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Monitoring and Correlating Geotechnical Engineering Properties and Degree of Metamorphism in a four-stage alteration process passing from pure Limestone to pure Marble

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ABSTRACT

The Bernician Great limestone from Northumberland England has been divided into four metamorphic grades: a) un-metamorphosed, grade A, limestone, b) low metamorphic, grade B, limestone, c) high metamorphic, grade C, limestone and d) completely metamorphosed, grade D, limestone (marble).

Representative samples of these grades were collected, sectioned, their petrography and mineralogy described as well as the gradual influence of contact-metamorphism on its mineral composition, structure and texture determined.

Geotechnical Engineering tests were performed on rock cylindrical cores, and irregular lumps of the four selected grades. Among the tests carried out, were laboratory index tests for characterization, engineering «design» tests, and weathering simulation tests.

These, revealed the geotechnical properties and behaviour of all four metamorphic grades of the Great limestone and that metamorphism, as a geological agent, has a considerable effect and alteration on the geotechnical engineering properties, as shown by the gradual deterioration of its rock material geomechanical quality, with increasing metamorphosing action.

Finally, a mathematical relationship, using the correlation analysis, can be shown to exist between the geotechnical properties and the petrographic texture and structure of this rock type as metamorphosing action proceeds.

KEYWORDS: geotechnical engineering properties; degree of contact metamorphism; index & physical & mechanical properties of limestone and marble; rock material quality and geomechanical behaviour; mathematical correlation analysis.

INTRODUCTION

This paper forms a rock material study of the Great limestone, with respect to its engineering geological properties and their changes caused by contact metamorphosing action. The metamorphism occurred in certain localities in Northumberland, due to the Whin sill, being intruded between the Great limestone bedding planes.

Since the Great limestone is a well defined geological unit and underlies the greatest part of Northumberland, it plays an important role to many engineering fields and projects, such as concrete and roadstone aggregate production, underground excavations, road cuttings, dams, bridges, or in putting down other foundations for civil engineering projects. Furthermore, in many localities,, as for example in Longhoughton, this rock has been contact-metamorphosed to marble, and its engineering geological properties have been affected. The extent to which its geotechnical properties have been changed as well as the original properties of the Great limestone, are of utmost importance to the engineers.

In considering the engineering geology of this limestone, as an engineering material, its relevant physical and mechanical properties have been assessed; the most important being: strength, permeability and deformability (Dearman, W.R. 1974b), and their variations with increasing metamorphism, studied. These, in combination with petrographical and mineralogical aspects, determined its performance as individual rock fragment in many engineering situations.

Some of the previous works which have been carried out in this area, were only regarding the geological and some engineering geological studies of only pure Great limestone. Johnson, in 1953, studied its lithology and stratigraphy, and in 1958, its paleontological features. T.S. Westoll, D.A. Rodson and R. Green, in 1955, had studied its geological and depositional environments. K.A.G. Shiels in 1961, studied its petrography and dolomitization.

But, the effects of contact metamorphism on its engineering geological properties, have been studied only in this work.

This work has been undertaken in two quarries. The Mootlaw limestone, and the Longhoughton «Whinstone» Quarry, and is basically subdivided in two parts:

Fieldwork. At this stage, a systematic sampling was executed. Representative samples were taken from various locations of the quarry faces, in a sequence of increasing distance from the sill-limestone contact, for a subsequent detailed petrographical study in order that the different grades of metamorphism will be assessed as well as the process of metamorphism will be monitored. Geological mapping of the quarry faces was also carried out.

Laboratory work. This includes: the petrographic study of various metamorphic grades, index properties, engineering design and weathering simulation testing. The laboratory work has been carried out on irregular lumps, and cylindrical cores.

Finally, mathematical relationships among its various parameters, using the correlation analysis, have been included and the conclusions given.

BACKGROUND GEOLOGY

The Great Limestone studied, is the thickest limestone formation in Northumbrian series and the most characteristic, uniform and persistent band in the Yoredale of Northern England. It belongs to the wider Lower Carboniferous Limestone Series (Dinantian, after G.A. Lebour (1878) which is a dominantly marine, 1000 metres thick, succession.

The Great limestone has a normal thickness of some 15 metres, deposited during the upper Bernician age subdivision (G.A.L. Johnson 1958) and has been traced with fair certainty from the Southern Pennine area through the Northern Pennines to North Northumberland. In Northumberland, it rests on either sandstone, shale or on thin coal seam and there is often evidence of disconformity.

THE STUDY AREA GEOLOGY

In order to determine the effects of contact metamorphism on the engineering geological properties of the Great limestone, two quarries were used, from which sufficient rock materials were taken and tested in various ways and aspects in the laboratory.

One quarry, the Mootlaw quarry, is located in pure Great limestone, without being affected by any type of metamorphism, from which it was sampled the original unmetamorphosed rock (grade A). The other, the Longhoughton quarry, is located in the contact between the Great limestone (country rock) and the whin sill intrusion. This sill of north-eastern England is composed of dolerite and at the present location is about 15 metres thick.

In this location, the Whin sill intruded parallel to the Great limestone bedding planes. An absolute estimate of the age of the sill, by the helium method, gave a figure of $196x10^6$ years, i.e. during Hercynian age (F.J. Fitch and J.A. Miller. 1966).

As a result of this intrusion, a metamorphosing action was caused on the country rock, the Great limestone. The recrystallization was caused due to only temperature rise (pure thermal metamorphism). The mineral growth has taken place haphazardly in all directions, showing no signs of stress involvement in the process of recrystallization. No transfer of materials gases or fluids, from the intruded doleritic sill to the country limestone has taken place during metamorphism, without any evidence of pneumatolysis.

Therefore it is a pure thermal, isochemical and isophasial metamorphism of the limestone country rock.

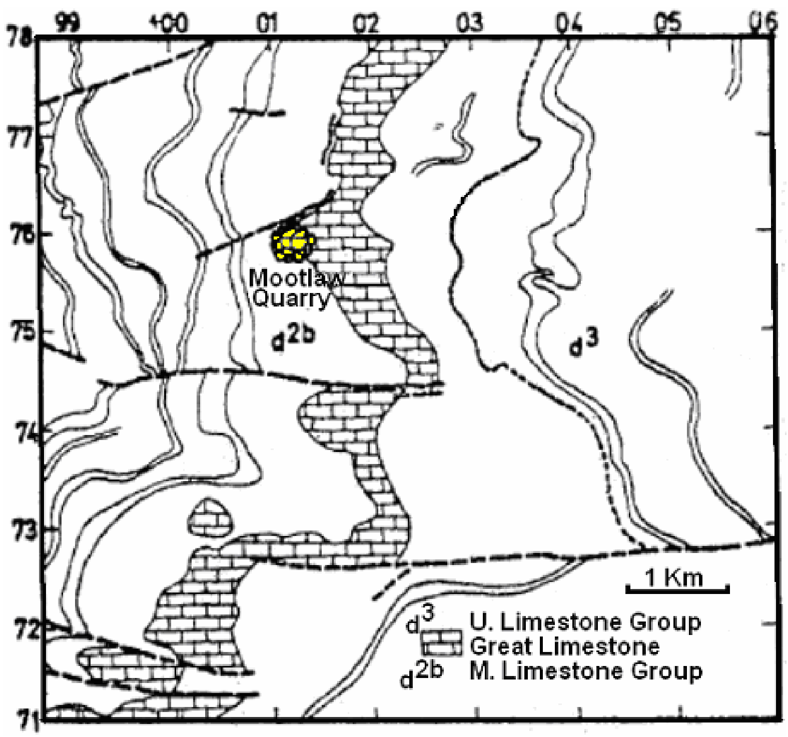


Figure 1a. Geological map of Mootlaw area.

From this quarry, three different groups of metamorphic limestone samples were taken, from various distances from the Whin sill-limestone contact, so that each group was metamorphosed to a different degree, depending on its distance from the contact; the closer to the sill the sample was taken, the higher the degree of its metamorphism it was. These are: Grade B: it was taken 5,5 to 5,75 metres away from the contact (Low metamorphic grade). Grade C: 2,25 to 2,5 metres away (medium grade) and Grade D: 0,25 to 0,5 metres away (High grade).

Therefore, there were sampled, four different grades of limestone, ranging in an increasing order of metamorphism from grade A, B, C to D; A being pure limestone and D marble, i.e. «Progressive metamorphic sequence». The location of the quarries as well as the geology of these areas are shown in the maps of fig. (1a,1b).

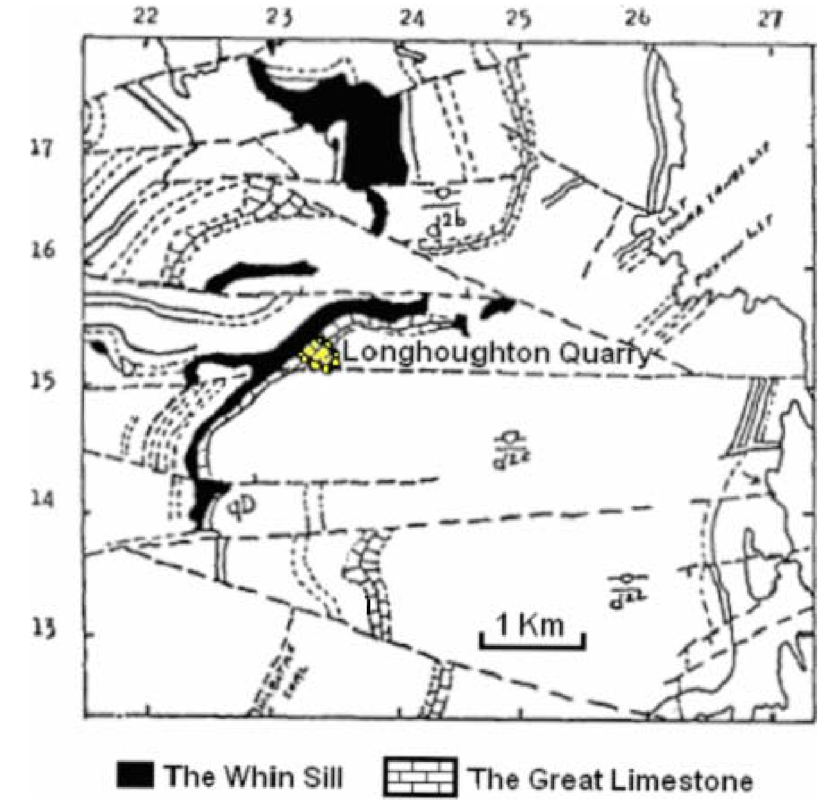


Figure 1b. Geological map of the Longhoughton area.

PETROGRAPHY AND MINERALOGY

Three thin sections - each one representing one orthogonal axis - of each rock grade, were cut-out of block samples, in order to determine their mineralogical constituents, texture types, mutual relationship between calcite and other particles, and the effects of metamorphism on petrography by using a common petrographical microscope and macroscopic description.

Grade A. Macroscopically, this is a «Dark greenish grey, very fine grained, crystalline textured, massive within the bed and thickly bedded, fresh, well calcite cemented, micritic shelly LIMESTONE, extremely strong, impermeable, exhibiting anisotropy due to bedding». Microscopically, it consists of skeletal shell fragments (40μ to 40mm) disseminated in the micritic matrix. The fragments are sparse allochems and are mainly composed of foraminifera, bryozoans, crinoid assicles, corals, fossil debris and a few pellets. Therefore, this rock grade is called «sparce biomicrite» following Folk's terminology. Also a few ferrous dolomite subhedral to euhedral crystals were observed (See plate 1).

