6	Calcareous marl	260	33	S6	Stiff marl	47	28
P7	Marlstone	120	30	S7	Stiff marl	43	28
P8	Marlstone	100	25	S8	Stiff marl	45	25
P9	Marlstone	130	17	S9	Stiff marl	47	28
P10	Marlstone	210	29	S10	Stiff marl	45	22
P11	Marlstone	150	30	S11	Hard marl	75	26
P12	Marlstone	110	16	S12	Hard marl	75	26
P13	Argillaceous lime	250	30	S13	Hard marl	73	26
P14	Argillaceous lime	100	25	S14	Hard marl	75	26
P15	Argillaceous lime	130	25	S15	Hard marl	70	26
P16	Marlstone	170	32				
P17	Marlstone	220	28				
P18	Marlstone	220	30				
P19	Marlstone	100	25				
P20	Calcareous marl	220	30				
P21	Calcareous marl	170	30				
P22	Calcareous marl	220	25				
P23	Calcareous marl	170	28				
P24	Marlstone	150	28				
P25	Marlstone	210	30				
P26	Marlstone	200	33				
P27	Marlstone	180	30				
P28	Calcareous marl	210	25				
P29	Calcareous marl	190	25				
P30	Marlstone	100	25				
P31	Calcareous marl	230	32				
P32	Calcareous marl	210	30				
P33	Marlstone	150	27				
P34	Marlstone	110	25				
P35	Marlstone	100	25				
P36	Marlstone	170	30				
P37	Marlstone	97	22				
P38	Marlstone	130	25				
P39	Marlstone	120	30				
P40	Marlstone	97	25				
P41	Calcareous marl	260	30				
P42	Calcareous marl	210	27				
P43	Marlstone	130	25				
P44	Marlstone	100	27				
P45	Marlstone	200	30				

and Seed charts as quoted by Yilmaz (2006).

3.2 Geomechanical rock (marlstone) testing

For the geomechanical evaluation of marly rock masses (marlstones), 45 rock specimens were taken from the Aghajari and Mishan formations in the SPZ region and subjected to carbonate content determination (ASTM D4373), uniaxial compressive strength testing (ASTM D7012), laboratory direct-shear testing (ASTM D5607) and durability assessment (ASTM D3744). By using the results of the carbonate content tests (ASTM D4373), the SPZ marls were classified as argillaceous lime, calcareous marl and marlstone which are illustrated in Fig. 10. This classification is performed based on the marl classification system of Pettijohn (1983) that is presented in Table 2. According to the results of this classification, it can be stated that the main marl group of the SPZ includes marlstone (carbonate content is 35-65%), calcareous marl (carbonate content is 65-75%) and argillaceous lime (carbonate content is 75-85%). Since variations in the carbonate content leads to variations in the physical and mechanical properties of the marls, physical tests (ASTM C830) were conducted to determine the physical properties of the SPZ marls (Table 3). Based on the laboratory test results, the physical properties of the samples seemed to be quite variable that are most probably related to the complex geological background of the SPZ region (Aghanabati 2004).

The geomechanical properties of the SPZ marlstones had a direct relation with the mechanical characteristics of these materials. For this purpose, geomechanical tests entailing uniaxial compression (ASTM D7012), laboratory direct-shear (ASTM D5607) and durability (ASTM D3744) have been performed. The results of these tests are presented in Figs. 11, 12 and Table 4. Figure 11 indicates that the marlstones are classified in six deterioration classes (where, I is the worst case and VI is best case; ASTM D3744). For the estimation of the deterioration index (DI), the durability tests were conducted on specimens in 4 cycles (I_1, I_2, I_3, I_4) followed by observing the sample conditions in the water tank that are classified in 6 classes as presented by Fig. 11. To this end, if the specimen is still durable after 4 cycles, this type of marl is deemed to possess a lower potential for deterioration and is categorised as class IV. On the other hand, if the specimen has turned into mud (i.e., has fully disintegrated) then it is categorised as class I. Hence, if the specimens in the cycles are less damaged, then they are deemed more resistant in real weathering conditions. As can be observed in Fig. 11, the results show a wide variation but in general, an increase in DI leads to a decrease in the swelling potential. Six samples were classified as I and twelve samples were classified as VI. The other specimens were determined to lie in the middle classes.

