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Assessment of excavability classification in a Limestone Quarry: A case study from Bayburt, Turkey

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Abstract

Excavability is a measure of material which can be excavated with classical excavation equipment. Studies to decide the rock excavability characteristics contribute to the suitability of engineering projects. In this study, a limestone quarry (in Bayburt, Turkey) was analysed with excavability classification systems and appropriate systems were determined. To accomplish this aim, point load index and Schmidt hardness tests were practiced and changed to uniaxial compressive strength tests. After that, findings were categorized with classification systems in excavation and matched against practices from field. In this study, rock mass was addressed as “pre-explosion”, “hard ripping” and “hammer and blasting” in accordance with distinctive classification systems. All determined as rock mass should be blasted for loosening then dug with hydraulic breakers. This practice is totally compatible with in-site excavations fulfilled. According to study results, the most suitable parameters to decide surface excavational classification are load strength index, geological strength index and the degree of rock mass weathering.

Keywords: *Degree of Weathering; Excavability Limestone Quarry; Point Load Index Test; Classification Systems*

1. Introduction

In quarry operations, besides the extent of material or orebody, the strength and excavability grade of the material (minerals, rocks, ores, etc.) are important parameters to be considered. Excavability is an expression of the excavation classification degree with excavation equipment (Külekçi 2018; Ceylanoğlu et al. 2007). The degree of dissociation, strength, and discontinuity distance plays a significant role in rock excavability (Külekçi 2021a; Alemdağ et al, 2011; Külekçi and Vural 2021).There are numerous studies suggesting excavability and removability classifications using rock mass and material properties for excavability classifications (Franklin et al. 1971; Weaver 1975; Kirsten 1982; Abdullatif and Cruden 1983; Scoble and Müftüoğlu 1984; Singh et al. 1986; Smith 1986; Bozdağ 1988; Karpuz 1990; Alemdağ et al, 2011; Kaya et al. 20011;Külekçi 2019; Aliyazicioğlu and Külekçi 2018).

The Schmidt hammer test, an easily applicable, economic, and rapid test method, is used frequently in determining the hardness concrete and rock strength and also estimating the uniaxial compressive strength (UCS) indirectly. Indirect method Schmidt hammer (SH) test used in predicting UCS is simpler, faster, and more economic than UCS (Kahraman 2001; Külekçi 2021b).

Schmidt first developed the test in 1948 to test the attractive stiffness of concrete (Schmidt 1951; Goudie 2006). Subsequently, the test began to be used to test rock strength (Katz et al. 2000). SH value was used to figure out the UCS of rocks from the beginning of the 1960s (Deere and Miller 1966; Aufmuth 1973; ISRM 1981; Gökçeoğlu 1996; Yaşar and Erdoğan 2004; Aydın and Basu 2005; Göktan and Güneş 2005; Külekçi and Yilmaz 2017). Factors affecting the number of recoil readings with the SH include hammer type used, decomposition of the sample rock, rock surface roughness, and moisture content of the rock surface (Poole and Farmer 1980; Sumner and Nel 2002; Büyüksağış and Göktan 2007). There are very different measurement and evaluation methods in the literature (Hucka 1965; Deere and Miller 1966; Poole and Farmer 1980; ISRM 1981; Haramy and DeMarco 1985; Göktan and Ayday 1993; USBR 1998; ASTM 2001; Külekçi and Yılmaz 2016, 2018; Külekçi and Çullu 2021).

The point load index (PLI) test is performed to analyse the rocks according to their strength. In addition, other strength parameters such as UCS and tensile strength are indirectly determined by using PLI values and used as input parameters for rock material in some rock mass classification systems. However, today point load index testing is often used to indirectly determine the pressure and tensile strengths of the strength index since it is a cheaper and more practical method than other methods.

The point load test was first used by Protodyokonov to determine the strength of non-uniform sections (Arıoğlu and Bilgin 1978). Since this experiment is cheap and practical, it can be done in the field and applied to unformed specimens, making the experiment very practical. The point load test is applied to classify the rocks according to the point load index or to estimate the uniaxial compressive strength (McFeat and Tarkoy 1979).