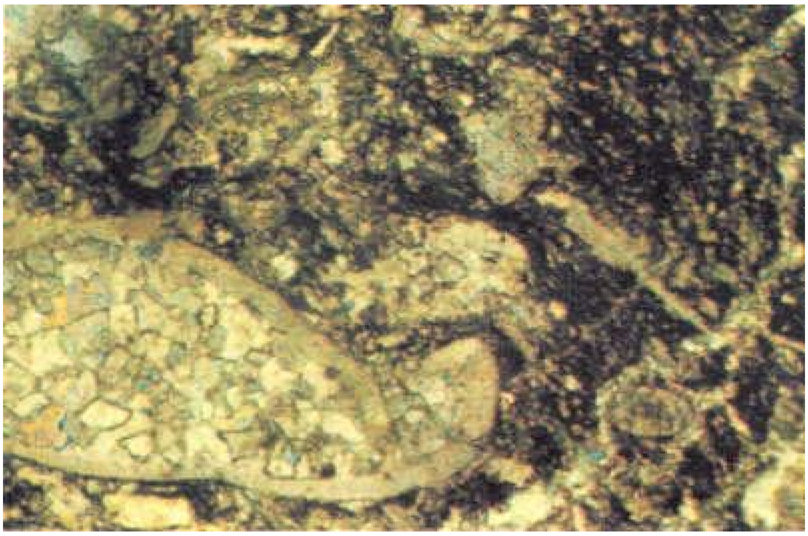


Plate 1. Photomicrograph (x nicols) for grade A «Sparse biomicrite».

Grade B. Macroscopically, this is a «Dark grey, very fine to fine grained, crystalline textured, massive within the bed and medium bedded, fresh, slightly affected due to contact metamorphism, sparry shelly LIMESTONE, very strong, impermeable». Microscopically the slight effects of contact metamorphism can be noticed on both micro-texture and mineral composition. It: consists of skeletal shell fragments (sparse allochems) disseminated in a microsparry matrix - 5 to 15μ rarely up 30μ - produced by recrystallization of micrite. In this phase, all allochems start changing their shape and boundary sharpness against the matrix due to slight and partial recrystallization. Only the largest shell fragments can still be easily recognised under the microscope. This grade is called «sparse biomicrospar» according to Folk's terminology. The main minerals identified were mainly calcite also some diopside, wollastonite, iron oxides and a few scattered dolomite crystals (see plate 2).

Plate 2. Photomicrograph (x nicols) for grade B «Sparse biomicrospar».

Grade C. Macroscopically, this is a «Dark bluish grey, fine grained, crystalline textured, massive within the bed and medium bedded, fresh, highly affected due to contact metamorphism, partially recrystallized LIMESTONE, strong, with very low permeability». Under the microscope, the effects of recrystallization on the rock texture, are more pronounced here, showing clearly the conversion of the original micritic and sparry calcite grains, into grains of larger size (phenomenon known as «grain growth»). This grade according to Folk (1965) can be termed as «pseudospar». In this phase almost all of allochems have been altered or obliterated; except of a few, the largest ones, of which their existence can be hardly traced. There have been traced some subhedral to euhedral dolomite crystals, forming a greater amount of dolomite content in this grade. Also some diopside, wollastonite and iron ore have been identified (see plate 3).

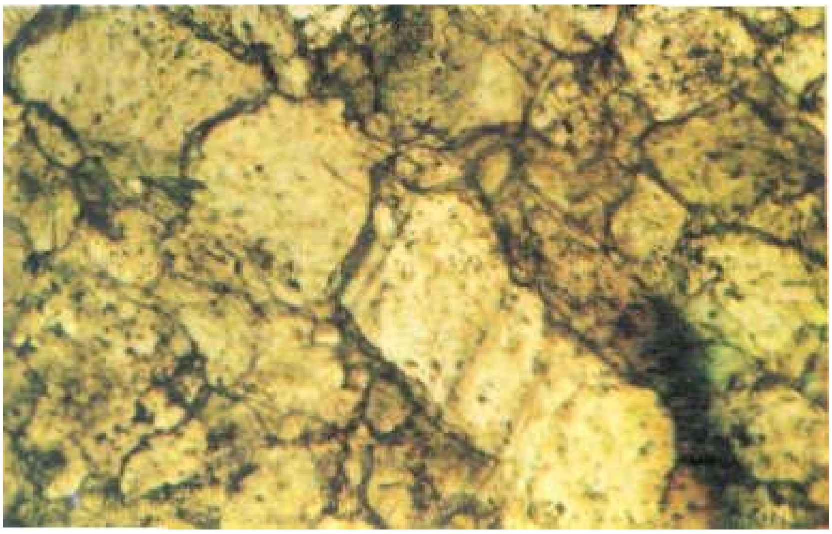


Plate 3. Photomicrograph (x nicols) for grade C «Pseudospar».

Grade D. Macroscopically, this is a «Very light bluish grey, medium grained, crystalline textured, massive, fresh, contact metamorphosed and completely recrystallized limestone or MARBLE, strong, impermeable». As shown in thin sections, all of the crystals have been completely recrystallized and grown, giving a coarser texture. The mean crystal size is about l mm and the rock is called «arenaceous marble». The main mineral constituents are calcite with a 10% of dolomite. Also small quantities of diopside and wollastonite have been identified (see plate 4).

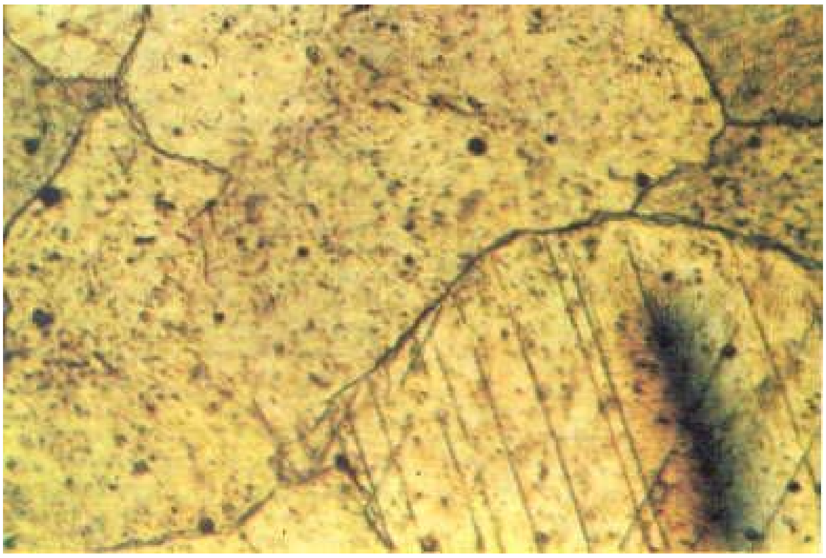


Plate 4. Photomicrograph (x nicols) for grade D «Arenaceous Marble».

TESTS ON ROCK CORES AND LUMPS

Sampling and Preparation methods

After determining the geology and establishing the different units or levels of the metamorphic grades in the Longhoughton Quarry, representative samples, of metamorphic grades B, C, and D, were collected.

The samples of pure unmetamorphosed Great limestone, grade A, were collected from the Mootlaw Quarry.

The samples had the form of: a) block rock samples (0,25 x 0,25 x 0,20m) and b) lump rock samples (about 6cm in diameter). Out of them, cylindrical cores were cut and lumps taken for various tests. A flow chart illustrating the testing sequence is shown in fig. (2).

The Index tests on rock cores

This group of tests mainly includes the determination as well as the variation of the physical and related properties of the four different grades of Limestone.

These are: bulk density (dry and saturated), saturated moisture content, effective and total porosity, void ratio - conducted in accordance with I.S.R.M., Anon, 1979 - mineral grain specific gravity - B.S. 1377: 1967 - ultrasonic velocity (dry and saturated) - Deere et al., 1969, Thill and Peng (1974) - and permeability - Akroyd, T.M.W. 1964.

The bulk volume was calculated using the Vernier calliper technique, and the saturation was done using Deere's (1969) method.

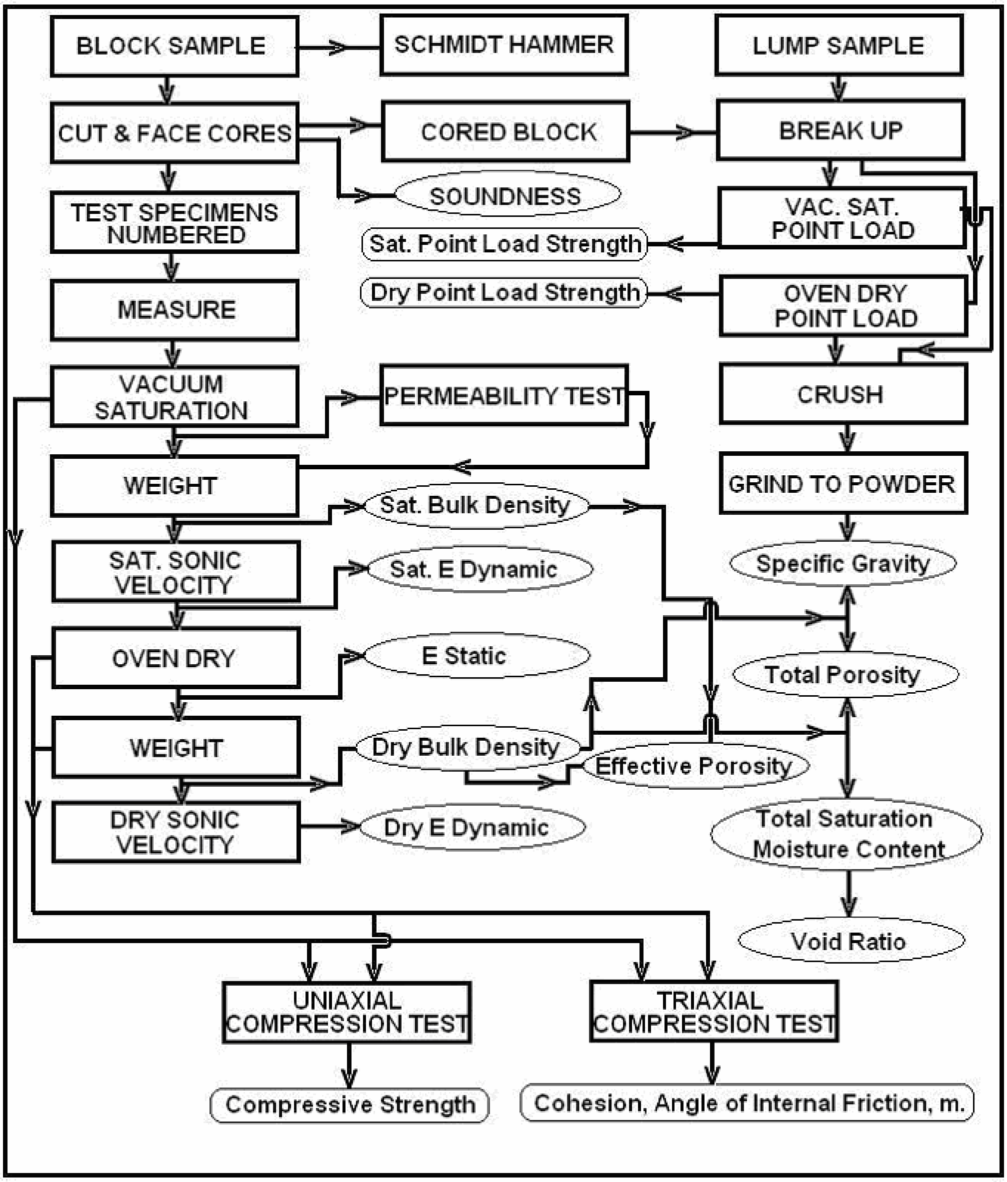


Figure 2. Flow Chart of Testing Procedure.

Physical properties

Table 1 shows the physical properties results, indicating that the densities as well as the mineral grain specific gravity increase as the metamorphism proceeds.

Ultrasonic Velocity

In the present study, this test was employed to assist in the classification of metamorphosed limestone, in terms of different engineering metamorphic grades. Modern portable non-destructive digital ultrasonic testers (known as Pundit) were used on prepared rock cores. The Pundit generates ultrasonic pulses at a rate of 10 per second, each with a frequency of 200KHz. 25 to 30 cores of each grade, in both oven-dried and saturated condition, were prepared and tested perpendicular to bedding planes. (See table (2)).

Figures (3), (4), (5), (6) show plots of: effective porosity - dry and saturated sonic velocity, dry velocity - dry density, dry sonic velocity - saturated sonic velocity, for each rock grade, as plotted by using graphic techniques and programming in computer, employing the linear regression analysis. The coefficients of determination for each plot were determined and given in table (3). A computer programme for the graphs as well as for the linear regression analysis was also developed, but not given in this study.

TABLE 1: Index properties of rock cylindrical cores.