Table 4 presents the results of the mechanical features of the SPZ marlstones which show variable results. For example, the cohesion and friction angle show variations in the range of 97-320 kPa and 16-35 degrees, respectively. This variation in the SPZ marl strength parameters and mechanical characteristics is most probably related to the environmental (e.g., weathering, climatic status, distance to the sea) and geo-structural conditions (e.g., tectonics, structural failures, man-made activities, land-use type) in the region.

4. Relationships between marl characteristics and geo-engineering properties

In order to estimate the relationships between the geo-materials empirical variables, regression analysis is generally used (Draper and Smith 1998). Regression analysis is especially effective to understand how the dependent variable values change by changing each independent variable while the other independent variables are kept constant (Draper and Smith 1998). In the regression analysis, determining the dependent variable dispersion around the regression function is considered which can be explained by probability distribution functions (Fox 2015). The regression analysis includes various linear or nonlinear analytical methods which are used for different circumstances. Ordinary least squares (OLS) is a type of linear least squares regression method for estimating the unknown parameters in a linear regression model. OLS chooses the linear function parameters of explanatory variable sets by the least squares principle for minimising the squares differences sum between the obtained dependent variable (predicted variable values) in the given data-set and the prediction by application of linear functions (Seber and Lee 2003).

When the data shows a wide distribution, using the OLS can be effective in reducing the error rate of data regression implementation. As seen in the results of the SPZ marls testing results, the index characteristics are mainly scattered which indicates that the OLS regression can be appropriate for the marl geomechanical behaviour predictions. In this regard, the estimated parameters have been linked with the geotechnical properties. The results of the regression analysis for the geotechnical properties are presented in Figs. 12 to 22. Figs. 23 to 26 illustrate the variation of the index properties with the strength parameters. According to these results, an increase in the carbonate content leads to a decrease in the absorbed water, degradation potential and an increase in the dry and total density, strength parameters and geo-engineering features such as durability and compressive strength. According to the results of the regression analyses of the SPZ marls, the empirical relations between the physico-mechanical properties and geo-engineering features are presented as follows