In this study, excavability classification was performed and the validity of the method was analyzed in practice in a quarry. Within this scope, different excavability classification systems were applied to the quarry by performing discontinuity distance measurements, Schmidt hardness, and PLI. In the quarry which was

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calculated to be difficult to dig/scrape, the blasting design was examined by applying loosening blasting. In this regard, practical modeling and analysis of aggregate production from the orebody model to the excavation is presented for a limestone quarry.

2. Materials and Method

2.1. Site Information

The working area is located in Tepetarla village in the provincial center of Bayburt (north-east Turkey) (Fig 1). The study area contains limestone (Berdiga Formation) products excavated by Bayburt Municipality (Fig 2).

The material obtained from the quarry is sent to the municipal crushing and screening plant located 3 km from the worksite. The material which is ground to suitable sizes in the crushing screening plant is used in various infrastructure works and projects by Bayburt Municipality.

2.2. General Geology

The working area (Bayburt-Tepetarla) is located within the Eastern Pontides Orogenic Belt, which is located within the Sakarya Zone in Turkey.

This belt is also part of the Alpine-Himalayan orogenic belt which contains remnants of the Tethys oceanic basin (Şengör and Yılmaz 1981).

The oldest units in the Bayburt-Tepetarla area are Late Carboniferous granitoids (Topuz et al. 2010; Kaygusuz et al. 2016) called the Gümüşhane Granitoid and Late Carboniferous-Early Permian metasedimentary rocks called Kopuzsuyu Deresi Formation (Özer 1984; Topuz et al. 2001) (Fig 1).

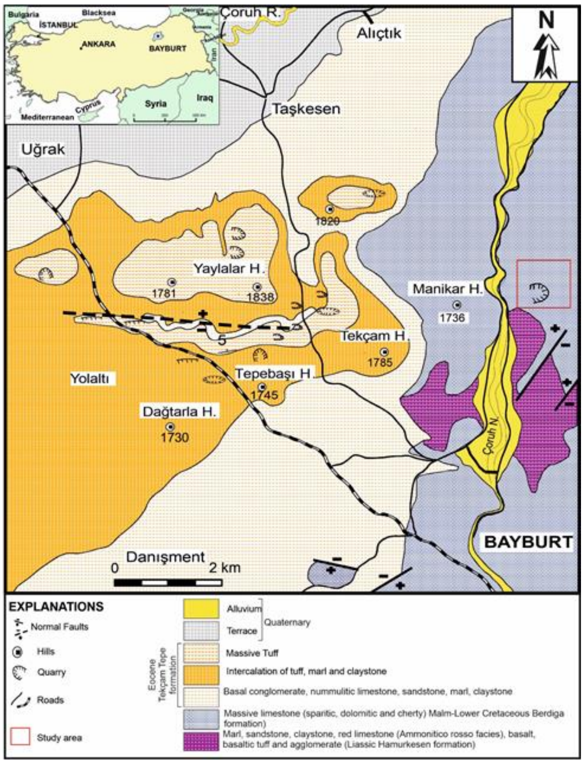

Fig 1. Geological & location map of the Bayburt-Tepetarla area (After Arslan et al. 2005b)

The metasedimentary rocks outcrop in the south of the region outside the Bayburt-Tepetarla areaand they are the continuation of the Hercynian basement rocks, called the Pulur Metamorphics (Ketin 1951) and the Pulur Massif (Korkmaz and Baki 1984). These rocks are unconformably overlain by Early-Middle Jurassic volcano-sedimentary units called the Hamurkesen Formation by Ağar (1977). The Hamurkesen Formation begins with basal conglomerate and continue with red-coloured limestones (Ammonitico-Rosso facies), and end with sandstone, marl, and tuff-tuffite alternations at the top of the series (Arslan et al. 2005a). This formation is conformably overlain by Late Jurassic-Early Cretaceous carbonates, called the Berdiga Formation by Pelin (1977).