ROCK GRADE	No. of cores tested	Bulk Density Dry	Bulk Density Saturated	Effective Porosity	Total Porosity	Saturated Moisture Content	Mineral Grain Specific Gravity	Void Ratio
		ρ_d gr/cm^3	ρ_{sat} gr/cm^3	N_{eff} %	N %	I.S. %	G_S	e %
A	23	2,607	2,608	0,06	0,94	0,02	2,6318	0,95
B	27	2,660	2,668	0,82	1,06	0,31	2,6882	1,07
C	24	2,660	2,674	1,39	1,57	0,52	2,7027	1,60
D	26	2,692	2,696	0,41	0,98	0,15	2,7186	0,99

The coefficients of determination suggest that, although a clear trend on the plots is shown, a very accurate estimate of one variable cannot be obtained given the other. This fact is attributed to the complicated influence of all factors together, such as porosity geometry of voids, texture, composition, density and other physical properties.

TABLE 2: Shows the average test results of sonic velocity.

Rock Grade	No. of Cores tested	Laboratory sonic velocity oven-dried	saturated	Dynamic Modulus of Elasticity MN/m^2	Bulk Density gr/cm^3	Porosity %
		Km/sec	Km/sec			
A	23	6,044	4,459	9,5x10^4	2,607	0,94
B	27	4,226	5,275	4,7x10^4	2,660	1,06
C	24	2,496	3,233	1,7x10^4	2,660	1,57
D	26	3,370	5,068	3,1x10^4	2,692	0,98

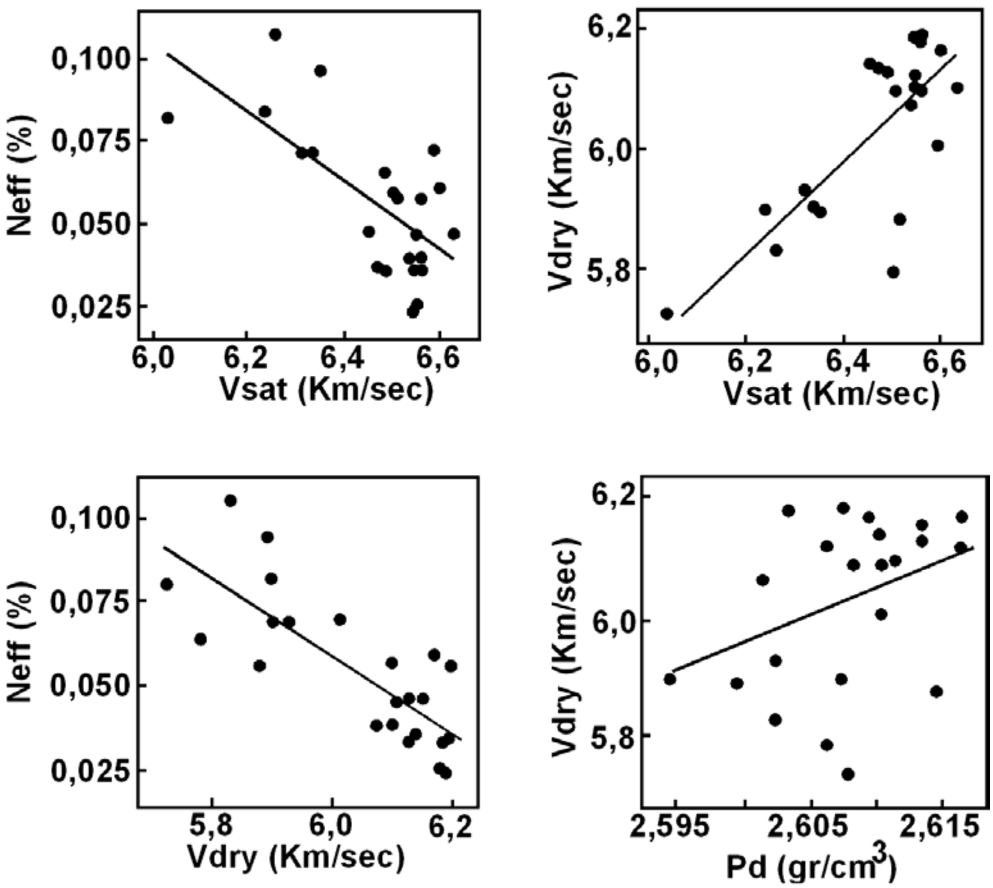
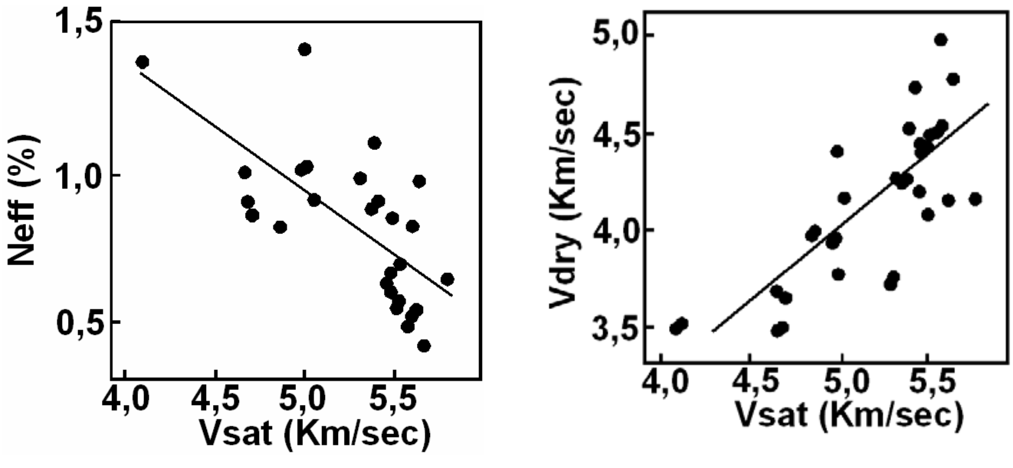


Figure 3. Grade A.



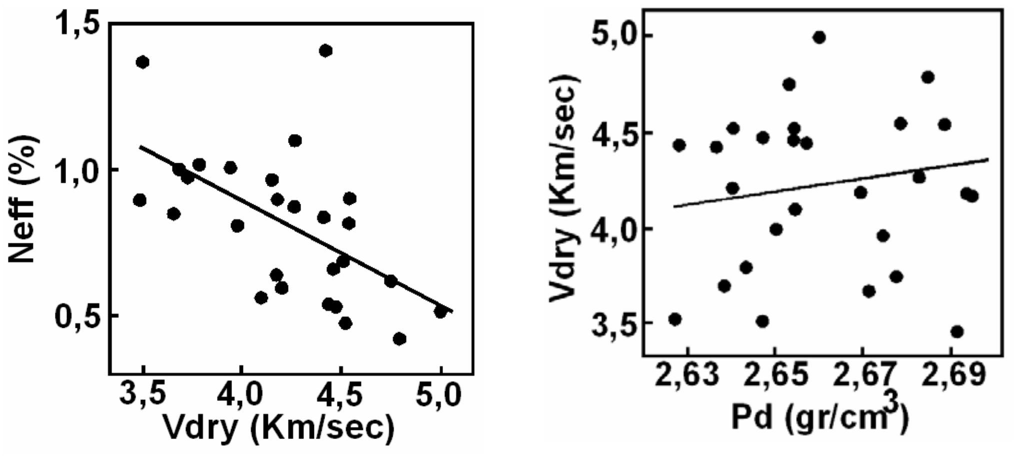


Figure 4. Grade B.

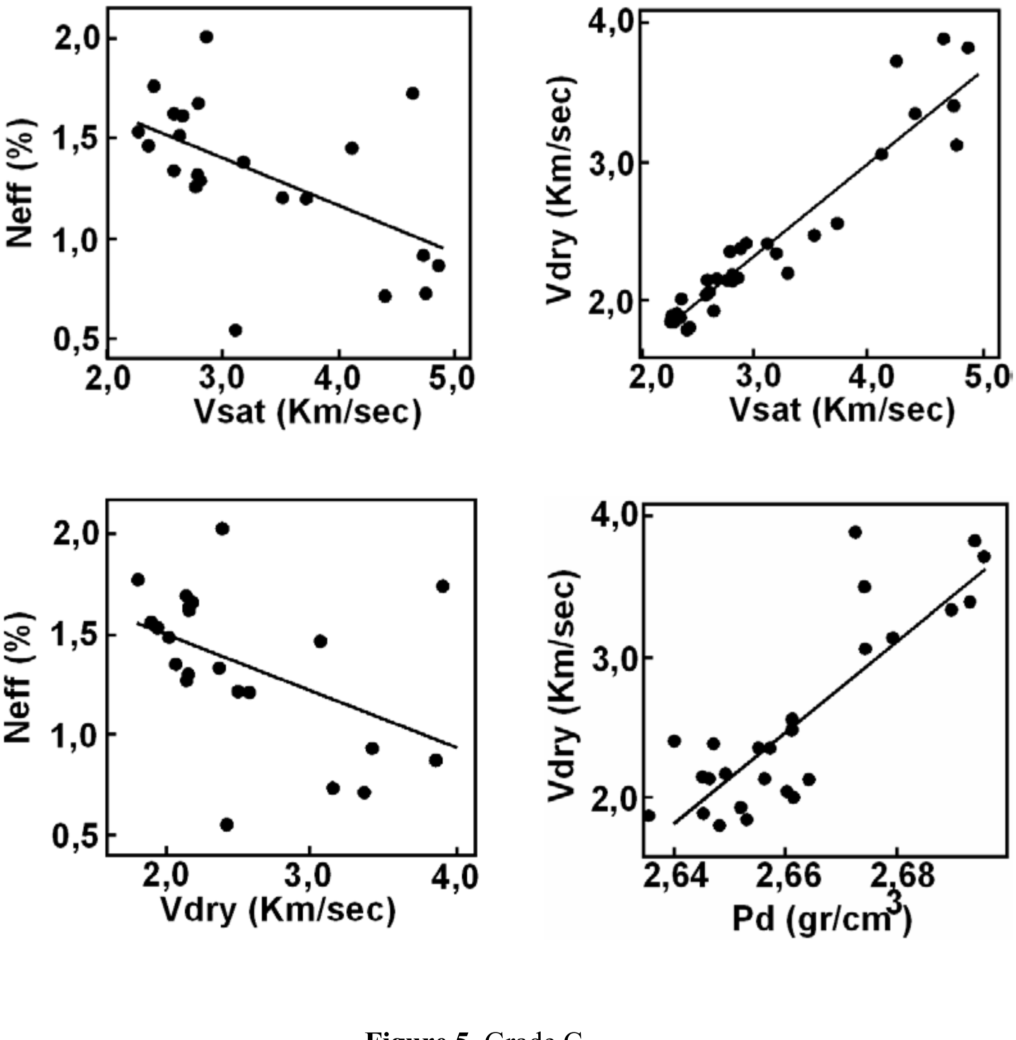


Figure 5. Grade C.