$$Water\ Abs.(\%) = -0.2\,CC + 15.2 \qquad R^2=0.639 \tag{2}$$

$$\gamma_d\,(\mathrm{kN/m^3}) = 0.10CC + 18.5 \qquad R^2=0.994 \tag{3}$$

$$\gamma_t = CC + 21.7 \qquad R^2=0.951 \tag{4}$$

$$UCS\,(MPa) = 0.3\,CC + 11.7 \qquad R^2=0.969 \tag{5}$$

$$c\,(kPa) = 2.5\,CC + 26 \qquad R^2=0.935 \tag{6}$$

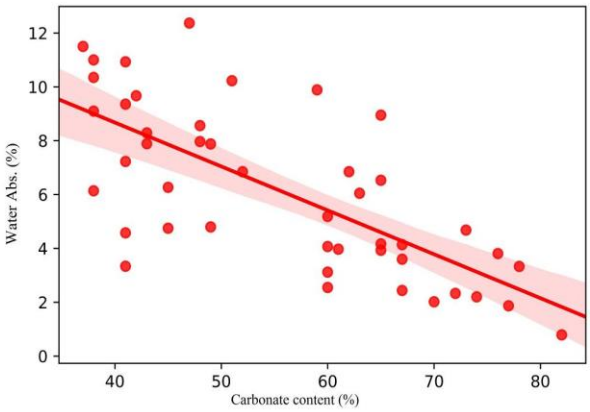


Fig. 12 Relationship between water absorption variation and carbonate content

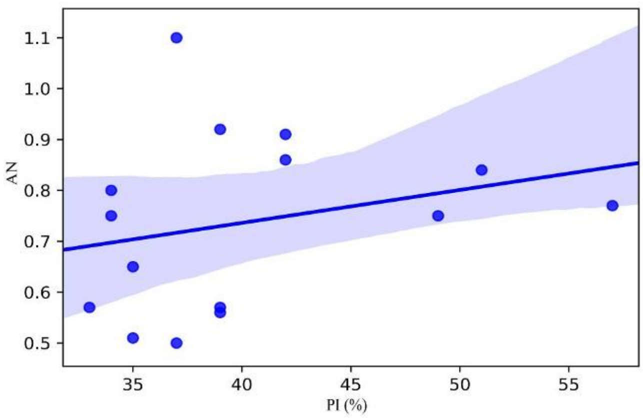


Fig. 16 Soil activity number versus plasticity index

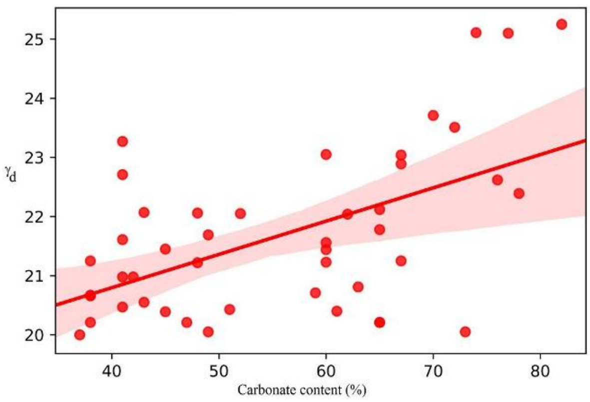


Fig. 13 γ_d (kN/m^3) variation versus carbonate content

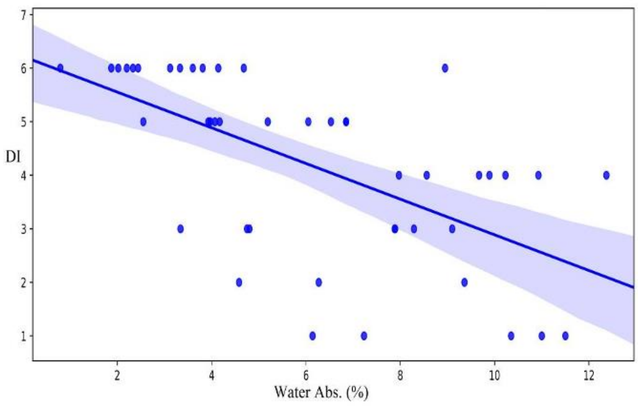


Fig. 17 Deterioration index versus water absorption

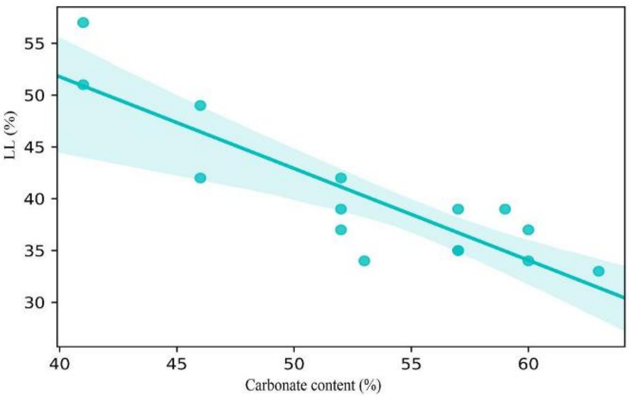


Fig. 14 Liquid limit versus carbonate content

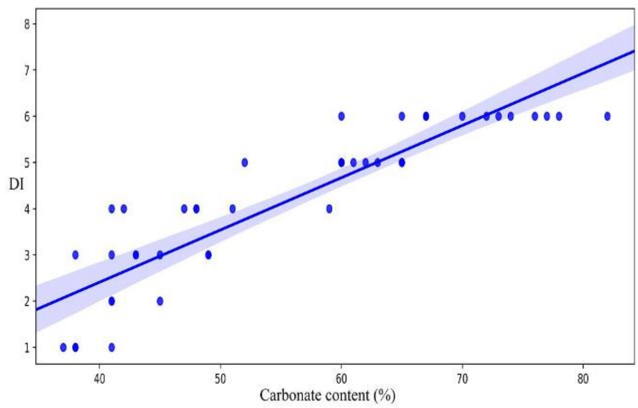


Fig. 18 Deterioration index versus carbonate content

