Engineering aspects of limestone weathering in Istanbul, Turkey

A. Tugrul · I.H. Zarif

Abstract Devonian limestones are widespread in the eastern part of Istanbul, Turkey. To assess the influence of weathering on the geological and geomechanical characteristics of these rocks, research was carried out on some profiles from the study area. Field observations show that the weathering has been rapid and the bedrock has been weathered to a depth of up to 8 m. A model for the weathering of limestones is established and modifications proposed to the material and mass weathering schemes for characterisation of the limestone for engineering uses, as both foundation and construction material. The paper also presents the results of field and laboratory investigations, including weathering characteristics and physical and mechanical properties. Interrelationships were determined for all test results. It is concluded that chemical characteristics and the porosity are good indicators of weathering.

Résumé Les calcaires Dévoniens sont largement représentés dans la partie est d'Istanbul (Turquie). Pour évaluer l'influence de l'altération sur les caractéristiques géologiques et géomécaniques de ces roches, une étude a été réalisée sur quelques profils d'une zone test. Les observations de terrain montrent que l'altération est rapide et la roche altérée jusqu'à huit mètres de profondeur. Dans cet article, un modèle d'altération des calcaires est présenté et sont proposées des modifications aux chartes de caractérisation de l'altération des matériaux et des masses rocheuses, pour leur usage comme matériau de fondation ou de construction. L'article présente aussi les résultats de travaux de terrain et de laboratoire, comprenant des paramètres d'altération et des propriétés physiques et mécaniques. Des corrélations ont été déterminées pour tous les résultats d'essais. On conclut que des caractéristiques chimiques et la porosité sont de bons indicateurs de l'altération.

Key words Engineering properties · Index tests · Limestone · Weathering

Mots clés Propriétés géotechniques · Tests de caractérisation · Calcaire · Altération météorique

Introduction

Weathered limestones are common in many parts of Istanbul, northwestern Turkey, and many engineering structures have been constructed or will be constructed on top of these rocks. However, the effect of weathering on the geological and geomechanical properties of this type of rock is not well known. Many authors (Jennings 1966; Sowers and Sowers 1970; Deere and Patton 1971; Fookes and Hawkins 1988; Chowdhury et al. 1990) have investigated the effects of weathering on the engineering properties of limestone. As a foundation material, limestone differs from other rocks in that voids may be found at almost any depth within the rock mass. They may result directly from solution weathering near the surface and along discontinuities, or as specific cave systems at depths related to present or past ground water levels (Fookes and Hawkins 1988).

This paper reviews the processes involved in the weathering by solution of the Devonian limestones. Studies were carried out in Kartal Quarry, Istanbul (Fig. 1). The depth of the quarry is 80 m. Thus, changes in the limestone from the surface were easily observed. During field studies, block samples were taken of limestones of different compositions and weathering states. Firstly, mineralogical, textural and chemical characteristics of the limestones were determined. Chemical and X-ray diffraction analyses were used to establish the rock mass chemistry and the nature of the insoluble residue. Experimental studies were then conducted on the same samples. At the end of the laboratory studies, specific gravity, dry and saturated unit

Received: 10 July 1999 · Accepted: 17 September 1999

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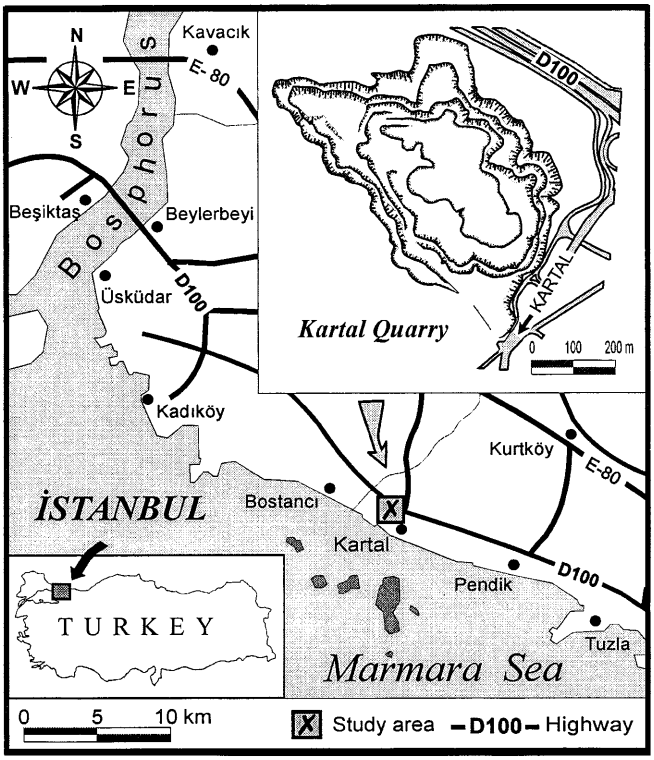


Fig. 1
Location map of Kartal Quarry

weight, water absorption, effective and total porosity, P-wave velocity, point load strength index, uniaxial compressive strength, indirect tensile strength and modulus of elasticity of the limestones of different composition and under different weathering states were determined.

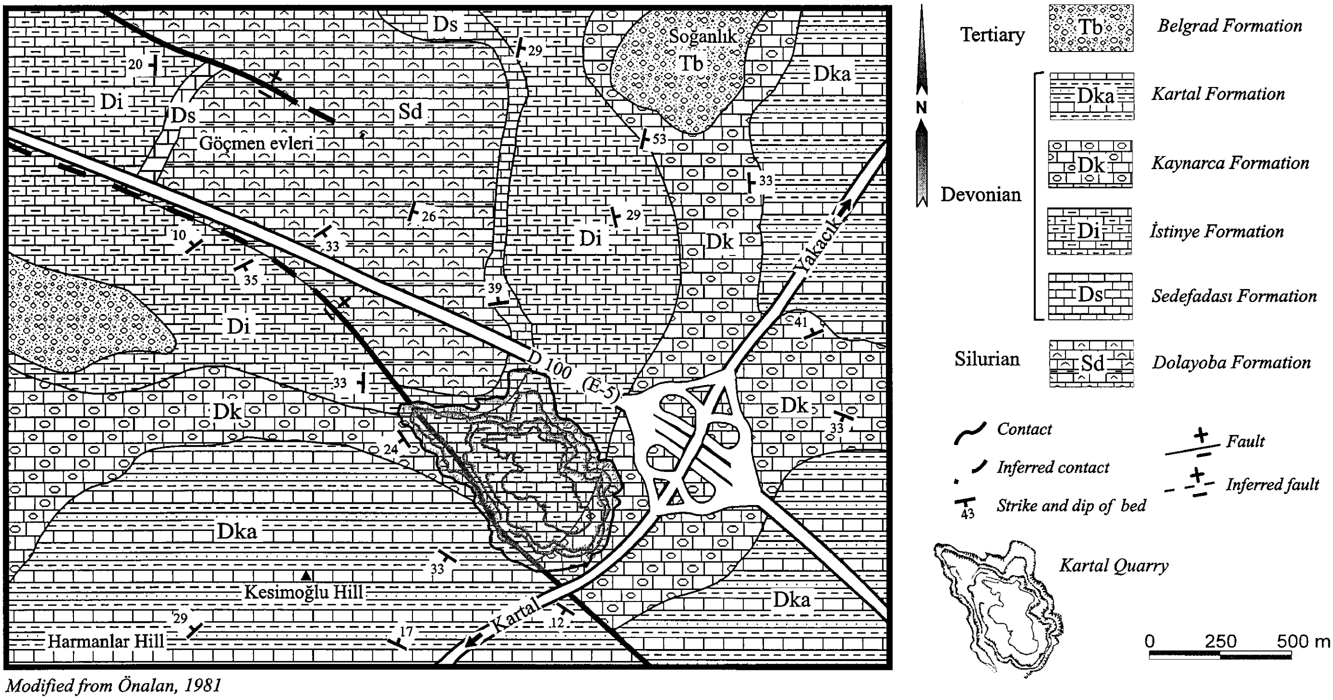
Geology

Limestones of Devonian age are widespread in the eastern part of Istanbul (Fig. 2). Önalan (1981) published his classic paper on the paleontological and stratigraphical subdivisions of the Devonian limestones. He appreciated the different types of carbonate rocks. The oldest rock stratum in the quarry is of the Lower Devonian-aged Sedefadasi formation. The formation comprises dark blue-grey coloured, thin-bedded clayey and silty limestones. This formation is conformably overlain by the Istinye formation. The Istinye formation consists of black-blue-coloured sparitic limestone. The Istinye formation is conformably overlain by the Kaynarca formation. This formation consists of dark grey-blue coloured lump limestones. The Kartal formation conformably locates at the top of the Kaynarca formation. This formation comprises brown coloured clayey shale and sandstone intercalated with limestone.
The limestones are affected by faulting. The NW-SE-trending faults are major structural features in the area. Usually, three or four clearly defined major sets of joints are found in the limestones. The strike of the joints is almost NW-SE and NE-SW. Minor sets or random joints also occur in the study area.