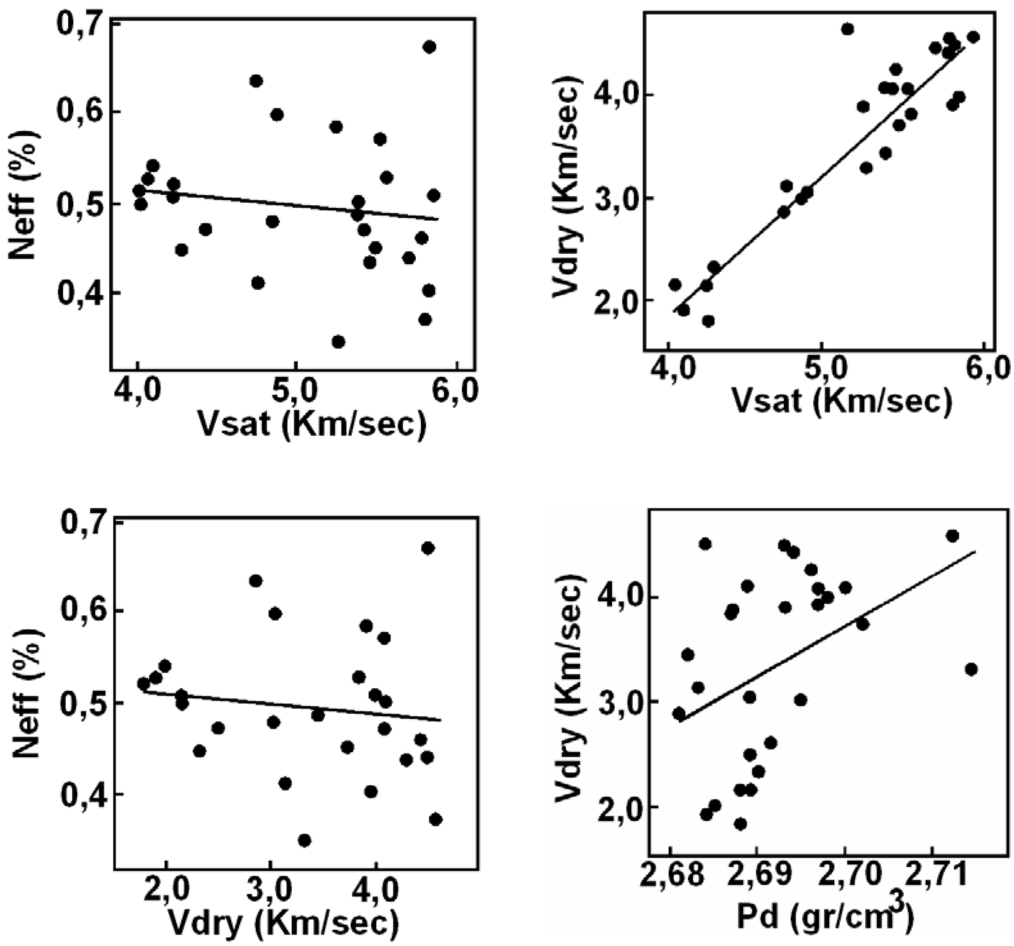


Figure 6. Grade D.

Finally it is noticed that:

1. Increase in metamorphic grade results in decrease of sonic velocity. It seems that as recrystallization proceeds the wave velocity is reduced. Grade C, however, gave lower sonic velocity than Grade D due to the fact that the porosity in grade C is approximately twice as high as in Grade D and has a major influence on the wave velocity.

2. Inside each grade, the wave velocity increases with increasing density and decreases with increasing porosity. But paradoxically, when comparing the bulk density with the sonic velocity amongst different metamorphic grades, the sonic velocity increases as the bulk density decreases, suggesting that factors like texture, composition, degree of recrystallization and mainly porosity, play a more important role on sonic velocity than bulk density does on its own.

3. The sonic velocity increases in water saturation. This is attributed to the fact that the ultrasonic pulses travel through the water filled pores and not all around the pore edges as they do in a dry state. As a result the travel path diminishes and the sonic velocity increases.

4. The average dynamic modulus of elasticity decreases as metamorphism increases.

5. Taking into account all the above mentioned notices as a whole, we can ultimately conclude that the most important and determining factor for the final formation of the magnitude of ultrasonic velocity, is mainly porosity. Other factors like texture, structure composition, density, and degree of metamorphism play a less pronounced role. For example although grade D has a higher degree of metamorphism than grade C, its sonic velocity is higher. On the other hand, grade's A and D porosities are about the same (0,94 and 0,98 respectively), but nevertheless grade's A sonic velocity is higher due to higher degree of metamorphism.

Permeability

Traxial cell designed by Hoek and Franklin (1968) was used to determine the permeability of all four grades of intact core cylinders.

105 bars confining pressure was applied to prevent leakage in between the cylindrical face and the membrane. Constant head pressure of 63,5 bar was exerted. The cores were tested perpendicular to bedding planes.

Three cores of each grade were tested and the average values taken. The test results are shown in table (4).

Therefore the above permeability results indicate that the permeability is generally very low, i.e. negligible values in engineering context, and all the four grades, with respect to their rock material permeability, could be considered as impermeable.

Schmidt hammer test

In the present study a type N hammer was used to relate the Schmidt Hammer Number (S.H.N.) to the unconfined compressive strength.

At least 40 readings were taken in each of two directions, parallel and perpendicular to the bedding planes, in the four different grades. The test was performed on rock blocks in the laboratory. Table (5) shows the SHN results as well as the (U.C.S.) for comparison reasons.

It may be seen from the results, that SHN generally decreases with increase of the degree of metamorphism in the rock. However, this criterion cannot always be accepted, because there are many other factors which affect these values, such as mineralogical constituents, texture and mainly porosity.

Fig. (7) shows the relationship between the perpendicular SHN and the U.C.S. It is clear from the curve that as the compressive strength increases so does the hardness. It should, however, be noted that the results of SHN and U.C.S. must not be directly compared; the reason being that during the compressive loading of a specimen, it is caused work which leads to a build up of potential energy within the specimen and then is released on failure, while the Schmidt hammer test reflects the absolute hardness, without an energy build-up. Therefore the S.H. test is only a rough method for estimating the strength of materials and a useful tool for preliminary work.

TABLE 3. Shows the coefficient of determination (r^2).

Plot	Coefficient of determination (r^2)				
	Grade	A	B	C	D
	No. of data	23	27	24	26
N_{eff} - V_{dry}		0,62	0,31	0,22	0,02
N_{eff} - V_{sat}		0,46	0,47	0,32	0,02
V_{dry} - p_d		0,12	0,03	0,69	0,19
V_{dry} - V_{sat}		0,57	0,59	0,92	0,93

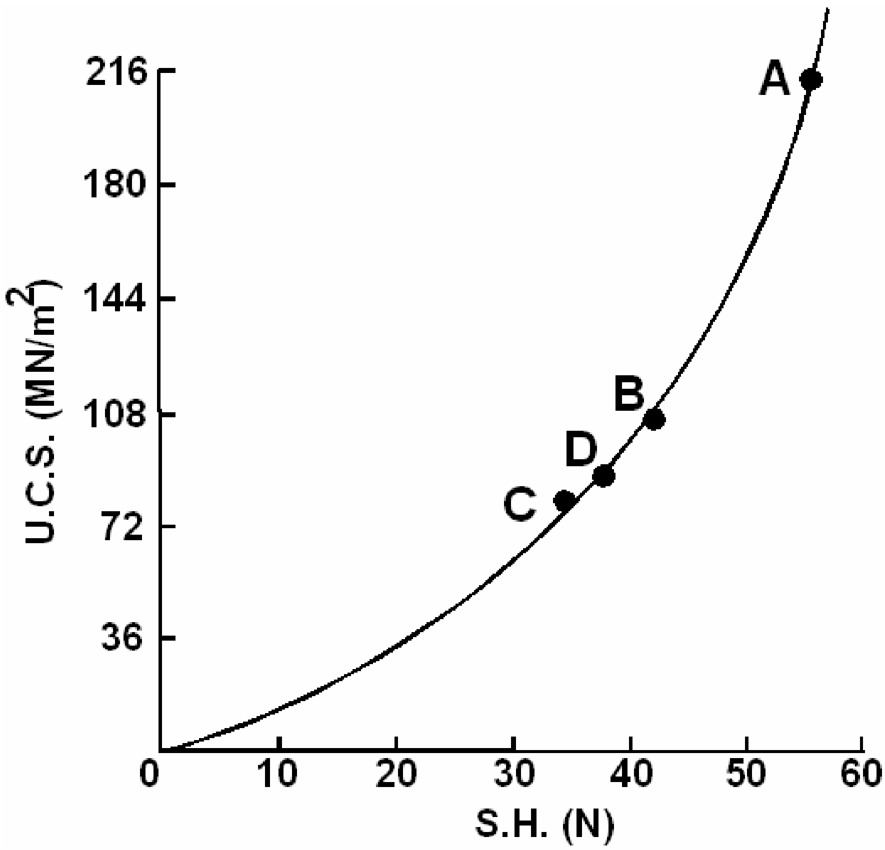


Figure 7. Diagram showing relationship between Uniaxial compressive strength and Schmidt hammer rebound number (N) for the four grades of limestone.

TABLE 4. Shows the average test results of coefficient of permeability.

Grade	A	B	C	D
Coefficient of permeability K (cm/sec)	0*	4,92 x 10^{-11}	8,58 x 10^{-9}	8,44 x 10^{-10}

* There was not any observable change in the volumetric tube for 2 hours time.

TABLE 5. Shows the average test results of Schmidt hammer rebound number (N).

Grade	No. of Data	Perpendicular to bedding rebound (N)	Parallel to bedding rebound (N)	U.C.S. (MN/m^2)
A	43	55,1	58,7	211,20
B	41	42,4	37,5	106,13
C	41	34,0	32,4	81,28
D	40	37,8	32,6	87,81

Point load strength test

A point load machine, built in accordance with the original design and recommended specifications (Franklin and Broch 1972), has been used in this research.

The P.L.T. is proposed as a standard test, for strength classification of rock materials and therefore as a replacement for the uniaxial (unconfined) compression test usually employed for this purpose. The advantages of both types of tests are given and compared in Bieniawski's paper in 1975 and the reader is advised to refer to it.

About 30 irregular prismatic rock specimens from each rock grade were tested in oven-dried (24 hours oven-drying at 105° ± 2° C) and about 30 in «saturated» (24 hours immersion in water at atmospheric pressure) condition.

To reduce the size effects to a minimum, specimens with diameters of more than 40mm and with ratios, of longest diameter to shortest one, of 1,0 to 1,7 were tested. (Broch and Franklin, 1972, Bieniawski, 1975).

For standard classification the normalized point load strength index, I_s (50), has been used, and was obtained from the I_s by correcting this value to a reference standard diameter of 50mm using the correction chart (Broch and Franklin, 1972).

The results of all the four grades, in both oven dried and saturated condition, are set out in table (6).

It can be observed a strength reduction on saturation. All strength values given in table (6) are in MN/m^2, and perpendicular to bedding planes.

TABLE 6. The P.L.T. results of all the four grades.

Rock Grade	No. Of Data	State	Mean $I_s(50)$	Conversion factor from U.C.S. to $I_s(50)$	Strength reduction on saturation	Description (according to Z.T. Bieniawski's classification)
A	30	Dry.	4,90	43,1	19,4%	High Strength
	30	Sat.	3,95	48,0		
B	28	Dry.	2,37	44,8	3%	Medium strength
	28	Sat.	2,30	41,1		
C	31	Dry.	1,79	45,4	37,9%	Low strength
	30	Sat.	1,11	56,7		
D	31	Dry.	2,21	39,7	3,6%	Medium strength
	30	Sat.	2,13	35,1		

When Bieniawski, in 1975, tried to correlate rock strength values as obtained by both P.L. test and U.C.S. test, he suggested a conversion factor of 24 for the equation:

$$\text{U.C.S.} = 24 \text{ x } I_s(50)$$

This study suggests an average conversion factor of 44, nearly twice as much, indicating a risk of replacing the U.C.S. test by the P.L.T. as a design test and that the P.L.T. should be carried out only as a preliminary index test. But nevertheless, it is clear that metamorphism has an adverse effect on strength.

GEOTECHNICAL ENGINEERING DESIGN TESTS

Uniaxial compressive strength test

The compressive strength of core samples of the four grades was determined, using the Type GD Grade A, Contest Instruments, Ltd., testing machine of 2000 KN capacity.

Tests were conducted on oven-dried and saturated cores perpendicular to bedding. Strain rates were adjusted to achieve failure in 10-15 minutes. The core dimensions were as close as possible to 76 χ 38 mm, however, the test results were standardized for a 2:1 L/D ratio, using the correction formula due to Szlavin (1974).

The rock cores were carefully prepared to ensure that the imposed stress was evenly applied to the specimen and tested in accordance with the recommended procedure for determining the uniaxial compressive strength of the I.S.R.M.

Field examination and hand specimens showed that the Grades A,B and C were often criss-crossed by calcite filled veins which, it was anticipated, would act as selective planes of weakness. Where possible, specimens were prepared so that they did not contain any veins. However, because of the apparent discontinuous nature of some of these veins, inspection of the test fragments indicated that veins were present in a few of the samples. Careful examination of the test fragments proved that no failure surface occurred within or at the margin of a calcite vein.

Following each uniaxial test it was noticed that the lower strength specimens, Grades C and D, generally sheared alone one inclined plane of failure, following the shear mode of failure. The relatively higher strength specimens, Grades A and B failed along more than one subaxial planes, leaving two conical fragments at the top and bottom.