The quarries that are the subject of the study are located in this formation (Fig 2). The formation is generally seen as a grey-beige coloured, massive, bedded limestone in the north of the Eastern Pontides Orogenic Belt, while it is found as a moderate-bedded, massive limestone in the study area south of the Pontides (Arslan et al. 2005a). In the south of the Pontides, the Upper Cretaceous units consist predominantly of sedimentary rocks named the Kermutdere Formation (Tokel 1972).

Fig 2. View of the study area. The area includes Berdiga Formation limestone and excavated in quarry mining operations

However, the existence of Upper Cretaceous units in Bayburt and its northern sections is not known yet (Arslan et al. 2005a).The Eocene units, which start with nummulitic limestones in and around Bayburt where the study area is located, continue with marls and end with tuff-suffices, and overlie Liassic clastics (Hamurkesen Formation) and Malm-Lower Cretaceous carbonates (Berdiga Formation) with an angular unconformity (Fig 1) (Özer 1984; Arslan et al. 2005a)

Eocene volcanism around Gümüşhane and Bayburt is generally represented by basaltic-andesitic-dacitic volcanic and pyroclastic rocks (Arslan and Aliyazicioglu 2001). The Eocene sequence, which was named the Alibaba Formation by Tokel (1972) in Gümüşhane and its surroundings, was defined as the Tekçam Tepe Formation in Bayburt and its surroundings by Özer (1984) (Fig 1) and starts with nummulitic limestones and continues with claystone and marl in this region. The unit gradually transitions to tuffs. The tuffs consist of two levels separated by a claystone-marl level.

Each level shows a graduation from coarse to fine grained, and they are very thickly bedded at the base levels and thin bedded at the top (Arslan et al. 2005a).

The tuffs were used for many years as building stone, dimensioned stone and are famous as Bayburt stone. Apart from the study area, there are also granitoid intrusions formed during the Eocene period in different parts of the Eastern Pontides (Kaygusuz and Öztürk 2015; Vural 2017; Vural et al. 2018; Vural and Kaygusuz 2021; Sipahi et al. 2021). The post-Eocene volcanic sequences in the region are characterised by clastic rocks and Neogene-Quaternary volcanic/subvolcanic rocks (Okay and Şahintürk 1997). The youngest units in the region are Quaternary alluvium, which are sometimes operated as sand quarries, and travertines, which are small-scale tourism destinations (as geotourism sites (Vural 2018a, b, 2019)).

2.3. Mineralogical-petrographic and chemical analysis and density determination

Seventy-five samples of limestone were collected from the Berdiga Formation from the quarry site for mineralogical, petrographic and geochemical analyses. Mineralogical-petrographic analyses were carried out in Gümüşhane University Engineering and Natural Sciences, Geological Engineering laboratory. Thirty-two samples were sent for whole-rock analyses of major oxides by XRF (X-Ray Fluorescence) at the General Directorate of State Hydraulic Works Technical Research and Quality Control Department (Ankara, Turkey) according to TS EN 196-2 standard. In this study, density analysis was carried out at Gümüşhane University laboratory using the pycnometer method.

2.4. Schmidt Hardness

For determination of excavability, discontinuity distance measurements were made in the study area. In-situ Schmidt hardness and point load experiments were also applied for use in excavability diagrams (Fig 3). In addition to excavability, the blasting parameters were analyzed in the quarry where the loosening detonation explosion was made. Additionally, an adequate design for excavation was applied by determining the minimum explosive and maximum pore spacings for an efficient and safe open pit operation.The Schmidt hardness values found as a result of the fieldwork were compared with the Brown (1981) classification given in Table 1 and the class was determined.