Geography

The studied area is in northwestern Turkey. The area has irregular land morphology depending on the lithology and

Fig. 2
Geological map of studied area



Modified from Önalan, 1981

tectonics of the region. The limestone generally forms the highest, sharper peaks with deeply dissected slopes in the hilly terrain. Rock outcrops are common on the upper slopes. Weathering products cover the lower slopes. Peaks around the region are generally NW-SE trending. The climate is an east Mediterranean one. In the region, the summer is hot and humid and the winter is mild and wet. Precipitation occurs mostly in the form of rainfall, intensifying in the autumn and winter. The average temperature is 13.9 °C. Annual rainfall at the Istanbul (Kartal) observation post is 630 mm. Annually, the actual amount of evapotranspiration for Istanbul is 564.6 mm.

Weathering of limestone

The two most important chemical processes operating in the humid and marine environment of Istanbul are oxidation and solution. The brownish-red and yellow colours of weathering products are produced by oxidation. The solution of limestones depends upon many environmental factors such as rainfall, temperature and vegetation. Increased jointing and decreased thickness of beds appear to increase the solution of rock in their vicinity (Sowers and Sowers 1970; Deere and Patton 1971; Fookes and Hawkins 1988; Konecka-Betley and Langier-Kuzniarowa 1989). The rate at which weathering proceeds depends not only upon the vigour of the weathering agent but also on the durability of the rock mass concerned. This, in turn, is governed by the percentage of impurities, texture and porosity of the rock on the one hand and the incidence of discontinuities within the rock mass on the other (Bell 1983; Fookes and Hawkins 1988). On the basis of micromorphological examination, Konecka-Betley and Langier-Kuzniarowa (1989) determined no influence of the age of parent limestones on the kind of weathering material.

Devonian limestones contain relatively small non-carbonate admixtures and they become saturated with water slowly, to a minor degree and with difficulty. A long time is necessary for the origin of a non-carbonate layer thick enough for the development of a soil profile (Konecka-Betley and Langier-Kuzniarowa 1989; Legros 1992).

The weathering process

The weathering of limestones is a very complicated process, despite the many publications concerning this problem, because the weathering processes are controlled by a variety of factors (Durand and Dutil 1972; Bell 1983; Blyth and de Freitas 1984; Konecka-Betley and Langier-Kuzniarowa 1989).

Weathering processes distinguish between the evolution of limestones and the soils arising from them. Texture and structure are very important factors influencing the evolution of limestones because they control their porosity. Durand and Dutil (1972) indicated that hard limestone mainly undergoes chemical weathering and dissolution. That is because non-carbonate admixture occurs between the crystals, preventing mechanical disintegration. The dissolution of carbonates increases as the non-carbonate particles decrease.

In the study area, chemical weathering is much more significant than physical weathering. Chemical weathering leads to dissolution of the limestones. The degree and rate of weathering in humid regions depend primarily on the temperature and amount of moisture. The rate of solution generally depends on the stability and specific solution rate constant of the mineral concerned, the degree of saturation of the solvent, the area presented to the solvent and the motion of the solvent (Bell 1993). Chemical weathering also aids rock disintegration by weakening the fabric and by emphasizing structural weaknesses, however slight (Bell 1993).

The presence of moisture hastens the rate tremendously, first, because water is itself an effective agent of weathering and, second, because it holds in solution substances that react with the component minerals of rock-carbon dioxide being especially important in the case of limestone (Bell 1993). Blyth and de Freitas (1984) indicated that the speed and severity of weathering in wet climates depend essentially upon the activity of the root zone, i.e. the rate of growth of vegetation and production of CO_2 in the root zone, and the frequency with which percolating rainwater can flush weathered constituents from the weathering profile.

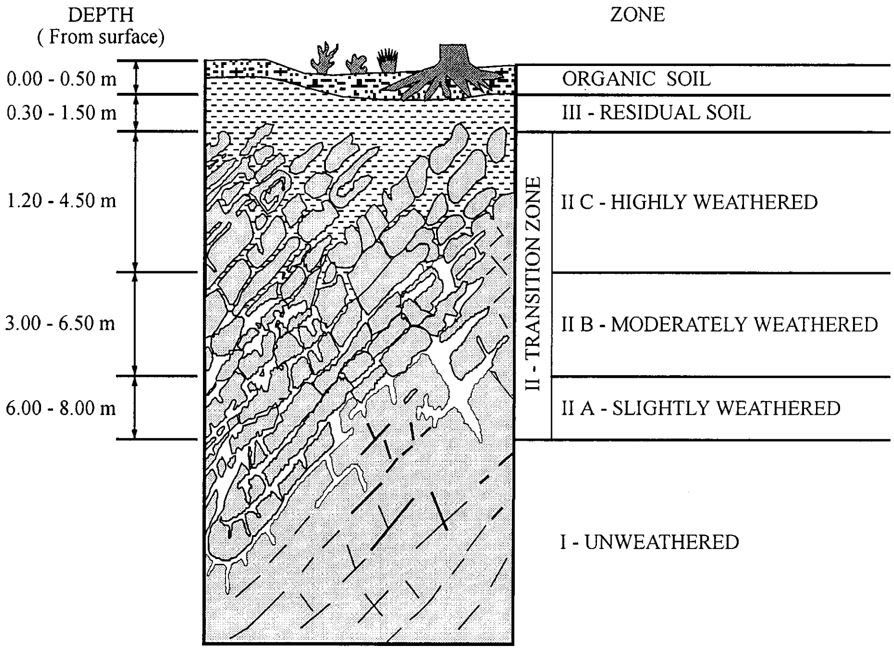
The weathering process of limestones depends on the presence of acids, derived from gases such as CO_2 and SO_2 that enter into solution in percolating rainwater. The limestones are mainly composed of calcium carbonate and they are susceptible to acid attack. The calcium carbonate of the limestone is slowly dissolved by rainwater containing carbon dioxide and held in solution as calcium bicarbonate (Blyth and de Freitas 1984).

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$$

The upper surface of the limestone shows many features, known as ‘pipes’, caused by this process and seen where intersected by quarry faces.

The weathering profile

Soluble rocks develop their own style of profile, often with voids of various sizes which may be later infilled by secondary materials (Anonymous 1995). The Devonian limestones have weathering profiles that differ in several respects from other types of rocks. A review and critique of various descriptive schemes, particularly those applicable to limestones, can be found in Deere and Patton (1971), Blyth and de Freitas (1984) and Fookes and Hawkins (1988). The residual soil developed over carbonate rocks is simply the insoluble portion of the original rock (principally quartz, iron and manganese oxides and clay minerals) (Deere and Patton 1971). The weathered products form a residual soil that is usually clayey but occasionally silty and sandy. The residual soil may only represent a small percentage of the original carbonate rock, the major part having been removed by solution. Weathering profiles themselves can vary considerably from place to



(Modified from Deere and Patton 1971)

Fig. 3
Weathering profile of limestones

place, even in the same rock formation, as a function of variations in rock mineralogy and texture, mass structure, topography, rate of erosion, groundwater conditions and climate (Irfan 1996).

Figure 3 illustrates a typical weathering profile of limestone. The profile, from bedrock to soil, can be mainly divided into three horizons (unweathered limestone, the transition zone and residual soil) on the basis of macroscopic features (the colour of the rock mass, rock:soil ratio, opening of discontinuity surfaces, the colour and filling of the discontinuity surfaces) visible in the field. The weathering of the limestones decreases with increasing depth. In the unweathered zone discontinuities are closed. An upper zone, III, overlies an irregular and sometimes very thick zone II. For most practical purposes, the contact can be considered to be an abrupt contact. There are also changes within the transition zone generally with increasing depth (rate of solution, mass structure, opening and filling of discontinuities). Therefore, the transition zone has been distinguished into three horizons as slightly weathered (IIA), moderately weathered (IIB) and highly weathered limestone (IIC). In the slightly weathered zone, the rock:soil ratio is 100%, discontinuity surfaces are open and there is very slight solution etching of discontinuity surfaces. In the moderately weathered zone, up to 50% of the rock has been removed by solution. A small quantity of residuum is present in the voids. The structure of the rock is preserved as defined by Bell (1998). In the highly weathered zone, more than 50% of the rock has been removed by solution and a large quantity of residuum is present in the voids. The variable properties of the transition zone material result from the extremely irregular shape of the contact. Deep solution cavities filled with clays and sometimes called "pockets of decalcification" can be found within the transition zone. In some cases there may be no transition zone and a boring may pass directly from zone III to zone I. The red, clayey soil typically derived from limestone is called terra rossa (Rahn 1986). In the study area, old brownish-red weathering materials such as terra rossa are predominant. The deep pockets of weathering often develop along joints, fault zones or bedding planes. Clayey weathering products accumulate mainly in funnels, wells, kettles and crevasses.

Petrographical and chemical characteristics

The solubility of carbonate rock is related to its carbonate content. Thus, petrographical and chemical analyses were performed on limestones of different composition and under different degrees of weathering.