Table (7) shows the mean U.C.S. values fc, as derived from 5-6 cores in both oven-dried and saturated state of each grade.

Fig. (8), shows a correlation of the U.C.S. with the density, saturated density, dry sonic velocity and saturated sonic velocity as derived from cores of each grade.

The diagrams suggest, clearly, that as the density and ultrasonic velocity increases the U.C.S. also does so.

Finally, it was seen that the U.C.S. was dependent to some extent, on the specimen size, i.e. L/D ratio, moisture content, rate of loading, smoothness of bearing plates and core surfaces, and other factors which depend on the test specimens themselves and the nature of the solid mineral grains within the rock materials.

TABLE 7. The mean U.C.S. values fc in both oven-dried and saturated state of each grade.

Rock Grades	No. of cores tested	State	fc in MN/m^2	Strength term
A	5	Dry.	211,20	Extremely strong
	5	Sat.	189,70	
B	5	Dry.	106,13	Very strong
	5	Sat.	94,59	
C	5	Dry.	81,28	Strong
	5	Sat.	62,95	
D	5	Dry.	87,81	Strong
	6	Sat.	74,77	

Also, other factors which have an influence on this test are porosity and the nature and extent of the voids within the mineral aggregate which constitutes the rock material, also the presence or absence of fissures, mineral veins, fractures and other planes of weakness within the rock specimens.

However a general conclusion which can be drawn about this test, performed on the differed metamorphic grades is that as metamorphism proceeds the U.C.S. diminishes. This is believed to happen mainly due to grain growth, which takes place as metamorphism increases. But nevertheless, porosity has a major influence on the test result. This becomes apparent in the case of grade C, where, although its grain size is somewhat finer than grade's D, the U.C.S. of grade C is slightly lower than grade D, showing clearly that this amount of increase in porosity brought about more severe effects on U.C.S. than the amount of increase of grain size. It is considered, however, that if there would be no difference in porosity between grades C and D, then the grade's D U.C.S. would be lower than grade's C.

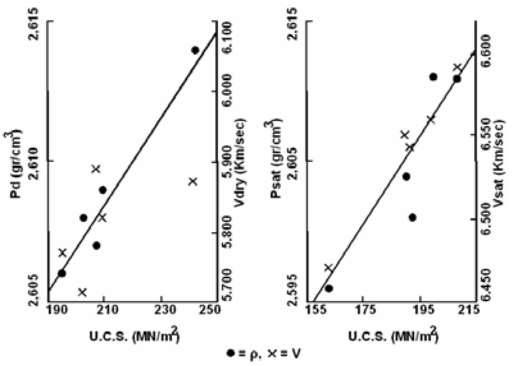


__Figure 8a__. GRADE A.

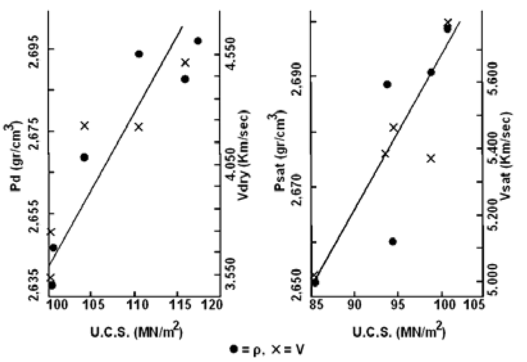


__Figure 8b__. GRADE B.

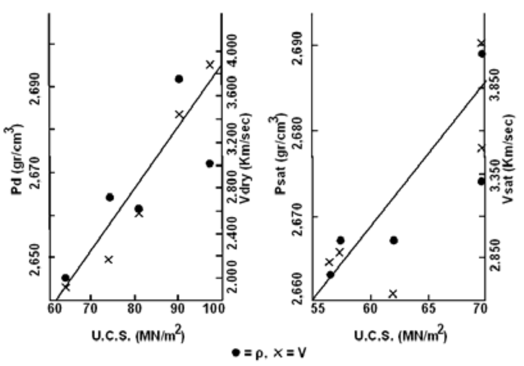


__Figure 8c__. GRADE C.

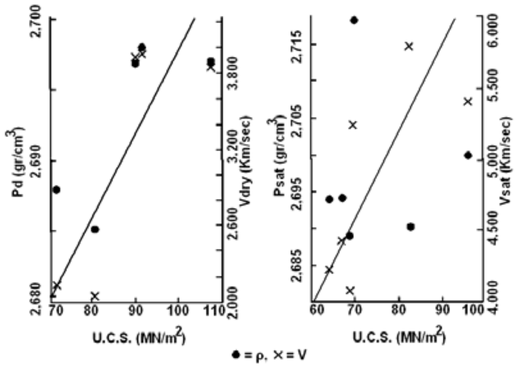


Figure 8d. *GRADE D.*

Stress-Strain Behaviour test

This test has been applied to measure Young's Modulus and Poisson's Ratio, as well as to study the deformation characteristics of metamorphosed limestones and pure limestone under cyclic loading.

The static modulus of deformation and Poisson's ratio have been obtained by using linear electrical resistance strain gauges bonded on the smoothest parts of the sample surfaces. (Two vertical and two horizontal strain gauges on each core were used).

Two cores from each grade were tested and the average values were obtained. The strain gauges were attached at mid-height of the specimen so that the end effects were minimised and the strains were determined employing a sensitive strain measuring indicator.

Both the axial (Ey) and lateral (Ex) strains were recorded at different stress levels by subjecting the rock samples to the appropriate load in a compression testing machine. Three cycles of loading and unloading were measured for each rock sample studied.

The stress-strain curves were plotted for each grade and are shown in Fig.(9). The static tangent and secant modulus of elasticity and the Poisson's ratio were measured at 50% of the unconfined compressive strength of each grade, see Table (8).

TABLE 8. Static Young's Modulus and Poisson' s Ratio of each grade.

Grade	Static Young's Modulus* MN/m^2		Poisson's Ratio (v)	Residual axial strain at the end of the 3rd cycle
	Tangent	Secant		
A	$7,1 \times 10^4$	$7,5 \times 10^4$	0,313	$0,1 \times 10^{-4}$
B	$4,7 \times 10^4$	$3,2 \times 10^4$	0,181	$4,8 \times 10^{-4}$
C	$3,4 \times 10^4$	$1,7 \times 10^4$	0,262	$17,4 \times 10^{-4}$
D	$5,7 \times 10^4$	$3,7 \times 10^4$	0,253	$4,5 \times 10^{-4}$

* All static data perpendicular to bedding.

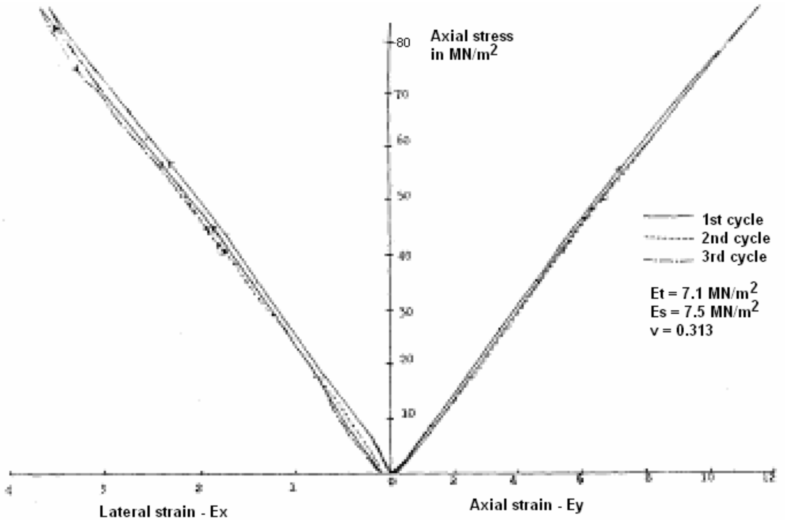


***Figure 9a**. GRADE A.*

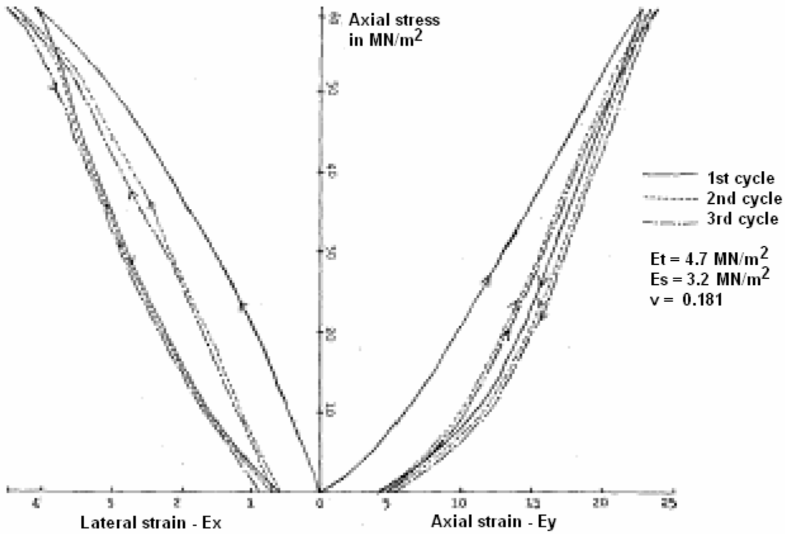


***Figure 9b**. GRADE B.*

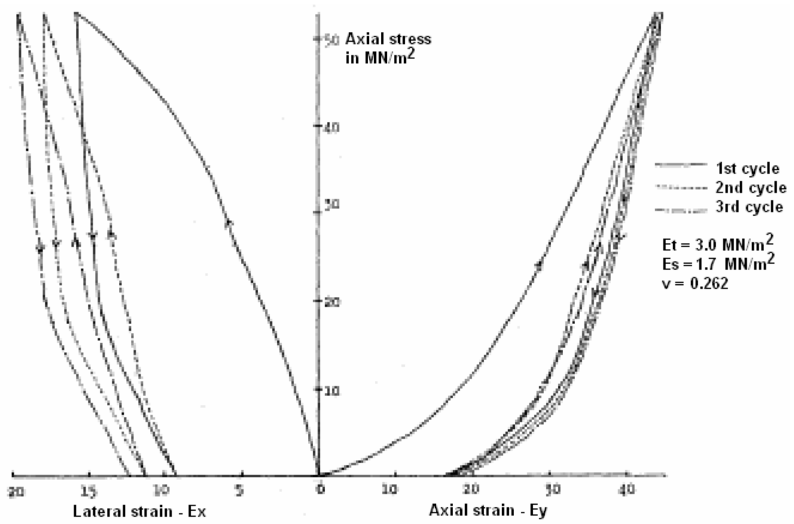


***Figure 9c**. GRADE C.*

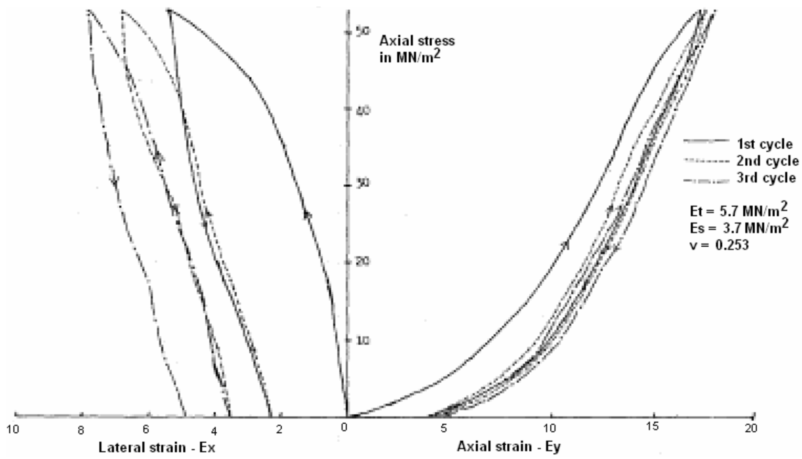


Figure 9d. *GRADE D.*

Discussion of the stress-strain results

The stress-strain curves clearly indicate the effect of metamorphism on the elastic behaviour of the limestone. From fig. (9) it can be seen that the hysteresis loops, as a result of cyclic loading and unloading, have enlarged - especially those which represent the lateral strain (Ex) - when metamorphism increases.