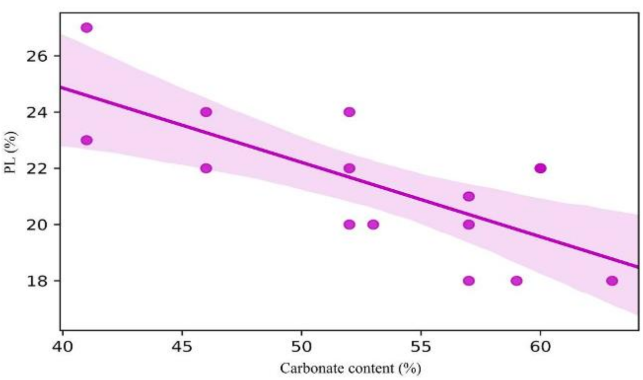


Fig. 15 Plasticity limit versus carbonate content

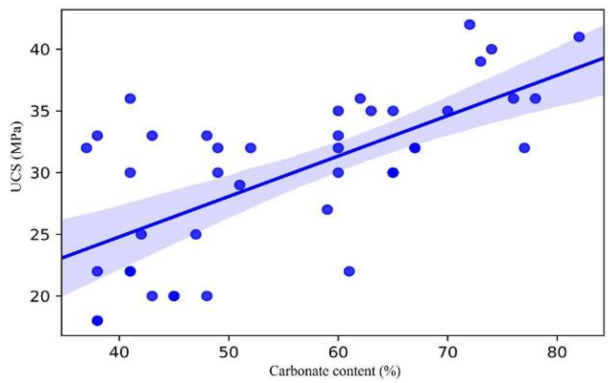


Fig. 19 UCS versus carbonate content

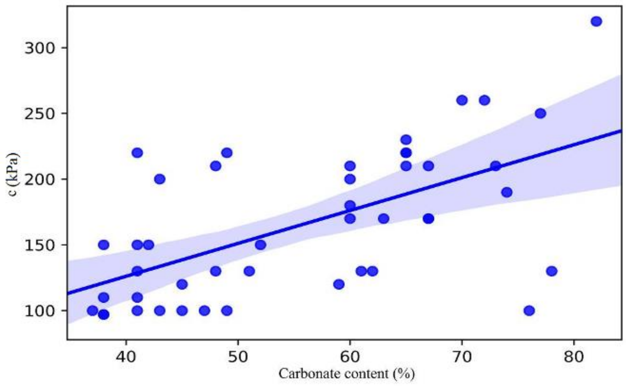


Fig. 20 Cohesion versus carbonate content

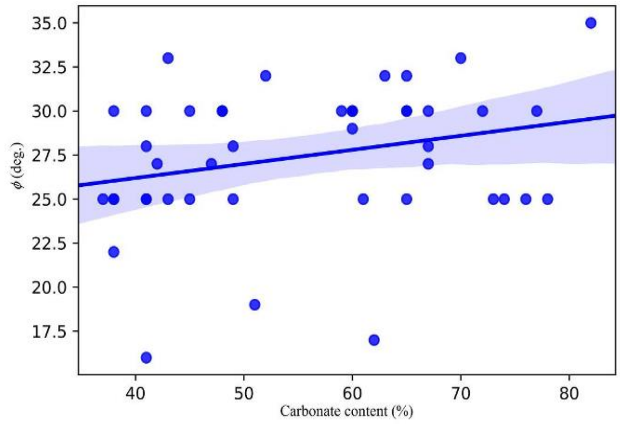


Fig. 21 Friction angle versus carbonate content

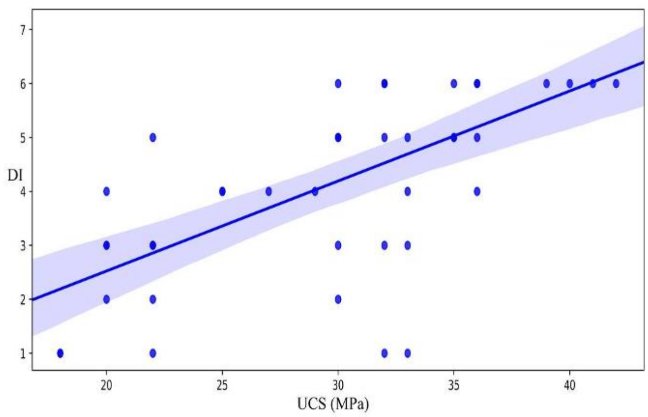


Fig. 22 Deterioration index versus UCS

Table 5 Empirical equations representing the geo-engineering properties of marls according to carbonate content (CC)

Reference	Empirical relationship	R^2
El-Amrani Paaza *et al.* (2000)	ϕ (deg.) = 0.114 CC + 20.2	0.259
Lamas *et al.* (2002)	LL (%) = -0.51 CC + 71	0.894
Lamas *et al.* (2002)	PL (%) = -0.27 CC + 34	0.644
Lamas *et al.* (2002)	c (kPa) = 1807.4 $CC^{-1.748}$	0.736
Atalar and Das (2004)	LL (%) = -0.62 CC + 52	0.442
	PL (%) = -0.72 CC + 43	0.599