Petrographical analysis

Rock samples were collected from the Devonian limestone in Kartal Quarry, Istanbul. The samples were cut and peels taken to allow a petrographic description and were classified according to their carbonate content, weathering degree, texture and fabric characteristics. Grain to micrite ratio and the percentage of insoluble residue of all samples were also determined. Grain to micrite ratio was determined by point-counter and the insoluble residue was determined by HCl. The results are given in Table 1. The samples were firstly classified according to Folk's (1962) classification scheme. According to this classification most of the samples are biomicrite (Table 2). Leighton and

Table 1
Petrographical and chemical characteristics of limestones

Sample no.	Grain to micrite ratio (GMR) (%)			Insoluble residue (IR) (%)		
	Min.	Max.	Mean	Min.	Max.	Mean
K1-I	38.81	40.63	39.13	11.9	12.2	12.1
K1-IIA	35.43	38.17	36.64	15.7	16.0	15.9
K1-IIB	32.83	37.45	34.99	19.2	19.5	19.3
K1-IIC	21.36	23.74	22.39	33.9	34.3	34.1
K2-I	36.23	39.66	38.14	1.7	1.8	1.8
K2-IIA	35.55	38.22	36.95	8.0	8.3	8.2
K2-IIB	30.66	32.77	31.05	21.5	21.9	21.7
K2-IIC	27.20	30.07	29.22	23.7	23.9	23.8
K3-I	28.81	31.34	29.72	7.1	7.2	7.2
K4-IIA	41.28	43.98	42.08	18.5	18.9	18.7
K5-IIB	51.17	53.82	52.80	11.7	11.9	11.8
K6-IIA	42.18	50.75	46.47	13.2	13.6	13.4
K7-IIA	31.51	34.02	32.27	16.4	16.8	16.6
K8-IIA	41.05	43.96	42.01	4.6	4.9	4.8
K9-I	23.18	25.34	24.26	19.2	19.5	19.3
K10-I	9.76	11.26	10.51	14.6	15.1	14.9
K11-IIB	50.73	54.30	52.52	4.7	4.9	4.8
K12-I	16.67	17.88	17.28	26.7	27.2	26.9
K13-I	43.51	45.27	44.39	32.3	32.6	32.4
K14-I	28.31	30.09	29.20	31.7	32.0	31.9

Table 2
Classification of Devonian limestones (*lst.*)

Sample no.	Formation name	Lithological name[a]	Textural classification[b]	Engineering classification[c]	Engineering classification[d]	Weathering grade
K1-I	Kaynarca	Biomicrite	Micritic lump lst.	Limestone with some clay	Fine-grained micritic lst.	Unweathered
K1-IIA	Kaynarca	Biomicrite	Micritic lump lst.	Limestone with some clay	Fine-grained micritic lst.	Slightly weathered
K1-IIB	Kaynarca	Biomicrite	Micritic lump lst.	Limestone with some clay	Fine-grained micritic lst.	Moderately weathered
K1-IIC	Kaynarca	Biomicrite	Micritic lump lst.	Limestone with some clay	Fine-grained micritic lst.	Highly weathered
K2-I	İstinye	Biomicrite	Micritic skeletal lst.	Limestone with some clay	Fine-grained micritic lst.	Unweathered
K2-IIA	İstinye	Biomicrite	Micritic skeletal lst.	Limestone with some clay	Fine-grained micritic lst.	Slightly weathered
K2-IIB	İstinye	Biomicrite	Micritic skeletal lst.	Limestone with some clay	Fine-grained micritic lst.	Moderately weathered
K2-IIC	İstinye	Biomicrite	Micritic skeletal lst.	Limestone with some clay	Fine-grained micritic lst.	Highly weathered
K3-I	Kaynarca	Biomicrite	Micritic lump lst.	Limestone with some clay	Fine-grained micritic lst.	Unweathered
K4-IIA	Kaynarca	Biomicrite	Micritic skeletal lst.	Limestone with silt or clay	Fine-grained micritic lst.	Slightly weathered
K5-IIB	İstinye	Biomicrite	Skeletal micritic lst.	Limestone with some clay	Fine-grained micritic lst.	Moderately weathered
K6-IIA	İstinye	Biosparite	Sparitic skeletal lst.	Limestone with some clay	Fine-grained micritic lst.	Slightly weathered
K7-IIA	İstinye	Pelmicrite	Micritic pellet lst.	Limestone	Limestone	Slightly weathered
K8-IIA	Kaynarca	Biopelsparite	Sparitic pellet lst.	Limestone	Limestone	Unweathered
K9-I	İstinye	Pelsparite	Sparitic pellet lst.	Limestone	Limestone	Unweathered
K10-I	İstinye	Micrite	Micritic limestone	Limestone	Limestone	Unweathered
K11-IIB	İstinye	Biomicrite	Skeletal sparitic lst.	Limestone	Limestone	Moderately weathered
K12-I	Sedefadası	Clayey biomicrite	Micritic detrital lst.	Clayey limestone	Argillaceous limestone	Unweathered
K13-I	Sedefadası	Biomicrite with quartz clast	Micritic detrital lst.	Silty-clayey lst.	Argillaceous limestone	Unweathered
K14-I	Sedefadası	Clayey biomicrite with quartz clast	Micritic detrital lst.	Silty-clayey lst.	Argillaceous limestone	Unweathered

[a] According to Folk (1962)
[b] According to Leighton and Pendexter (1962)
[c] According to Burnett and Epps (1979)
[d] According to Hawkins (1986)

Pendexter's (1962) classification considers three variables: grain size, the proportion of matrix to allochems and the degree of dolomitization. The limestone was then classified according to this classification scheme (Table 2), and most of the samples were classified as micritic lump or micritic skeletal limestone.

A number of engineering classification schemes have been used to describe and classify carbonate rocks for engi-

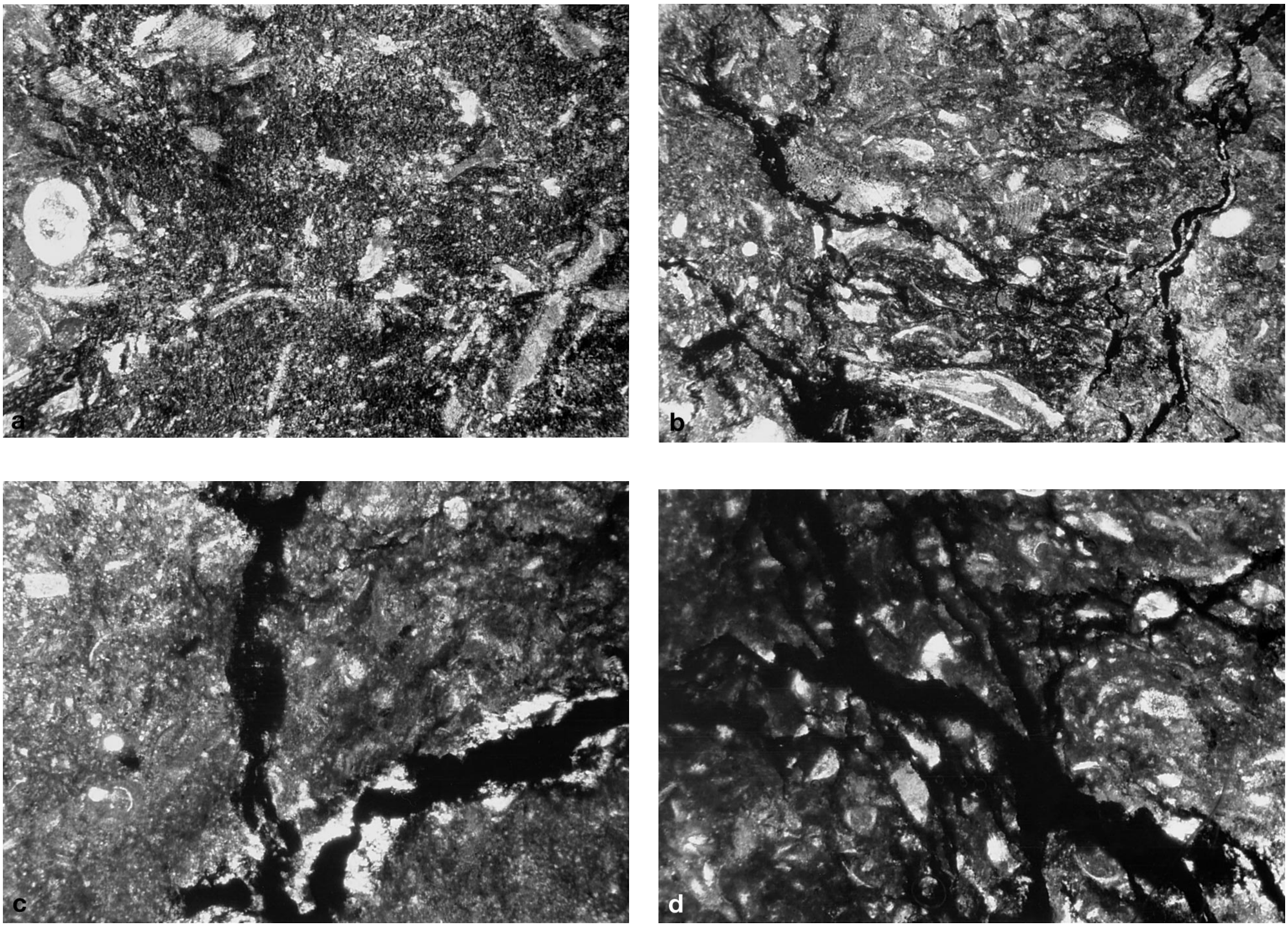


Fig. 4
General aspect of: **a** unweathered biomicrite K1-I; **b** slightly weathered biomicrite K1-IIA, texture showing fossil fragments with a few microfracture; **c** moderately weathered biomicrite K1-IIB, pores are partly cemented; **d** highly weathered biomicrite K1-IIC, showing opening of microfractures and iron staining of whole rock (25 ×, cross-polarized light)

neering purposes (Fookes and Higginbottom 1975; Clarke and Walker 1977; Burnett and Epps 1979; Hawkins 1986). Fookes and Higginbottom (1975) proposed a classification based on texture and the degree of induration. Some authors modified this classification. Burnett and Epps (1979) proposed a classification of pure and admixtures of carbonate rocks for engineering purposes, which is based on texture. Hawkins (1986) accepts the usefulness of a visual grain size terminology for carbonate rocks. The classification according to authors are shown in Table 2.