The residual strain or deformation (i.e. the irrecoverable strain) which was usually formed at the end of the first cycle in the highly metamorphosed rock samples (grades C and D), was reduced in the subsequent cycles under the effect of rock compaction by the load applied. This variation has also changed the values of Poisson's Ratio and Young's Modulus. For this reason the elastic constants were measured from the second cycle of loading and unloading. The results clearly showed also the increase of tangent (E_t) and secant (E_s) moduli of elasticity when metamorphism decreases. The completely recrystallized limestone (grade D) however, gave higher moduli, probably as a result of rearrangement of mineral grains due to complete recrystallization producing a closer crystal packing.

Failure Criterion for Rocks and Triaxial Testing Including (m) parameter

Strength of rock material has been used by Hoek and Brown (1980) as a basis for a failure criterion for rock masses. They have drawn on their experience in both theoretical and experimental aspects of rock behaviour to develop, by a process of trial and error, the following empirical relationship between the principal stresses associated with failure of rock:

$$\sigma_1 = \sigma_3 + (m\cdot\sigma_c\cdot\sigma_3 + S\sigma_c^2)^{1/2} \qquad (1)$$

where:

σ_1 is the major principal stress at failure,

σ_3 is the minor principal stress applied to the specimen,

σ_c is the uniaxial compressive strength of the intact rock material in the specimen.

The parameter, m, appears to vary with rock type, the angle of interparticle or interblock friction, and the degree of particle interlocking within the rock mass.

The parameter, s, appears to depend upon the extent to which the rock has been broken before being subjected to the stresses σ_1 and σ_3. This relationship can be represented graphically by means of a diagram such as that presented in Fig. (10a).

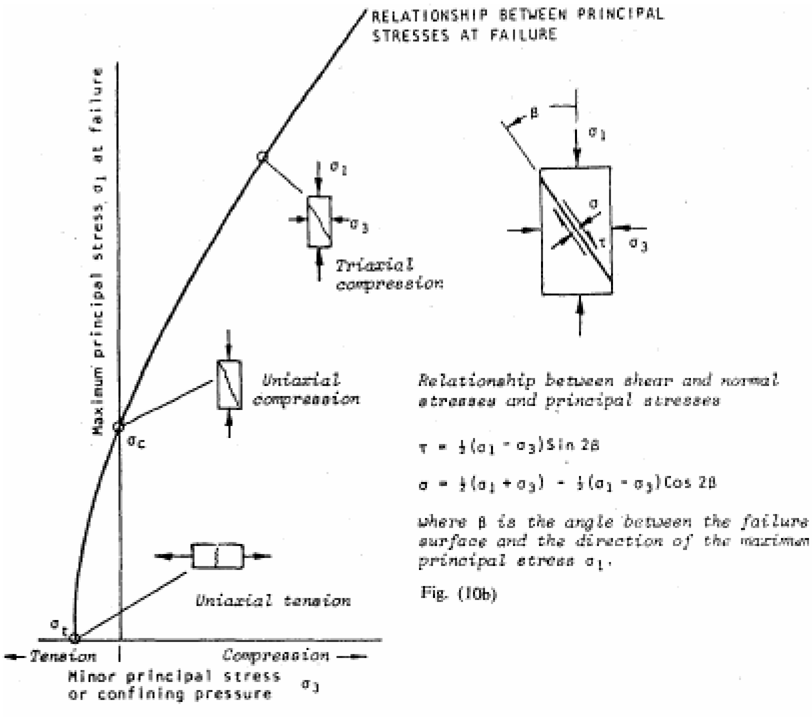


Fig. (10b)

Fig. (10a)

The uniaxial compressive strength of the specimen is given by substituting $\sigma_3 = 0$ in the equation 1, giving:

$$\sigma_{cs} = (S \cdot \sigma_c^2)^{1/2} \tag{2}$$

For intact rock, $\sigma_{cs} = \sigma_c$ (because, s, for intact rock, is s = 1).

In addition to the relationship between the major and minor principal stresses at failure, it is sometimes convenient to express the failure criterion in terms of the shear and normal stresses acting on a plane inclined at an angle β to the major principal stress direction, as illustrated in the figure (10b).

When the inclination β of the failure surface is known, the shear and normal stresses, τ and σ, can be determined directly from the equations presented under the figure (10b).

When an isotropic specimen is tested, it is usually assumed that the relationship between shear strength τ and normal stress σ is defined by the envelope to a set of Mohr circles representing the principal stresses at failure. Under these conditions it is assumed that the inclination β of the failure surface is defined by the normal to Mohr envelope as illustrated in figure (10c). But, nevertheless, this assumption is probably an oversimplification. It has been included in this discussion because of its historical importance in literature and also because it does provide a rough guide to the inclination of the failure surface or surfaces under some stress conditions.

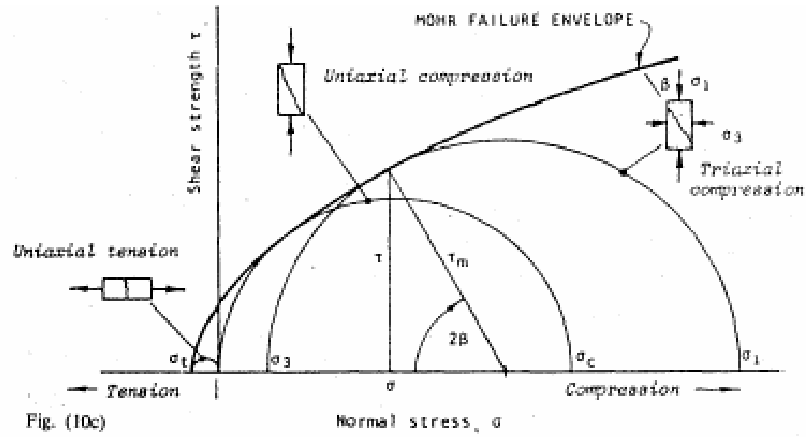


Fig. (10c)

Fig. 10a,b,c. Graphical representation of stress conditions for failure of intact rock.

Balmer derived a general relationship between the shear and normal stresses and the principal stresses at which failure of an isotropic rock specimen occurs.

$$\sigma = \sigma_3 + \frac{\tau_m^2}{\tau_m + m \cdot \sigma_c / 8} \qquad (3)$$

$$\tau = (\sigma - \sigma_3) \cdot (1 + m \cdot \sigma_c / 4 \cdot \tau_m)^{1/2} \qquad (4)$$

where:

$$\tau_m = 1/2 \ (\sigma_1 - \sigma_3)$$

The angle β is defined by:

$$\sin \ 2\beta = \frac{\tau}{\tau_m}$$

Traxial testing on intact rock specimens

Balmer derived a general relationship between the shear and normal stresses and the principal stresses at which failure of an isotropic rock specimen occurs.

Triaxial compression tests were carried out on the four grades, using the Hoek Triaxial Cell produced in accordance with the ISRM suggested method.

Five to seven 76mm x 38mm core specimens from each grade, in both oven-dried and saturated condition, were tested, loading them perpendicular to bedding, using confining pressures of 2.5, 5, 10, 15, 20, 25 and 30 MN/m^2. In order to establish the shear strength parameters, i.e. the angle of internal friction φ and cohesion C, the test data were plotted as Mohr circles, figure (11).