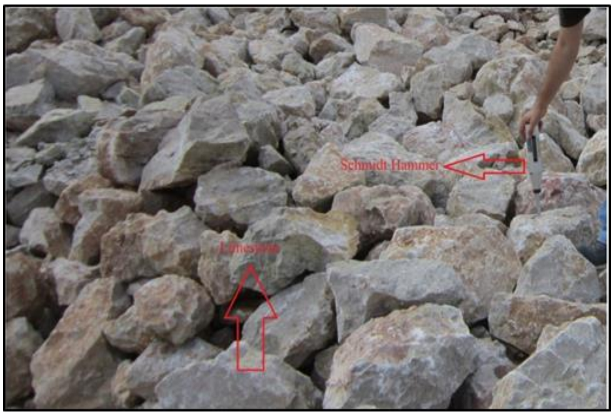

Fig 3. Schmidt hammer measurements

2.5. Point Load Index (PLI)Test

The PLI test is based on the fracture of rock samples placed among two conic edges and core samples (for diametrical and axial experiments), cut block samples, or irregular size samples can be used (Bieniawski 1975). The rock sample dimensions are measured, and it is placed between the conic edges to be broken within a certain time. The failure load is read from the load indicator and strength values are calculated using the appropriate calculation method. In this study, irregular-shaped samples taken from the field were used with samples of 50 mm ± 35 mm size. For the irregular samples, the ratio of the thickness to the width was taken between 0.3 and 1 as standard.

Table 1. Schmidt hammer test rock hardness classification (Brown 1981)

Rock type	Schmidt hardness rebound values
Extremely strong rock	>60
Very strong rock	50-60
Strong rock	40-50
Medium strong rock	20-40
Weak rock	10-20
Very weak rock	0-10

The length from the edges to the loading point of the specimen is at least half of the thickness. The thickness and width of the sample measured with calipers were placed between the conical ends and the loading was started (Fig 4).

The measured failure load was calculated using the ISRM (1985) test formula as follows:

$$Is_{(50)}=F_x Is \quad (1)$$

$$F=(De/50)^{0.45} \quad (2)$$

where; $Is_{(50)}$: corrected point load strength (MPa), F: correction factor, Is: uncorrected point load strength, and De: equivalent diameter (mm)

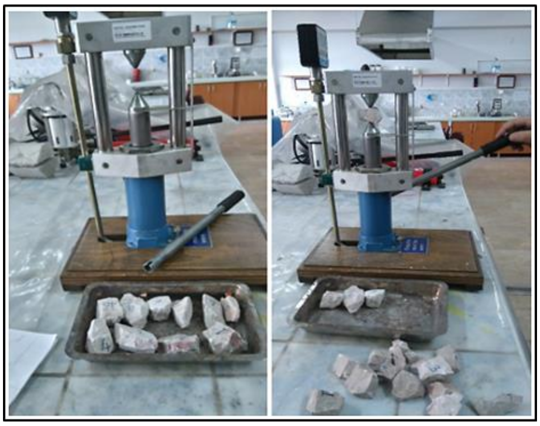

Fig 4. Point load index test of samples from the limestone quarry

2.6. Degree of Rock Mass Decomposition of Study Area

The alteration may occur at the surface and close to the surface of rock masses due to weathering, and at deeper levels with the effect of hydrothermal fluids. The classification of weathering grade proposed by ISRM is a visual classification that can be easily determined during field study (Fig 5, Table 2).

Table 2. Weathering class description classification table (ISRM 1981)

Description	Weathering class	Term
Not discolored, original aspect rock. Geological hammer hardly scratches rock surface. Rock gives ringing sound within hammer struck.	I	Fresh rock
Little discoloration, only in joint surfaces. Original rock mass completely preserved. Geological hammer difficultly scratches rock surface. Rock gives ringing sound within hammer struck.	II	Slightly weathered rock
Discolored rock material, locally original colored. Original rock mass preserved in good condition. Geological hammer scratches rock surface. Rock gives intermediate sound within hammer struck.	III	Moderately slightly weathered rock
All rock material discolored. Original rock mass as yet present, generally intact. Geological hammer hardly dig a hole. Rock gives a dull sound within hammer struck.	IV	Highly slightly weathered rock
Completely discolored rock material. Original rock mass still visible. Geological hammer hardly dig a hole. Rock emits dull sound within hammer struck.	V	Completely slightly weathered rock
Completely converted to soil. Original rock mass completely cracked. Geological hammer easily dig a hole. Rock not emitting sound.	VI	Residual and colluvial soils