It is very difficult to distinguish the limestones according to their weathering grade in the field. However, differences (from bottom to top) were determined by petrographical studies conducted on samples taken from where the complete weathering profile is available in the quarry (K1 and K2). As shown in Fig. 4, as the weathering increases, the solution rate of the limestones also increases. In slightly weathered limestone there is slight discoloration along the fractures, and most of the fractures are unfilled with insoluble residue. In moderately weathered limestone most of the samples were affected by dissolution, and penetrative discoloration was observed. In highly weathered samples the solution rate is more than 50%, the colour of the rock changed from grey to brown and insoluble materials are concentrated along microfractures or stylolites.

Chemical analysis

Chemical analyses by the inductively coupled plasma spectroscopy (ICP) method were used to establish the rock mass chemistry and the nature of the insoluble residue. According to chemical analyses performed on some different limestone samples, the limestones (except biomicrite with quartz clasts) consist of 2.09–8.50% SiO_2, 0.40–2.15% Al_2O_3, 0.21–1.05% Fe_2O_3, 0.87–2.56% MgO, 46.37–54.06% CaO, 0.03–0.18% Na_2O, 0.11–0.53% K_2O, 0.01–0.12% TiO_2 and 0.01–0.03% MnO. The losses on ignition (LOI) obtained from the chemical analyses can be used to determine the degree of weathering. Loss on ignition is the loss in weight of samples after they were heated to 1000 °C. The percentage of losses on ignition ranges from 39.1 to 42.8 (Table 3).

Chemical analyses on some samples having fresh and different weathering grades were also carried out. The

Table 3
Results of chemical analyses of major element oxides of limestones of different compositions. *LOI* Loss on ignition

Major element oxide	Sample no.								
	K1-I	K2-I	K3-I	K5-IIB	K6-IIA	K7-IIA	K9-I	K11-IIB	K13-I
SiO_2 (%)	6.36	5.14	5.24	8.50	7.71	5.22	2.09	2.55	46.25
Al_2O_3 (%)	1.69	1.73	1.71	2.15	1.92	0.94	0.40	0.64	14.94
Fe_2O_3 (%)	0.76	0.78	0.73	1.05	0.85	0.41	0.21	0.30	5.65
MgO (%)	0.99	1.09	2.17	1.17	2.33	2.56	0.87	2.47	2.84
CaO (%)	49.59	49.52	49.36	46.77	46.37	49.07	54.06	50.81	12.12
Na_2O (%)	0.17	0.14	0.18	0.11	0.10	0.10	0.03	0.10	0.53
K_2O (%)	0.41	0.39	0.40	0.53	0.41	0.25	0.11	0.15	2.97
TiO_2 (%)	0.12	0.05	0.12	0.10	0.09	0.03	0.01	0.02	0.72
P_2O_5 (%)	0.02	0.02	0.05	0.01	0.03	0.04	<0.01	<0.01	0.11
MnO (%)	0.02	0.02	0.02	0.03	0.02	0.01	0.01	0.01	0.06
Cr_2O_3 (%)	0.006	0.006	0.006	0.008	0.005	0.007	0.007	0.007	0.014
Ba (ppm)	29	31	28	50	57	38	22	20	347
Ni (ppm)	26	26	26	42	52	21	<20	39	98
Sr (ppm)	552	698	532	737	930	1085	832	716	510
Zr (ppm)	24	21	25	23	20	21	21	<10	110
LOI (%)	39.8	41.2	40.1	39.1	39.7	41.4	42.1	42.8	13.7
C/total (%)	11.21	11.36	11.23	10.54	10.75	11.35	12.02	11.95	3.51
S/total (%)	0.16	0.06	0.17	0.25	0.02	0.05	0.05	0.01	0.97
Sum (%)	100.07	100.22	100.16	99.63	99.66	100.1	100.01	99.95	100.01

Table 4
Results of chemical analyses of major element oxides of limestones under various degrees of weathering. *LOI* Loss on ignition

Major element oxide	Sample no.											
	K1-I	K1-IIA	K1-IIB	K1-IIC	K1-III	K2-I	K2-IIA	K2-IIB	K2-IIC	K2-III	K7-IIA	K7-III
SiO_2 (%)	6.36	9.46	13.00	16.12	48.57	5.14	7.17	8.98	12.06	46.70	5.22	51.30
Al_2O_3 (%)	1.69	2.51	3.55	4.21	20.99	1.73	1.89	1.97	3.11	21.71	0.94	20.05
Fe_2O_3 (%)	0.76	1.28	1.77	1.89	8.70	0.78	0.96	1.36	1.86	9.07	0.41	6.85
MgO (%)	0.99	1.03	1.33	1.46	1.87	1.09	1.18	1.36	1.39	1.58	2.56	0.87
CaO (%)	49.59	46.24	43.63	41.72	1.12	49.52	48.18	45.74	42.78	1.87	49.07	2.59
Na_2O (%)	0.17	0.21	0.35	0.37	0.28	0.14	0.15	0.19	0.26	0.16	0.10	0.34
K_2O (%)	0.41	0.46	0.66	0.78	3.01	0.39	0.42	0.49	0.67	2.81	0.25	2.21
TiO_2 (%)	0.12	0.13	0.20	0.26	0.75	0.05	0.08	0.11	0.22	0.77	0.03	0.73
P_2O_5 (%)	0.02	0.02	0.09	0.09	0.10	0.02	0.03	0.03	0.08	0.11	0.04	0.05
MnO (%)	0.02	0.03	0.04	0.06	0.15	0.02	0.02	0.03	0.04	0.14	0.01	0.15
Cr_2O_3 (%)	0.006	0.007	0.008	0.009	0.020	0.006	0.007	0.08	0.09	0.023	0.007	0.015
Ba (ppm)	29	62	94	109	410	31	35	61	92	425	38	345
Ni (ppm)	26	34	28	36	73	26	28	35	29	88	21	94
Sr (ppm)	552	663	565	546	53	698	675	656	598	42	1085	57
Zr (ppm)	24	26	33	32	99	21	22	24	31	103	21	118
LOI (%)	39.8	38.5	35.7	33.4	14.4	41.2	39.3	38.6	35.4	14.9	41.4	14.8
C/total (%)	11.21	10.61	9.70	9.12	0.37	11.36	11.05	11.22	9.81	0.55	11.35	0.57
S/total (%)	0.16	0.02	0.01	0.01	0.090	0.06	0.04	0.04	0.03	0.03	0.05	0.05
Sum (%)	100.07	100.00	100.40	100.5	100.00	100.22	99.50	99.10	99.10	99.93	100.10	100.00

results of these analyses are shown in Table 4. As the weathering increases the percentages of SiO_2, Al_2O_3, total Fe_2O_3, MgO, Na_2O and K_2O increase and the percentage of CaO and loss on ignition decreases (Fig. 5). The $CaCO_3$ content of the weathering products is small or minimal (Table 4). The residual soil (terra rossa) over the limestones is simply the insoluble portion of the original rock, principally quartz, iron and manganese oxides and clay minerals.

Mineralogical analysis

To investigate the mineralogical composition of the residual soil (terra rossa) derived from the limestones, X-ray diffraction analysis was conducted on the clay fraction of the samples. According to the results, samples K1-III consist of 63% illite, 25% kaolinite and 12% smectite and samples K2-III consist of 64% illite, 17% kaolinite and 19% smectite (Fig. 6). Illite occurs as the main clay mineral.