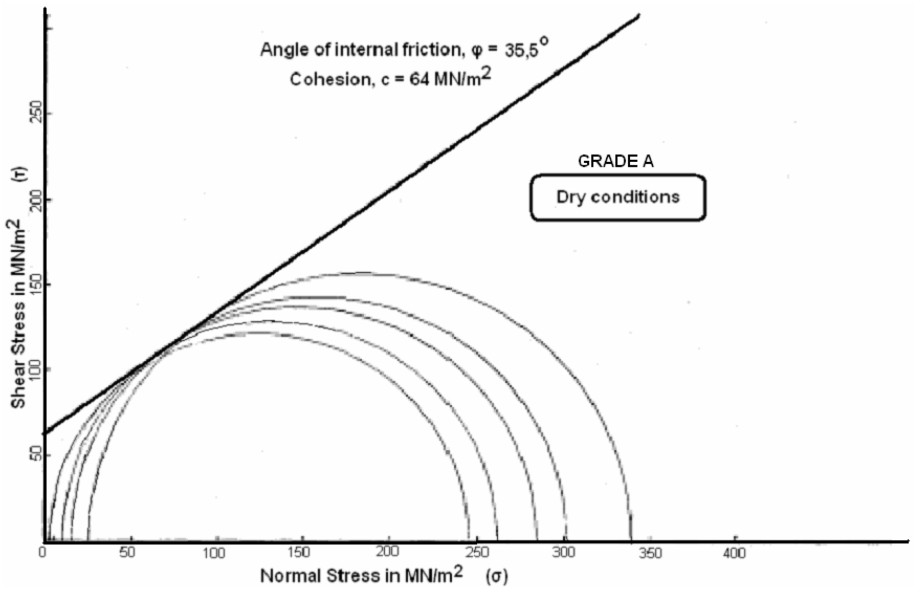


Figure 11a. *Mohr's circles and failure envelope for Grade A - Dry.*

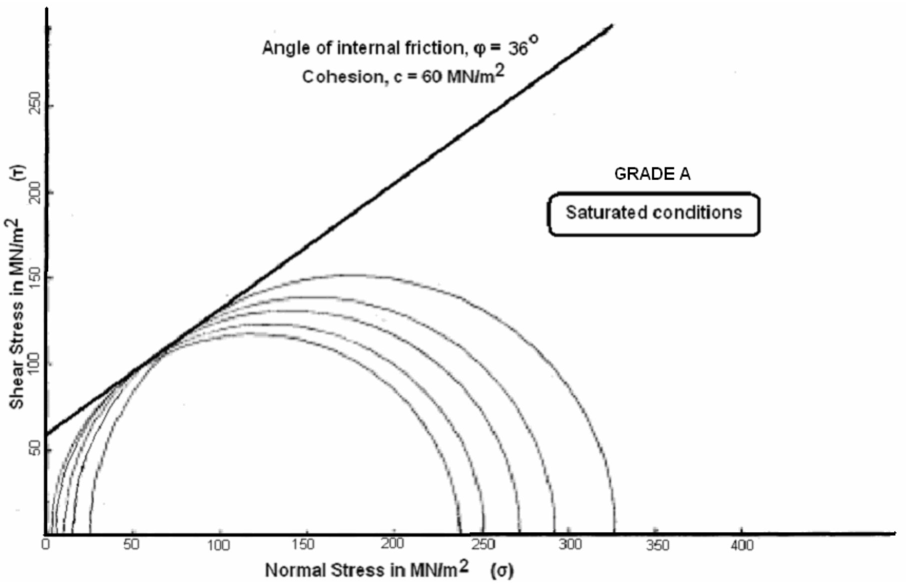


Figure 11b. *Mohr's circles and failure envelope for Grade A - Saturated.*

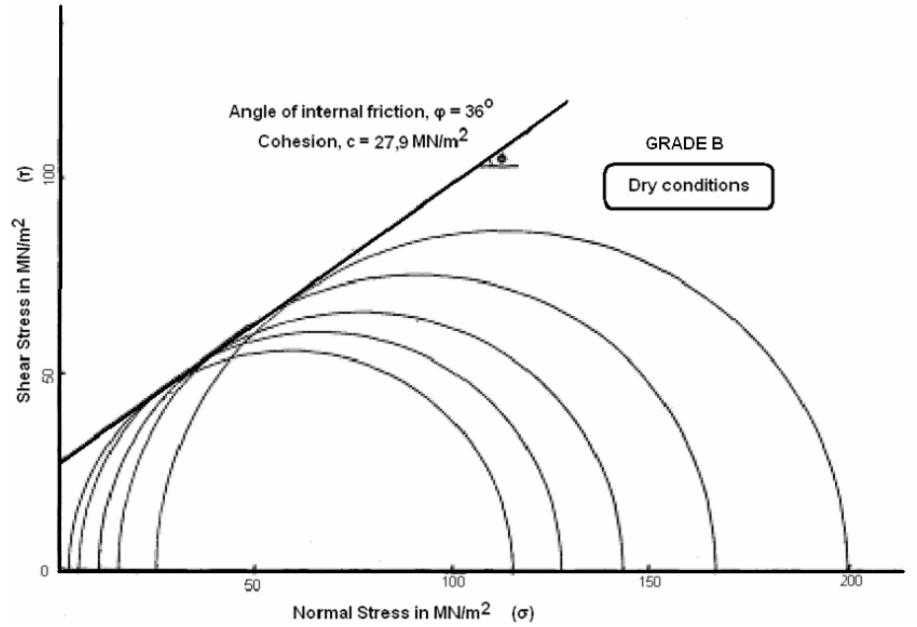


Figure 11c. *Mohr's circles and failure envelope for Grade B - Dry.*

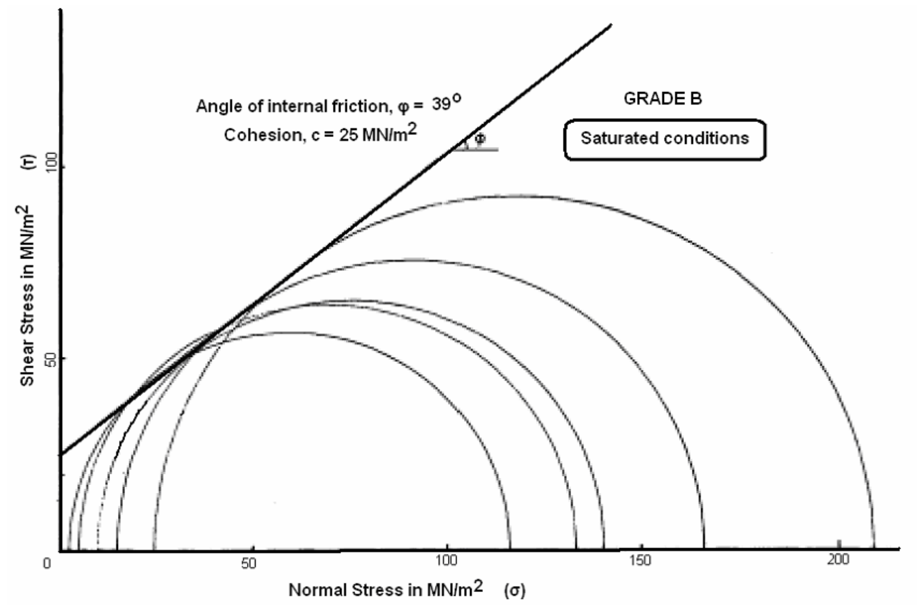


Figure 11d. *Mohr's circles and failure envelope for Grade B - Saturated.*

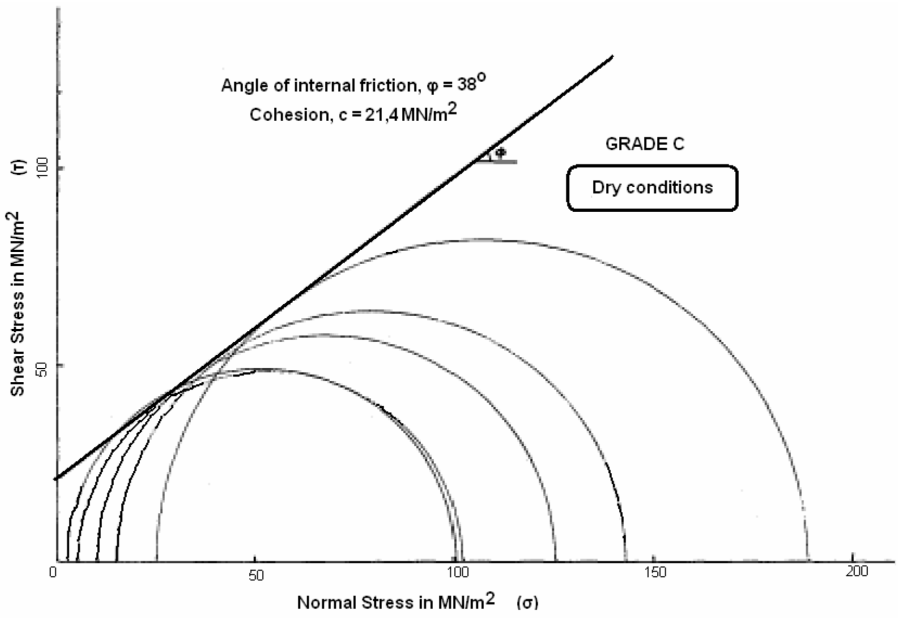


Figure 11e. *Mohr's circles and failure envelope for Grade C - Dry.*

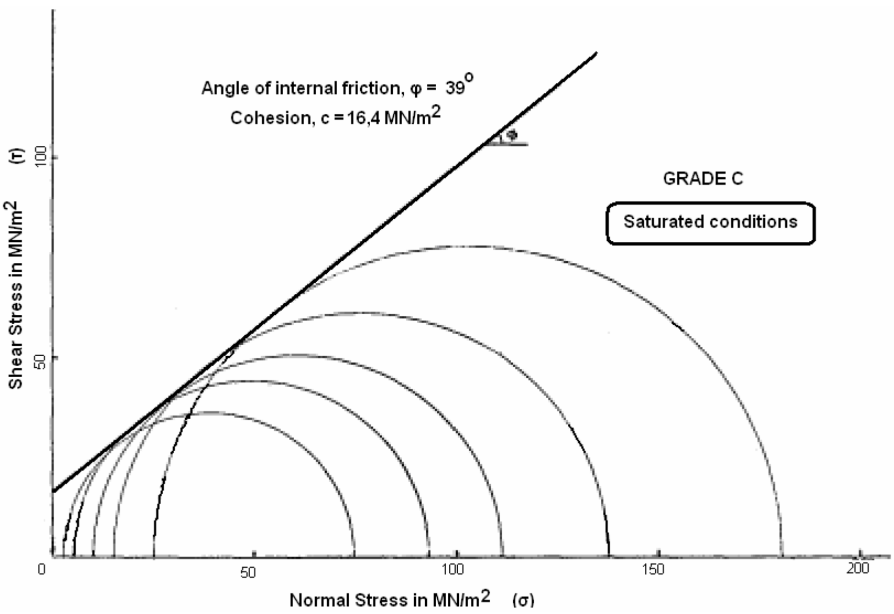


Figure 11f. *Mohr's circles and failure envelope for Grade C - Saturated.*

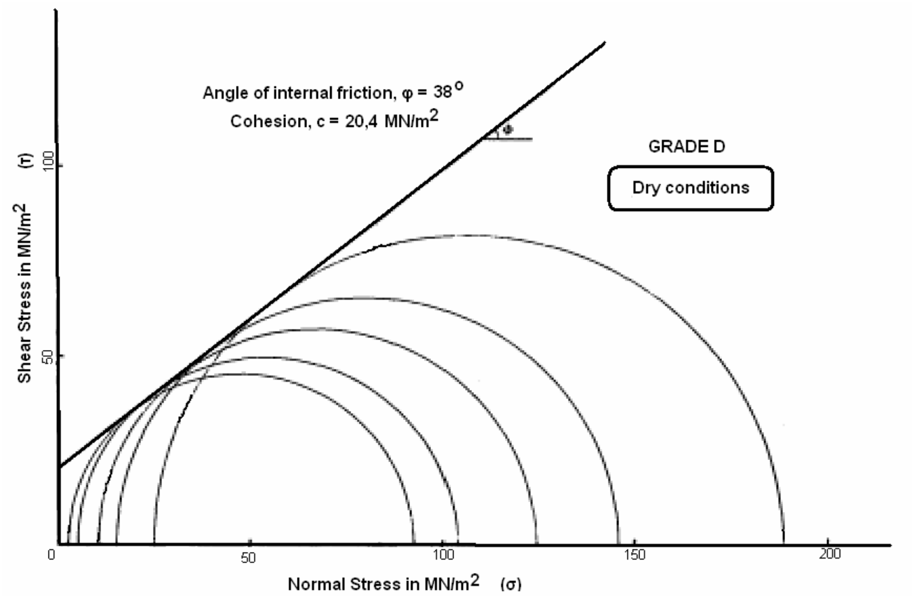


Figure 11g. *Mohr's circles and failure envelope for Grade D - Dry.*

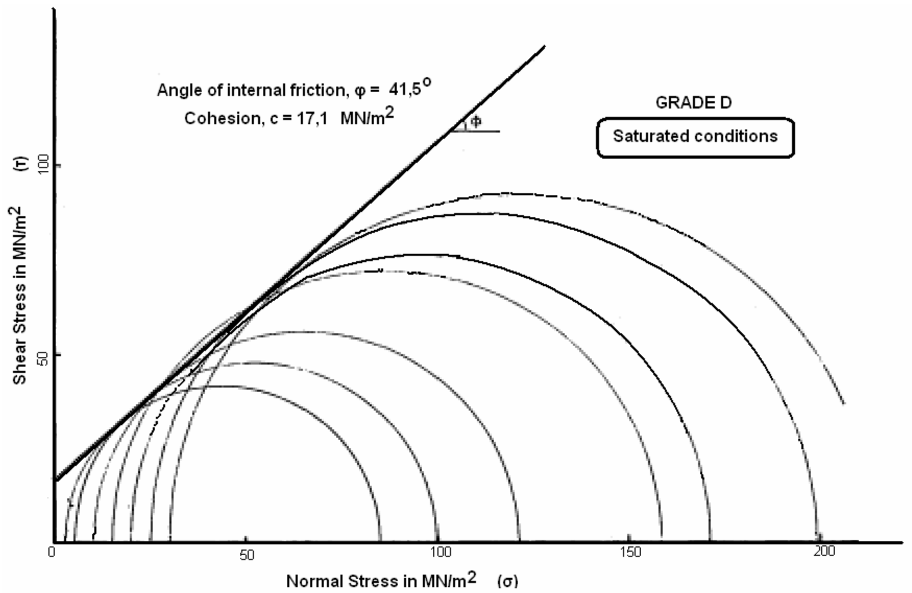


Figure 11h. *Mohr's circles and failure envelope for Grade D - Saturated.*

The figure shows the Mohr envelopes to be linear; probably resulting from the strong nature of the rocks and the low confining pressures applied to the cores compared with the normal stress. From the Mohr diagrams, · it is evident that the deviator stress is a variable which is directly related to the material type and consequently the compressive strength of the rock.

The graphically calculated cohesion, angle of internal friction as well as the resultant values of the strength parameter m are listed in Table (9).

The results plotted diagrammatically, Fig. (12), show a correlation between the cohesion and the angle of internal friction. In Fig. (13) the shear strength parameters are plotted such that the graphically calculated cohesion is shown against the, vertical axis and the tangent to the Mohr circles drawn at the graphically calculated angles.

Table 9 and Figures 14 and 15, show that there is a relationship between the shear strength parameters and the unconfined compressive strength. As expected the best relationship, forming a linear one, is between the cohesion and the unconfined compressive strength.

TABLE 9. Relationship between the shear strength parameters, the strength parameter m and the unconfined compressive strength of each grade.