Table 5 Continued

Reference	Empirical relationship	R^2
Atalar and Das (2009)	c (kPa) = 11.2 CC + 82	0.348
	ϕ (deg.) = 0.28 CC + 16.6	0.309
	LL (%) = -0.20 CC + 15	0.480
	PL (%) = -0.971 CC+ 8.4	0.394
Ioanna *et al.* (2009)	UCS (MPa) = 0.6CC + 22.4	0.370
Jung *et al.* (2011)	PI (%) = -0.40 CC + 34	0.540
	LL (%) = -0.45 CC + 64	0.345
	PL (%) = -0.16 CC + 34	0.360
Grønbech *et al.* (2015)	PI (%) = -2.24 CC + 242	-
El-Howayek *et al.* (2015)	ω (%) = -0.78 CC + 17.5	0.664
	LL (%) = -0.74 CC + 23	0.625
	PL (%) = -0.47 CC + 6.5	0.607

Table 6 Comparisons of the results obtained herein with those of previous researchers

Reference	Geo-engineering indices				No. of tests
	c (kPa)	ϕ (deg.)	PI (%)	CC (%)	
El-Amrani Paaza *et al.* (1998)	3-107	4-44	1-40	2-86	171
El-Amrani Paaza *et al.* (2000)	-	7-35	2-52	8-71	33
Lamas *et al.* (2002)	1-4.6	15-35	15-35	32-73	32
Atalar and Das (2004)	60-130	12-31	13-69	15-40	30
Atalar and Das (2009)	52-130	6.5-66	24-79	23-48	33
Ioanna *et al.* (2009)	-	-	6-25	43-85	30
Jung *et al.* (2011)	-	-	8-43	6-73	30
Grønbech *et al.* (2015)			97-300	2-68	250
El-Howayek *et al.* (2015)	-	-	20-41	33-63	14
This study	25-320	16-35	16-27	37-82	60

$$\phi\ (\text{deg.}) = 0.1\ CC + 23 \qquad R^2=0.945 \qquad (7)$$

$$LL\ (\%) = -0.9\ CC + 87 \qquad R^2=0.922 \qquad (8)$$

$$PL\ (\%) = -0.3\ CC + 35 \qquad R^2=0.952 \qquad (9)$$

$$A_N = PL\,(\%) + 0.5 \qquad R^2=0.920 \qquad (10)$$

$$DI = -0.3 W_{abs}\,(\%) + 6.2 \qquad R^2=0.538 \qquad (11)$$

$$DI = 0.1 CC - 2.1 \qquad R^2=0.961 \qquad (12)$$

$$DI = 0.2 UCS\,(MPa) - 0.8 \qquad R^2=0.918 \qquad (13)$$

Note: CC in the above relations is calcium carbonate content in terms of percentage.

In order to evaluate the obtained regression equations in this study, comparative assessments were conducted