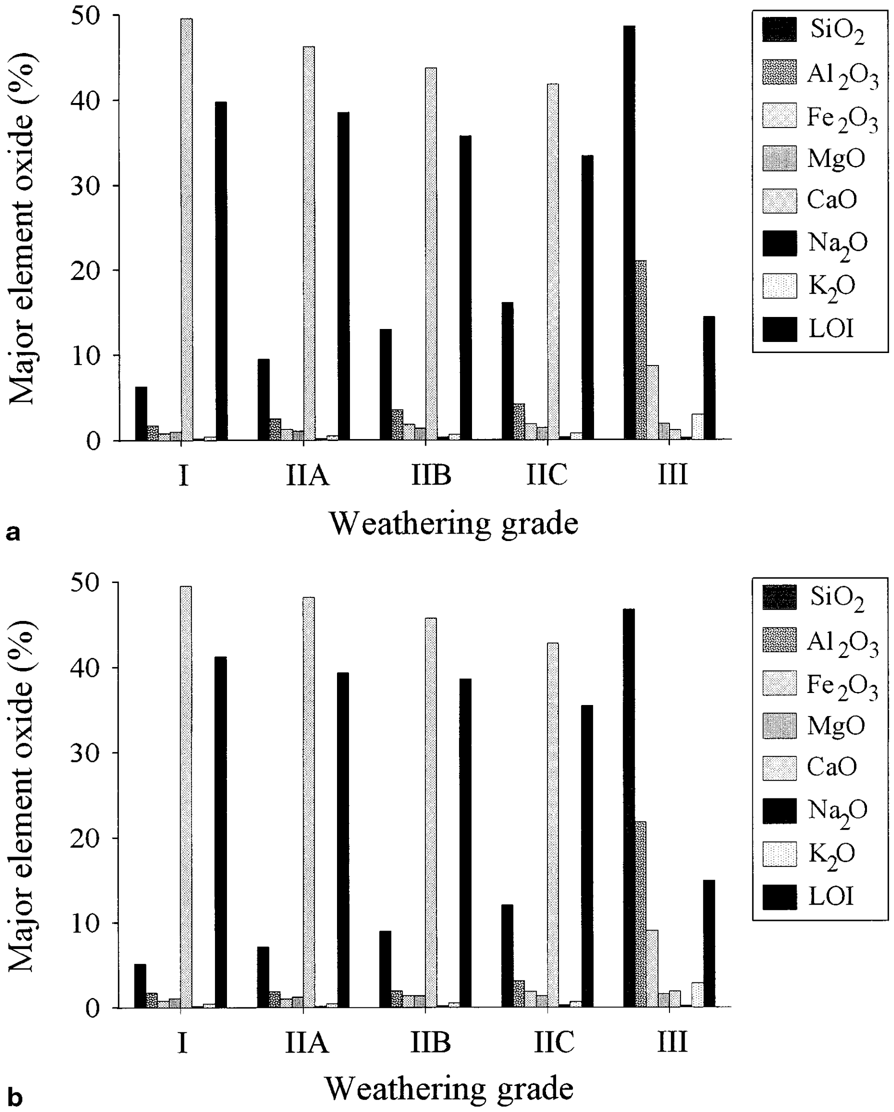


Fig. 5
Comparison of whole-rock chemical trend of limestones under various degrees of weathering: **a** K1; **b** K2. *LOI* Loss on ignition

Lower contents of kaolinite and smectite accompany it sporadically. Despite the red colour of the terra rossa samples, hematite detectable by X-ray was not found.

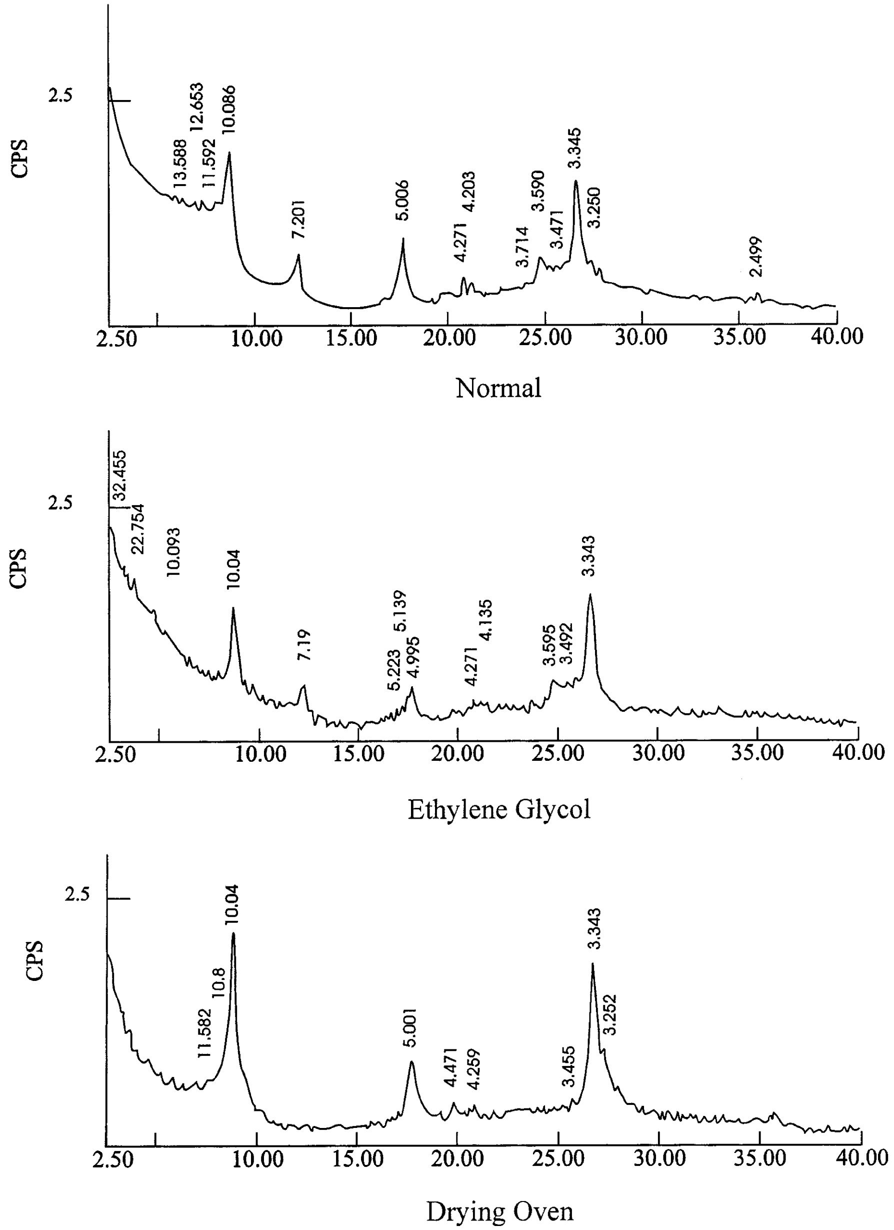
Physical and mechanical properties

Various laboratory tests were carried out on the core specimens prepared from block samples to determine the geomechanical parameters of the fresh and weathered limestones. The tests on NX-size specimens (diameter of cylindrical sample 54 mm) were performed according to the procedures recommended by the International Society for Rock Mechanics (ISRM) (1981). The testing programme comprised the determination of specific gravity, dry and saturated unit weight, water absorption, effective and total porosity, P-wave velocity, point load strength index, tensile strength, uniaxial compressive strength and modulus of elasticity of the limestones. More than two tests were carried out at each interval and their mean values were evaluated.

Physical properties

To determine the unit weight, water absorption and the porosity of the limestones under different degrees of weathering, a series of laboratory studies was conducted. According to experimental results, the dry unit weight changes from 25.19 to 26.83 kN/m^3, the water absorption changes from 0.10 to 1.67%, the effective porosity changes from 0.34 to 4.19% and the total porosity ranges between 0.75 and 5.64% (Tables 5 and 6). As weathering and clastic material increases, the unit weight decreases and the water absorption and the porosity increase. This is due to solution of the limestones.

Weathering of limestone is directly related to its internal surface area and average pore size. The more porous the rock, the more susceptible it is to chemical attack. An important effect of solution in limestone is enlargement of



Normal

Ethylene Glycol

Drying Oven

Fig. 6
Normal, ethylene and oven X-ray diffractograms of clay fraction of residual soil derived from limestone (K1-III). *CPS* Cycles per second

the pores, which enhances pore water movement, thereby encouraging further solution. This brings about an increase in stress within the fabric of the rock, thus reducing its strength and increasing stress corrosion (Bell 1983).

Pore size distribution of the limestones was determined using the forced mercury intrusion technique as suggested by ISRM (1981). The specimen is forced under mercury and its volume is determined from the displaced fluid volume. During the test, the mercury fills up large pores under low pressure and small ones under high pressure. The cumulative mercury intrusion per gram of sample and pore diameter are shown on the y- and x-axes, respectively, of Fig. 7. Cumulative mercury intrusion is equal to the pore volume. The effective porosity of weathered samples is generally higher than unweathered samples. Changes in pore geometry are caused by the solution of the limestone samples and increase in microfracture unit weight by progression of weathering.

Choquette and Pray (1970) explained porosity types in carbonate rocks. The basis of their comprehensive summary is a morphologic classification of carbonate pore types with emphasis on whether or not the porosity is fabric selective. Some types of porosity identified in the Devonian limestones are illustrated in Fig. 8. Interparticle porosity between grains and/or particles forms via leaching of matrix or cement (Fig. 9a). Intraparticle porosity within individual particles or grains is generally primary, but forms rarely by dissolution of cement or matrix (Fig. 9b). Inter- and/or intragranular porosity were enlarged somewhat by dissolution around the original pores. Moldic porosity forms by selective removal (solution) of grains

Table 5
Specific gravity, dry unit weight and saturated unit weight values of limestones under various degrees of weathering

Sample no.	Specific gravity (G_s)	Dry unit weight (γ_d) (kN/m^3)			Saturated unit weight (γ_s) (kN/m^3)		
		Min.	Max.	Mean	Min.	Max.	Mean
K1-I	2.65	26.15	26.40	26.35	26.33	26.51	26.42
K1-IIA	2.68	26.04	26.42	26.24	26.27	26.43	26.34
K1-IIB	2.67	25.91	26.26	26.18	26.31	26.59	26.36
K1-IIC	2.69	25.46	25.65	25.61	25.58	25.87	25.72
K2-I	2.67	26.70	26.83	26.79	26.75	26.96	26.83
K2-IIA	2.67	26.63	26.75	26.68	26.67	26.81	26.72
K2-IIB	2.66	26.04	26.45	26.25	26.32	26.67	26.43
K2-IIC	2.67	25.73	26.11	25.92	26.16	26.48	26.25
K3-I	2.70	26.31	26.74	26.54	26.43	26.95	26.62
K4-IIA	2.68	26.04	26.34	26.11	26.29	26.75	26.52
K5-IIB	2.66	26.23	26.71	26.52	26.36	26.83	26.61
K6-IIA	2.71	26.45	26.67	26.56	26.56	26.79	26.61
K7-IIA	2.65	25.52	25.88	25.78	25.93	26.32	26.15
K8-IIA	2.70	26.11	26.34	26.21	26.37	26.76	26.52
K9-I	2.70	26.13	26.57	26.30	26.46	26.91	26.56
K10-I	2.68	25.98	26.43	26.07	26.13	26.74	26.12
K11-IIB	2.68	26.16	26.62	26.41	26.33	26.87	26.58
K12-I	2.73	26.05	26.29	26.12	26.18	26.72	26.25
K13-I	2.67	25.70	26.08	25.92	25.97	26.64	26.12
K14-I	2.66	25.19	26.04	25.64	25.48	26.26	25.83