Rock Grade	Location	No. of data	σ_c in MN/m^2	Φ in degrees	C in MN/m^2	m	r^2
B_{dry}	Longhoughton Quarry	5	106,13	36	27,9	7,5	0,99
B_{sat}	Longhoughton Quarry	5	94,59	39	25,0	9,5	0,96
C_{dry}	Longhoughton Quarry	5	81,28	38	20,4	10,2	0,99
C_{sat}	Longhoughton Quarry	5	62,95	39	16,4	13,2	0,99
D_{dry}	Longhoughton Quarry	5	87,81	38	21,4	9,0	0,97
D_{sat}	Longhoughton Quarry	7	74,77	41,5	17,1	13,5	0,99
A_{dry}	Mootlaw Quarry	5	211,20	35,5	64,0	8,2	0,99
A_{sat}	Mootlaw Quarry	5	189,70	36	60,0	8,4	1,00

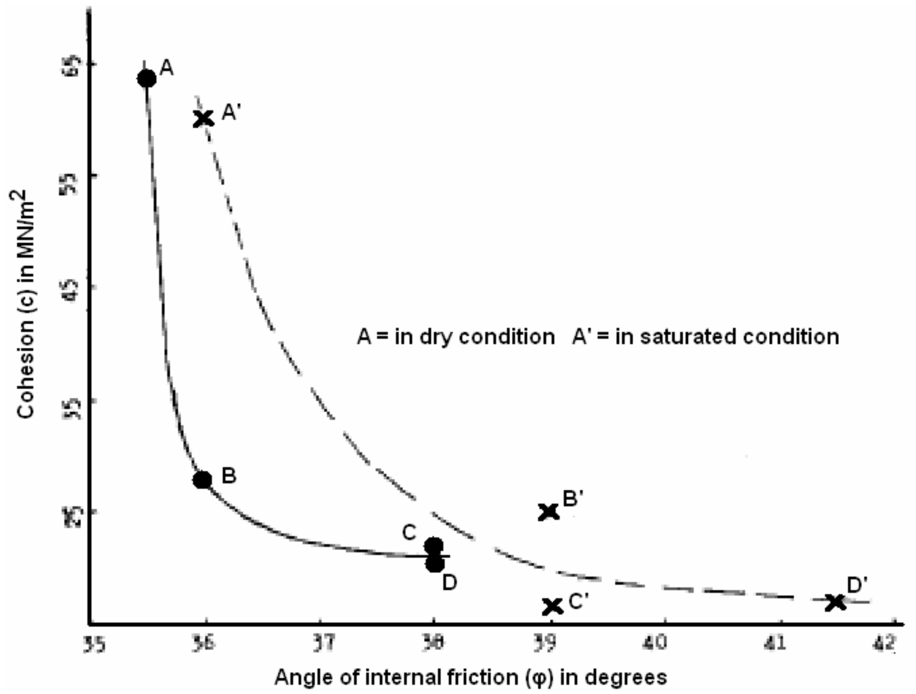


***Figure 12**. Correlation between the cohesion and the angle of internal friction of each grade.*

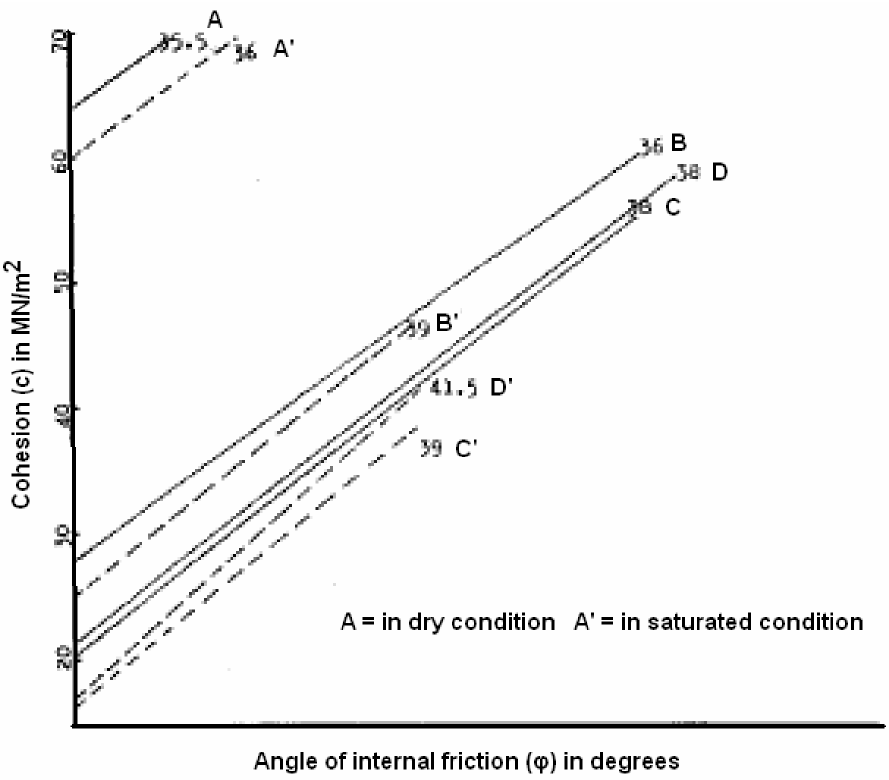


Figure 13. *Comparative diagram of the shear strength parameters of all grades.*

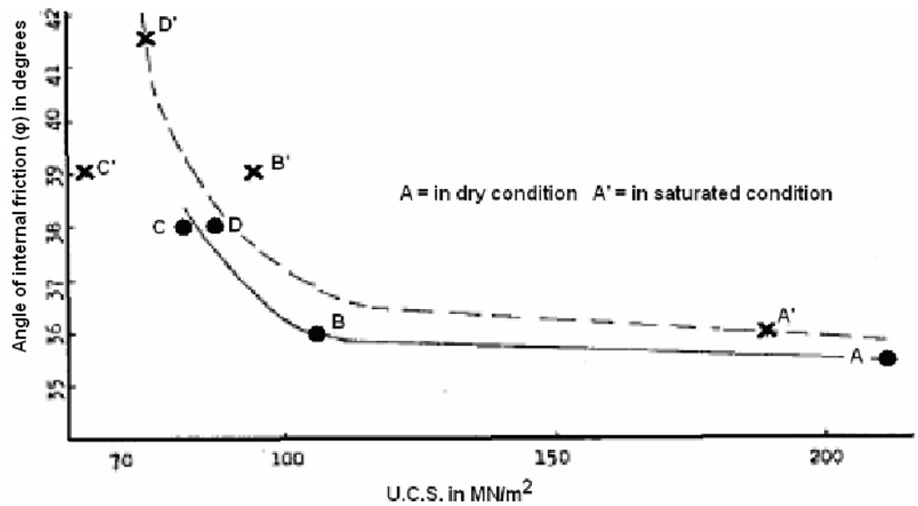


Figure 14. *Relationship between the angle of internal friction and the unconfined compressive strength of all grades.*

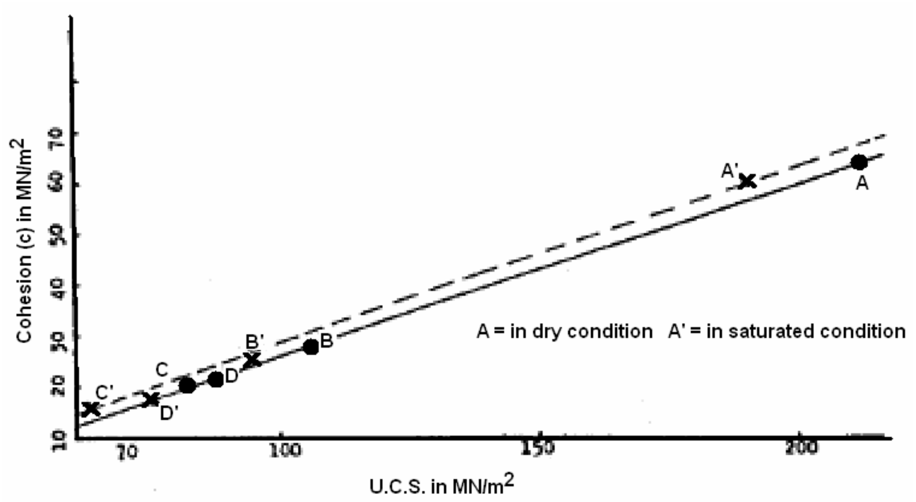


Figure 15. *Relationship between the cohesion and the unconfined compressive strength of all grades.*

Following each triaxial test it was noticed that the low strength specimens, grades C and D, generally sheared along one smooth inclined plane of failure. Also the higher strength specimens, grades A and B, failed along one inclined plane of failure, but it was rougher and undulating.

Finally, the values of m, for given data set, are determined by means of the linear regression analysis as set out below:

$$\sigma_1 = \sigma_3 + (m \ \sigma_c \sigma_3 + S\sigma_c^2)^{1/2}$$

may be rewritten as:

$$y = m \ \sigma_c x + s\sigma_c^2$$

where:

$$y = (\sigma_1 - \sigma_3)^2 \ \text{ and } \ x = \sigma_3$$

For intact rock, S = 1, the material constant m is given by:

$$m = \frac{1}{\sigma c} \left[\frac{\sum xi\, yi - \frac{\sum xi \sum yi}{n}}{\sum xi^2 - \frac{(\sum xi)^2}{n}} \right]$$

where xi and yi are successive data pairs and η is the total number of such data pairs.

The coefficient of determination r^2 is given by:

$$r^2 = \frac{\left[\sum xi\,yi - \dfrac{\sum xi \sum yi}{n}\right]^2}{\left[\sum xi^2 - \dfrac{(\sum xi)^2}{n}\right]\left[\sum yi^2 - \dfrac{(\sum yi)^2}{n}\right]}$$

This analysis has only been applied to data sets containing more than five experimental points well spaced in the stress space defined by $\sigma_3 < \sigma_1/3.4$.

The above table 9 shows the established values of strength parameter m for the four grades, under both oven-dried and saturated condition. They can, therefore, be substituted into the formula 1 (Hoek and Brown, 1980) and give an empirical strength criterion for intact rock of the corresponding grade.

WEATHERING SIMULATION TEST

The soundness test was conducted on rock cores of each grade, in order to simulate the crystallization phenomena occurring under natural environmental condition, and thus to determine their weatherability, durability or resistance to disintegration, as well as the effects of metamorphism on the stone weatherability. The test was carried out by using saturated solution of sodium sulphate, in accordance with the adopted method by: Commission 25 Pem. Protection et Erosion de Monuments. The results are shown in the following table.

Grade	The rock core weight Loss in %
A	0,0
B	0,0
C	0,2
D	0,0

The results indicate that the cores were unaffected by the solution after five cycles of soaking and drying, except of grade C which resulted only in a marginal loss. This is believed to be due to the Grade's C higher water absorption (Chorley 1969, Evans 1970).

Nevertheless, the whole spectrum of metamorphism can be considered that produces sound stones.

CONCLUSIONS

1) The stratigraphic succession of the Great Limestone in Mootlaw and Longhoughton areas has been recorded in terms of the biostratigraphy established by G.A.L. Johnson (1953). This

facilitated the choosing of the Quarries studied, as well as a stratigraphic control of sampling for subsequent material testing.

2) From the study of petrology and mineralogy of the metamorphic rock samples in thin sections, it was found that the alteration of the structure and microtexture of the rock material, due to metamorphosing action, has a great effect on the mechanical and physical characteristics of the rock material. The «grain growth» due to recrystallization seems to have an adverse effect on the mechanical properties of the rock.

3) The metamorphosing action was caused due to the Whin sill intrusion which consists of dolerite rock. It is a pure thermal isochemical and isophasial metamorphism.

4) Unconfined compressive strength tests, show a dramatic decrease of strength with increase of metamorphism, as well as a strength reduction on saturation.

5) Triaxial compressive strength tests show that saturation causes, in every metamorphic grade, an in crease of angle of internal friction (up to 3,5 degrees) as well as a decrease of cohesion. Furthermore as metamorphism proceeds, the angle of internal friction becomes higher, whilst the cohesion generally falls.

6) The ultrasonic velocity of the Great limestone decreases with increasing porosity and decreasing bulk density within each metamorphic grade. It also dramatically decreases with the degree of metamorphism thus indicating the major influence of metamorphism apart from the density and porosity. But nevertheless, it seems that the final magnitude of the ultrasonic velocity depends upon the combination of porosity, degree of metamorphism and bulk density, acting as a whole, in a rather complicated manner. Saturation of samples increases the ultrasonic velocity.

7) The stress-stain behaviour tests show also a reduction of the tangent and secant modulus of elasticity with metamorphism; the hysterisis loops become wider and residual strains or deformations (i.e. the irrecoverable strain), become greater due to metamorphism.

8) All the metamorphic grades of the Great Limestone have a high durability, and low weatherability as determined by the sodium sulphate weathering simulation tests on rock cores. The results show the effect of the water absorption of the tested material on its susceptibility to weathering.

9) A general notice which can be drawn from all tests results in this research, is that grade C presents a discrepancy with the general trend in the evolution of the test results, showing an inversion. This happens although detailed pertographical examinations indicated that grade C is metamorphosed to a lower degree than grade D. This is attributed due to relatively much higher porosity of grade C compared with that of all other grades. Porosity, as it is well known, plays a major role on the mechanical properties of rocks.

10) Finally, the general conclusion of this study is that metamorphism, as a geological agent, does affect the properties and the engineering behaviour of this rock type, rendering it considerably inferior in geotechnical terms.

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