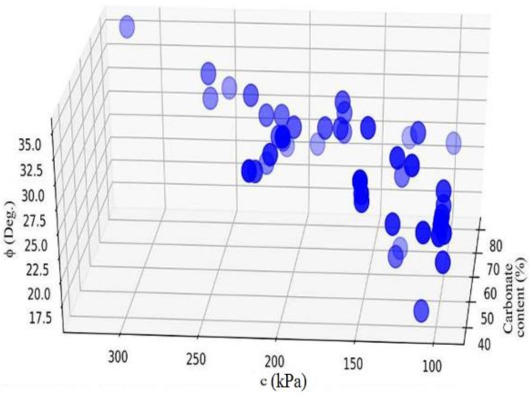


Fig. 23 Strength parameter variations of the SPZ marlstones

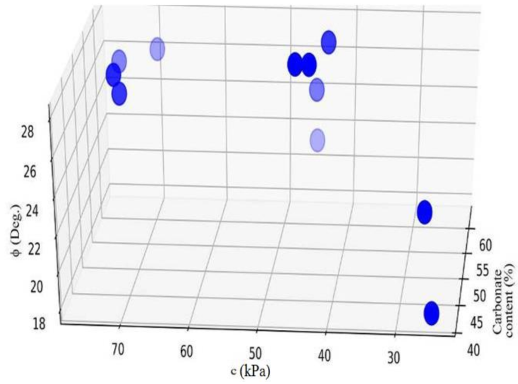


Fig. 24 Strength parameter variations of the SPZ marly soils

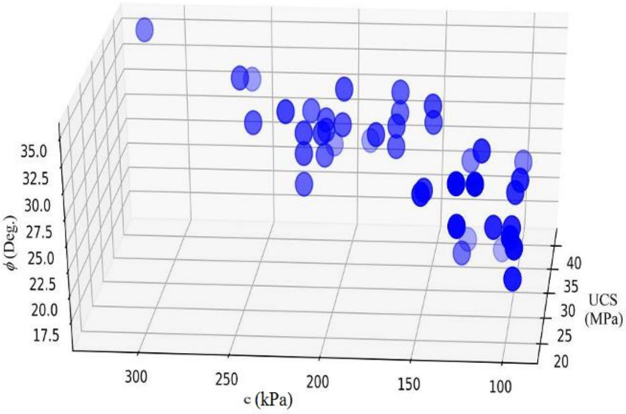


Fig. 25 Strength parameter variations of the SPZ marly soils

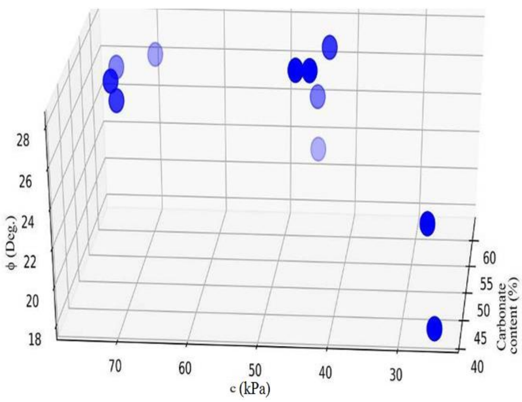


Fig. 26 Deterioration index vs. strength parameters of the SPZ marls

between the results of the tests from the SPZ and other equations proposed by other researchers who work on both marly soils and marlstones based on conducting geotechnical and geomechanical tests (Table 5). Table 6 illustrates a comparison of the obtained empirical relationships herein with the results obtained by other researchers.

The presented comparisons show that a similar trend of physico-mechanical properties/geo-engineering features has been obtained with the following interpretations:

-An increase in calcium carbonate content leads to a decrease in the plasticity index,

-The shear strength parameters of marls (cohesion and internal friction angle) are directly proportional to the carbonate content. On the contrary, an increase in the clay content leads to a decrease in the shear strength properties,

-The physical characteristics of marls improve with increasing carbonate content and with decreasing clay content,

-The uniaxial compressive strength (UCS) of the marls increases with increasing carbonate content which is related to the engineering classification of rock or soil materials. UCS decreases with increasing clay content,

-With increasing carbonate content, the clay content of marls decreases (Table 2), so the water absorption in marls which is more dependent on clay fraction and clay absorption mostly decreases,

-No specific trend of specific gravity with carbonate content has been observed.

5. Conclusions

Marls are classified as weak geo-materials with highly variable engineering behaviour which range from soils to rocks. The mechanical behaviour of the marls is controlled by the presence of clay minerals and carbonate content where an increase in the carbonate content improves the mechanical property of marls. In this study, the physico-mechanical characteristics of the SPZ marls have been determined by physical tests along with carbonate content tests, uniaxial compression, laboratory direct-shear, and durability tests. Geologically, the SPZ region has witnessed extensive tectonical events, which has led to the deformation of the geological units. The SPZ marls consist of clay minerals and calcium carbonate in different ratios and are classified as argillaceous lime, calcareous marl and marlstone. The swelling potential of the SPZ marls is generally classified to range from low to moderate and CL to CH according to USCS. For the SPZ marls, the LL ranges from 32 to 57%, and the PL ranges from 18 to 27% depending on the silt and clay content of the samples. Geomechanical rock testing results indicate a wide range in the physico-mechanical properties where the cohesion ranges from 97 to 320 kPa, the friction angle ranges from 16 to 35 degrees and the deterioration class ranges from I to IV. Also, by application of Ordinary Least Squares (OLS) regression to the scattered empirical data, it was evident that with increased carbonate content, the absorbed water and degradation potential decreased and the density, strength parameters and geo-engineering features such as durability, compressive strength were improved. These variations have been presented as empirical relationships for the marls of the SPZ region.

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