Table 6
Water absorption, effective porosity and total porosity values of limestones under various degrees of weathering

Sample no.	Water absorption (w_a) (%)			Effective porosity (n_e) (%)			Total porosity (n_t) (%)		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
K1-I	0.26	0.60	0.39	0.67	1.57	1.02	0.75	1.88	1.14
K1-IIA	0.13	0.65	0.60	0.34	1.69	1.56	1.38	2.89	2.24
K1-IIB	0.64	0.93	0.71	1.38	2.41	1.62	2.24	3.36	2.42
K1-IIC	0.93	1.48	1.25	2.61	3.26	2.82	3.75	4.37	4.12
K2-I	0.31	0.42	0.36	0.83	1.10	0.94	1.13	1.50	1.31
K2-IIA	0.14	0.18	0.16	0.37	0.48	0.42	1.17	1.72	1.31
K2-IIB	0.25	0.57	0.41	0.84	1.24	1.07	1.05	1.87	1.32
K2-IIC	0.10	0.35	0.15	0.96	1.64	1.38	1.75	3.49	2.99
K3-I	0.17	0.34	0.25	0.44	0.93	0.65	1.86	2.97	2.04
K4-IIA	0.55	0.94	0.79	1.45	2.66	2.05	2.49	3.14	2.80
K5-IIB	0.21	0.58	0.43	0.56	1.33	1.12	1.11	1.96	1.32
K6-IIA	0.47	0.55	0.50	1.28	1.38	1.33	1.48	2.21	1.85
K7-IIA	0.94	1.12	1.03	2.43	2.86	2.65	2.64	3.77	3.21
K8-IIA	0.14	0.18	0.16	0.39	0.42	0.41	2.59	3.33	2.96
K9-I	0.13	0.18	0.16	0.55	1.47	0.91	1.11	2.59	1.85
K10-I	0.17	0.62	0.39	0.45	1.61	1.03	1.49	2.99	2.24
K11-IIB	0.20	0.72	0.46	0.53	1.88	1.21	0.75	2.61	1.68
K12-I	0.54	0.62	0.58	1.45	1.64	1.55	1.47	2.93	2.20
K13-I	0.85	1.26	1.06	2.21	3.24	2.23	2.62	3.75	3.19
K14-I	0.58	1.67	1.13	1.51	4.19	2.35	2.26	5.64	3.95

(Fig. 9c). Fenestral porosity forms by dissolution of the cement or matrix sometimes caused by enlargement of microfractures. This type of porosity can be seen easily in hand specimens. Fracture porosity formed by fracturing. Some fractures are cemented (Fig. 4d). Vugs are irregular, usually secondary holes and are large enough to be visible to the naked eye (Fig. 9d). Vugs form by solution and are not fabric selective. Stylolitic porosity along stylolites (pressure solution seams) also occurs in the limestones. Although not included in the classification of Choquette and Pray (1970), stylolites can contain porosity (Longman 1982). They are significant pathways for water. Solution causes enlargement of fractures and the insoluble residue causes filling of the pore spaces.

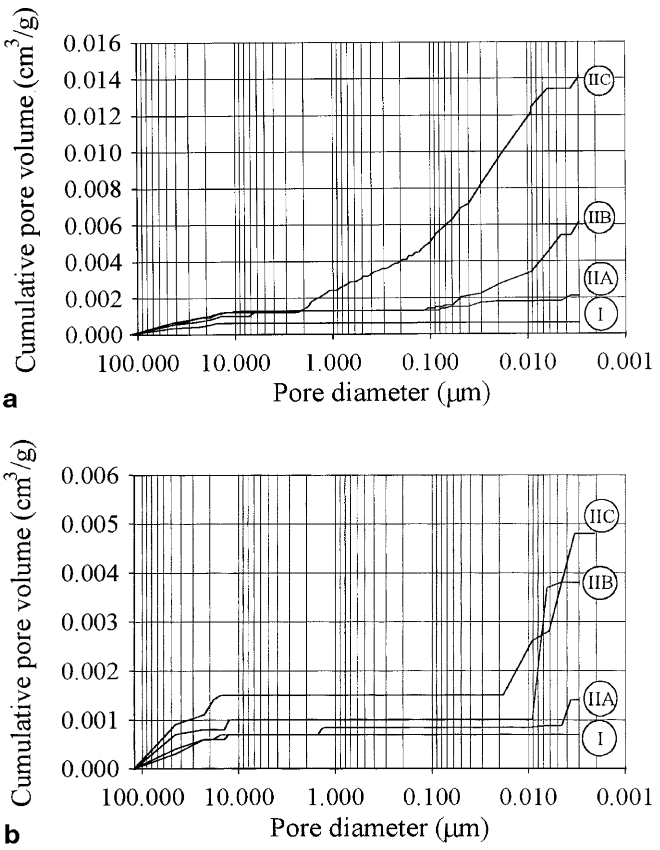


Fig. 7
Pore volume versus pore diameter for the limestone **a** K1 and **b** K2. *I* Unweathered; *IIA* slightly weathered; *IIB* moderately weathered; *IIC* highly weathered

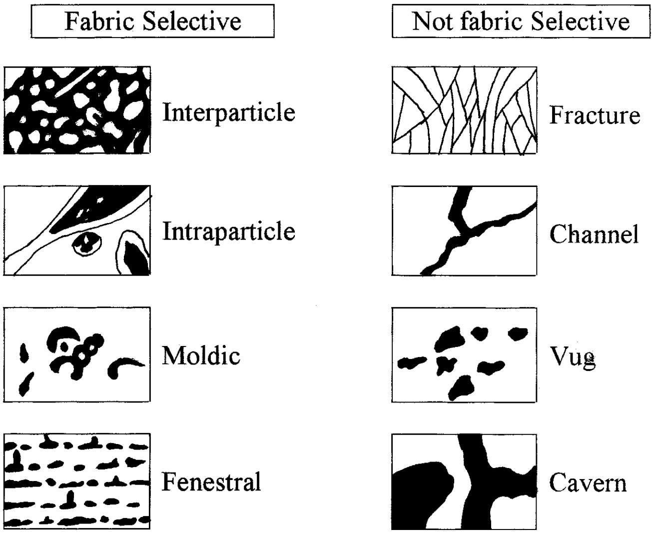


Fig. 8
Some types of porosity (proposed by Choquette and Pray 1970)

Ultrasonic P-wave velocity

P-wave velocity of the limestones under different degrees of weathering was obtained by application of ultrasonic compression wave pulses to the sample in accordance with American Society of Testing Materials (ASTM) test designation (American Society of Testing Materials 1980). Compression wave generators were attached to a prepared core specimen. Wave velocity through the specimen was calculated from the travel time from the generator to a receiver at the opposite end. The results are given in Table 7. As shown, the P-wave velocity of the limestones

Table 7
P-wave velocity and point load strength index values of limestones under various degrees of weathering

Sample no.	P-wave velocity (V_p) (km/s)			Point load strength index (I_s) (MPa)		
	Min.	Max.	Mean	Min.	Max.	Mean
K1-I	5.40	5.91	5.73	4.45	6.24	5.17
K1-IIA	4.62	5.76	4.99	4.15	5.89	4.61
K1-IIB	3.36	4.78	3.98	3.38	4.63	4.29
K1-IIC	3.06	3.61	3.21	1.85	2.62	2.24
K2-I	6.38	7.15	6.75	4.76	6.77	5.77
K2-IIA	5.71	6.47	6.08	4.70	5.84	5.46
K2-IIB	5.24	6.16	5.86	4.68	6.03	5.07
K2-IIC	4.45	5.49	4.84	4.00	4.60	4.30
K3-I	5.69	6.24	5.94	4.31	5.07	4.85
K4-IIA	5.23	5.87	5.59	3.52	4.32	3.89
K5-IIB	5.92	6.41	6.20	5.77	6.58	6.32
K6-IIA	4.77	6.06	5.55	3.80	5.92	4.86
K7-IIA	3.34	4.25	3.60	1.44	2.03	1.74
K8-IIA	4.49	5.14	4.99	3.97	4.86	4.42
K9-I	3.97	5.04	4.67	2.88	3.91	3.40
K10-I	3.08	4.35	3.88	2.47	4.62	3.55
K11-IIB	5.72	6.57	6.02	5.47	7.13	6.30
K12-I	3.27	4.12	3.47	1.95	3.27	2.61
K13-I	3.29	3.87	3.62	2.74	3.88	3.31
K14-I	3.26	3.95	3.52	2.96	4.12	3.54

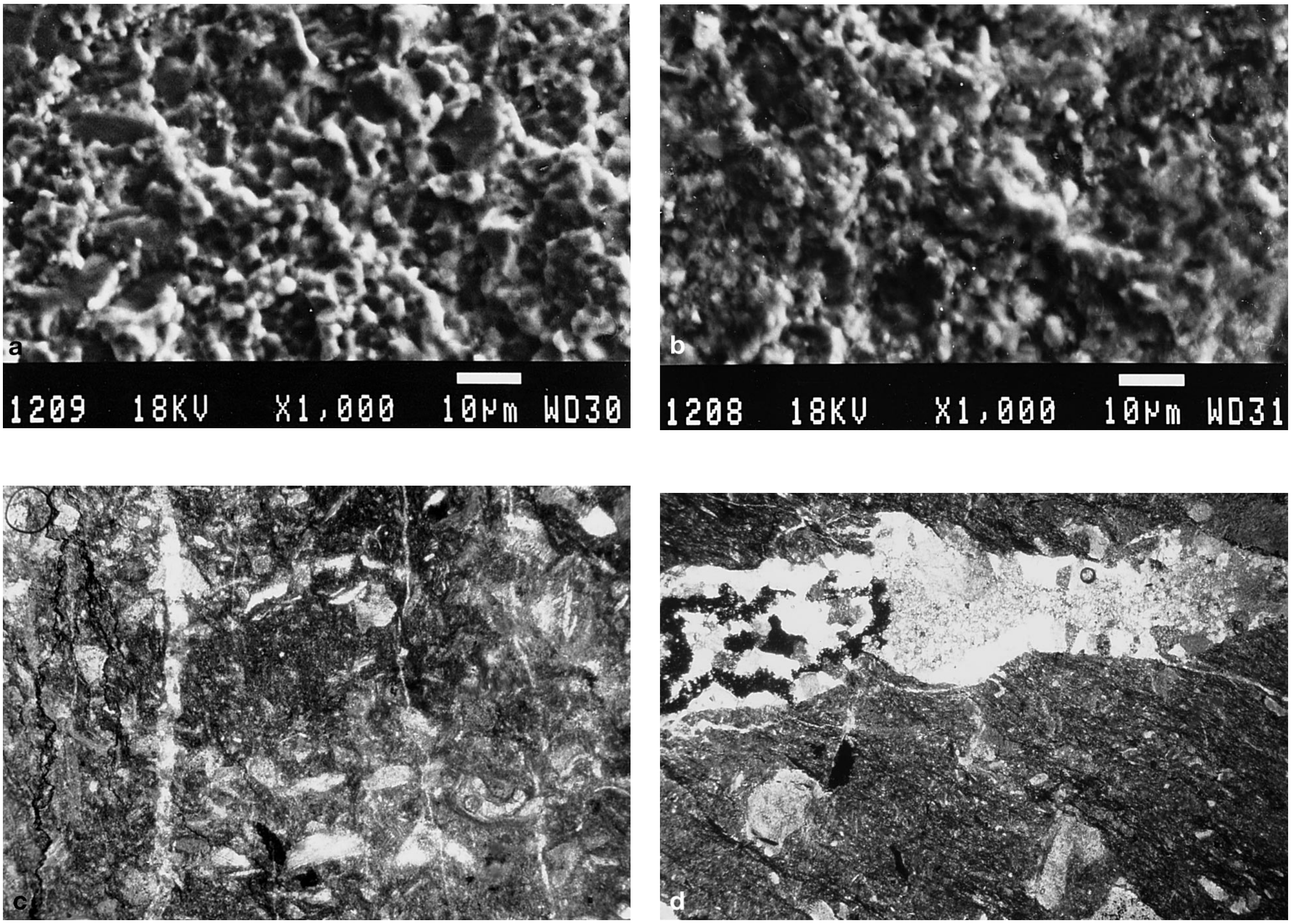


Fig. 9
Types of porosity in limestones. **a** SEM photomicrograph of primary interparticle porosity in sample K1-IIA; **b** SEM photomicrograph of intraparticle porosity in sample K2-IIB; **c** optical photomicrograph of moldic porosity in sample K7-IIA (25X, cross-polarized light); **d** optical photomicrograph of vuggy porosity in sample K4-IIA (25×, cross-polarized light)

ranges from 3.21 to 6.75 km/s. The P-wave velocities of the unweathered limestones are greater than the weathered ones.

Mechanical properties

A portable point load test machine was used to test cylindrical core specimens in accordance with the ISRM (1981). Results are given in Table 7. The uniaxial compressive strengths for several limestone materials representative of each weathering grade were determined by using a uniaxial compression test machine, according to the ISRM (1981) specification on prepared core samples. Determination of tensile strength was carried out by the Brazilian test in accordance with the ISRM (1981). The modulus of elasticity of the limestones under different degrees of weathering was derived from the slope of the stress-strain curves. Table 8 sets out the experimental results of mechanical tests. Results show the strength parameter of the limestones decreases with increasing weathering, clay content and porosity.

Interrelationships between petrographical characteristics and engineering properties

Selected petrographical, physical, mechanical index and strength properties of the fresh and weathered limestones were plotted against each other for the assessment of variations in engineering properties, depending on the degree of weathering. Correlation coefficients and best-fit curves were calculated by the "least squares curves fit" method using a computer. Some of the important results are illustrated and discussed. Equations for the curves plotted are given in Figs. 10–14.

The relationship between the uniaxial compressive strength and the grain to micrite ratio of the limestone of different composition and weathering grade is shown in Fig. 10a. There is a linear relationship between these two parameters. As the grain to micrite ratio increases, the uniaxial compressive strength also increases. However, this relationship is not very significant ($r = 0.62$). The strength

Table 8
Uniaxial compressive strength, tensile strength and modulus of elasticity values of limestones under various degrees of weathering

Sample no.	Uniaxial compressive strength (σ_c) (MPa)			Tensile strength (σ_t) (MPa)			Elasticity modulus (E) (GPa)		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
K1-I	92.6	125.7	121.8	57.3	65.9	61.6	37.24	50.37	40.42
K1-IIA	76.5	109.8	99.0	40.3	58.9	42.1	28.07	46.14	30.97
K1-IIB	68.7	95.2	90.6	32.7	37.2	35.0	15.43	29.51	19.74
K1-IIC	55.6	84.5	74.2	23.4	26.4	24.9	14.81	20.16	16.68
K2-I	122.8	147.1	138.1	63.7	67.9	65.4	39.41	53.05	46.23
K2-IIA	117.4	143.0	134.2	44.2	76.6	58.6	36.33	55.42	45.48
K2-IIB	100.5	123.0	109.1	29.3	38.4	35.8	31.46	49.34	38.06
K2-IIC	71.5	104.2	92.4	31.0	46.2	33.8	30.95	45.16	34.16
K3-I	96.5	127.5	118.2	44.8	75.3	55.1	41.66	58.45	46.81
K4-IIA	85.0	110.5	100.5	46.2	71.5	48.5	32.81	40.27	36.51
K5-IIB	114.5	135.0	131.6	46.3	62.8	51.6	35.01	46.27	41.56
K6-IIA	97.5	123.5	114.0	46.9	65.5	56.2	35.24	50.03	42.64
K7-IIA	64.5	86.0	76.0	26.0	33.3	29.7	15.82	21.67	18.58
K8-IIA	89.0	117.0	111.0	38.3	42.7	40.5	39.83	46.21	44.30
K9-I	82.0	96.5	93.7	36.6	41.2	38.9	28.73	34.76	31.60
K10-I	73.3	94.5	86.4	27.7	39.5	33.6	21.16	26.34	24.75
K11-IIB	113.8	128.0	124.8	38.5	52.1	45.3	37.59	45.31	41.46
K12-I	68.0	93.4	81.6	26.0	29.5	27.8	16.96	20.94	18.95
K13-I	88.6	97.5	90.0	28.7	32.8	30.7	14.75	20.48	17.62
K14-I	74.5	91.5	85.8	27.9	34.6	31.3	10.47	23.15	16.77

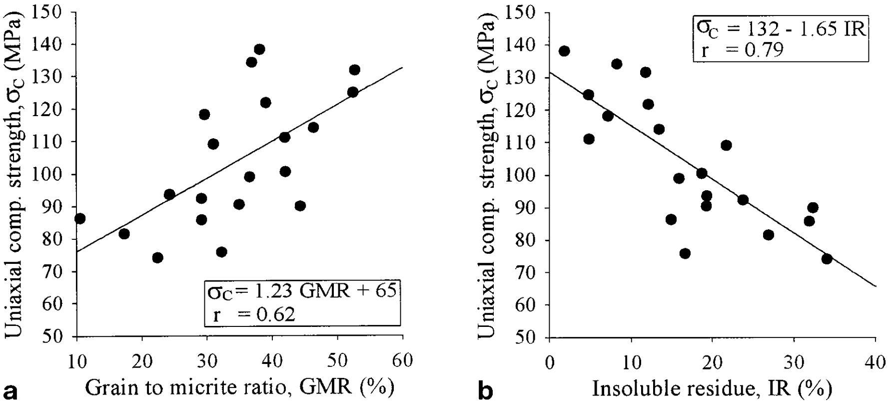


Fig. 10
Uniaxial compressive strength versus **a** grain to micrite ratio and **b** insoluble residue

of the limestones is controlled not only by the grain to micrite ratio but also by other parameters such as porosity. Correlations between the uniaxial compressive strength and the percentage of insoluble residue were also determined. As can be seen in Fig. 10b, as the percentage of insoluble residue increases, the uniaxial compressive strength decreases. The relationship between the uniaxial compressive strength and the insoluble residue for the limestones is more significant ($r=0.79$) than the other parameter.

There is a linear relationship between the total porosity and dry unit weight. The dry unit weight decreases as the porosity increases. There is also a similar relationship between the total porosity and P-wave velocity (Fig. 11). Theoretically, the velocity with which stress waves are transmitted through rock depends exclusively upon their elastic properties and their unit weight (Goodman 1989).

There are statistically significant correlations between uniaxial compressive strength and both unit weight and P-wave velocity (Fig. 12). The uniaxial compressive strength increases as the dry unit weight and P-wave velocity increase. The sonic velocity, as an index test, together with a petrographic description evaluate the degree of fissuring in an intact rock specimen (Ulusay et al. 1994). The value of P-wave velocity as an index of rock strength is well documented by Judd and Huber (1962), D'Andrea et al. (1965) and Irfan and Dearman (1978). On the other hand, as expected, inverse relationships exist between the uniaxial compressive strength and both the effective and total porosity (Fig. 13a). The porosity is an important factor in rock strength in those voids and reduces the integrity of the material. A small volume fractien of pores can produce an appreciable mechanical effect (International Society for Rock Mechanics 1981).

The point load strength index has been widely used to estimate the uniaxial compressive strength of rocks in the field

Fig. 11
Relationship between **a** dry unit weight and total porosity and **b** total porosity and ultrasonic P-wave velocity

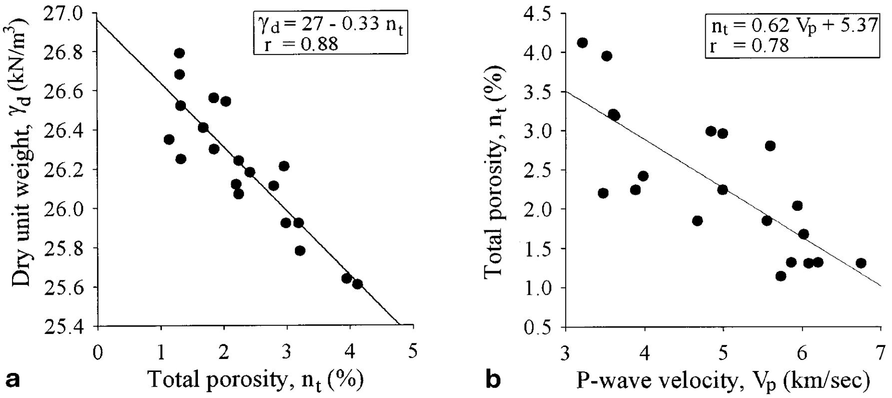


Fig. 12
Uniaxial compressive strength versus **a** unit weight and **b** P-wave velocity

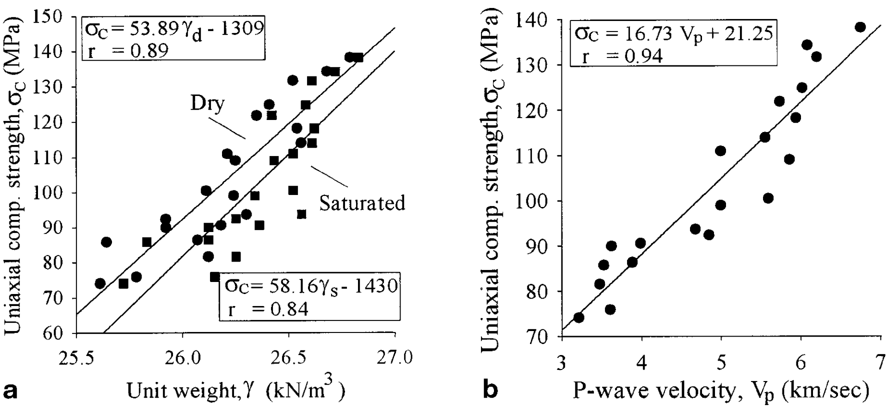
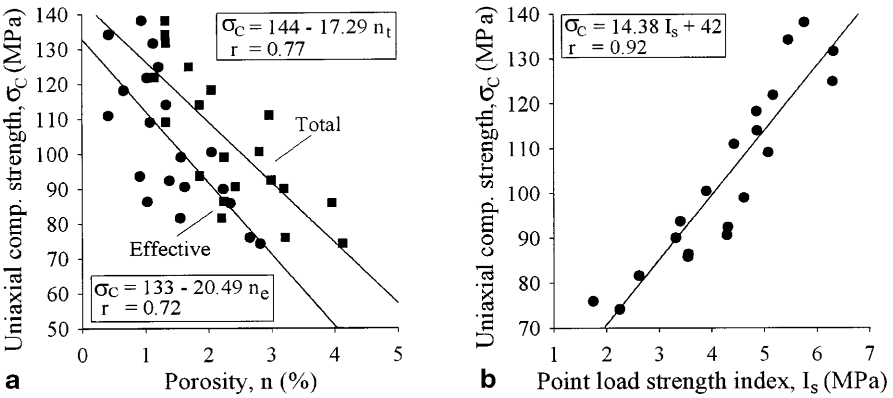


Fig. 13
Uniaxial compressive strength versus **a** porosity and **b** point-load strength index



and laboratory (D'Andrea et al. 1965; Deere and Miller 1966; Broch and Franklin 1972; Bieniawski 1975; Gunsallus and Kulhawy 1984; Ghosh and Srivastava 1991). The correlation between the point load strength index and the compressive strength for the limestones (Fig. 13b) is very significant ($r = 0.92$). D'Andrea et al. (1965) obtained the same correlation.

The correlation between the tensile strength and uniaxial compressive strength for the limestones is also very significant ($r = 0.90$). There is a linear relationship between these two properties (Fig. 14a). The same correlation between these two properties was obtained for basaltic rocks by Tugrul and Gürpinar (1997). D'Andrea et al. (1965) also reported the same relationship of tensile strength to uniaxial compressive strength. In Fig. 14b, the modulus of elasticity was plotted against uniaxial compressive strength determined by loading to failure. The relationship between compressive strength and modulus of elasticity is direct and linear. Judd and Huber (1962), D'Andrea et al. (1965) and Deere and Miller (1966) obtained similar relationships. The tensile strength and the modulus of elasticity of rock are controlled by the same factors as compressive strength, that is, composition and texture. The presence of oriented features in limestones, such as fractures within the intact specimen, lowers tensile strength as it lowers compressive strength.

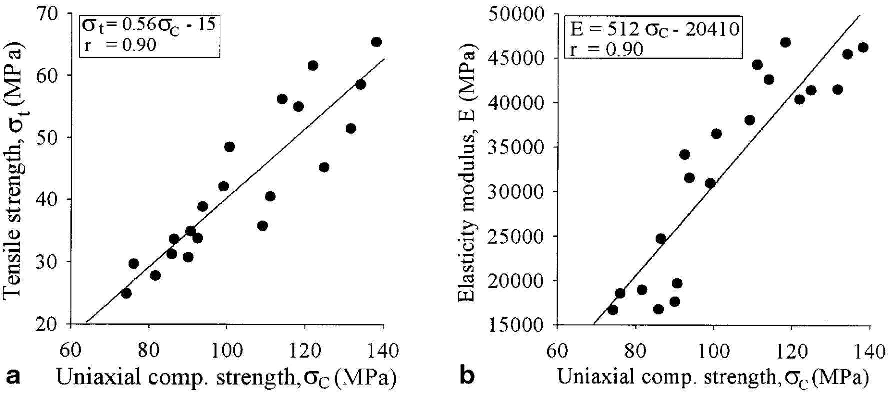


Fig. 14
Relationship between **a** uniaxial compressive strength and tensile strength and **b** uniaxial compressive strength and modulus of elasticity

Conclusions

Field and laboratory studies were carried out on limestone of Devonian age in order to clarify the effect of weathering on the engineering properties of this type of rock. The results are as follows:

1. The study showed that in the humid east Mediterranean climate of Istanbul, the dominant effect of weathering on the Devonian limestones was chemical rather than physical.
2. The degree of weathering depends on the carbonate content, texture and porosity and the incidence of discontinuities within the rock mass.
3. As weathering increases, so do the percentages of SiO_2, Al_2O_3, Fe_2O_3, Na_2O and K_2O, which make up the chemical composition of the limestones, but the CaO content decreases.
4. Microfabric changes are observed in the transition zone. Dissolution and increasing voids in the texture are the important phenomena for this rock.
5. Changes in microfabric of the limestones due to weathering control strength of this type of rock.
6. The textural and microstructural features in the rocks provide the most direct control on the material strength, but grain to micrite ratio and carbonate content are also recognized as important.
7. Porosity is a good indicator of weathering. The unit weight and the rock strength decrease with weathering while the porosity increases.

Acknowledgements This work was supported by the Research Fund of the Istanbul University. Project no. 877/090896. The authors would like to express their thanks to Prof. Okay Gürpinar, Prof. Namik Yalçin and Prof. Mehmet Önalan from Istanbul University and the staff of SET Concrete Inc.

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