2.7. Engineering Properties of Joints

Engineering properties of the joints contained in the rock masses from the study area were determined to conform to ISRM (1981) (ISRM 1981) definition criteria. To determine the engineering properties of the joints inslightly weathered limestone, the places where the rock feature was not completely lost were determined and measurements were made there. Measurements were made perpendicular to each other on the slope faces of rock masses, and the joint frequency (λ) values were determined. In order to determine the Rock Quality Designation (RQD), systematic joints in rock masses, as well as irregular joints, were developed, so equation 1 was used with the joint frequency (λ) value proposed by Priest and Hudson (Priest and Hudson 1976).

Fig 5. Display of stratification and decomposition degrees in limestone

$$RQD=100e^{-0.1\lambda}(0.1\lambda +1 \quad (3)$$

The second equation proposed by Palmström (2005) was utilized in determining the number of volumetric joints (Jv) of rock masses.

$$Jv= (110\text{-}RQD)/2.5 \quad (4)$$

3. Results and Discussions

3.1. Chemical Analysis of Rocks in the Bayburt-Tepetarla Area

Sedimentary rocks with a chemical composition of at least 90% calcium carbonate ($CaCO_3$) are called limestone. The mineralogical composition of this rock contains at least 90% calcite minerals. The limestone is composed of pure calcite and very small amounts of aragonite crystals. Calcite and aragonite calcium carbonate have two distinct crystal forms and theoretically contain 56% CaO and 44% CO_2. However, they are never pure in nature. Yellow, brown and black colors are seen originally due to different substances and compounds being included in the rock. As a consequence of the analysis, samples taken from the study area were 97.27% $CaCO_3$ and 1.55% MgO and the rock structure was limestone (Table 3).

Table 3. Major oxide analyses of rocks in the study area

Major oxides	Content (%)
In natural samples	
Fe_2O_3	0.24
$MgCO_3$	1.55
$CaCO_3$	97.27
For samples with CO_2-removed	
MgO	0.75
CaO	54.50

3.2. Mineralogical Structure and Density Determination Results

The purpose of thin section analysis is to determine the type of rock studied. Knowing the type of rock studied will facilitate the selection of the excavation equipment to be used.The analyzed rocks are limestone and some dolomite in composition, and they contain a large amount of calcite and a small amount of dolomite and have granoblastic texture. The co-sized calcite minerals are twisted in the poly-symmetrical twin laminates, which are broken from the edges. The rock also contains small amounts of opaque minerals (Fig 6).The samples were analysed by using the pycnometer method according to TS EN 1097-6 standard. Generally, limestone hardness is 3 and specific weight changes between 2.5 to 2.7 7g/cm^3. The limestone density of the study area is an average 2.65 g/cm^3 (Table 4).

Table 4. Density analysis results

SAMPLE NO.	DENSITY (G/CM^3)
S-1	2.93
S-2	2.49
S-3	1.97
S-4	2.78
S-5	2.66
S-6	2.97
S-7	2.79
AVERAGE	2.65

3.3. Schmidt Hardness (SH) Results

SH measurements have different standards; in the ASTM (2001) method, a single stroke is made on the sample with a SH at ten different points and the values above and below 7 units of the average are canceled, and the average of the rest is taken as SH value. In the ISRM (1981) method, a single shot is made at 20 different points with the Schmidt hammer, and the average of maximum 10 strokes is taken (Table 5). To estimate the UCS of the limestone quarry and to figure excavation degree of the site, limestone samples were subjected to the Schmidt hammer test. As a result of Schmidt hammer (SH) test results, the Schmidt hardness of the limestone was "*strong*" according to Brown classification (Brown 1981) (Table 2). The results found according to different standards are given in Table 4. According to Deere and Miller's (1966) Schmidt conversion chart, rocks' UCS can be estimated by using SH values.

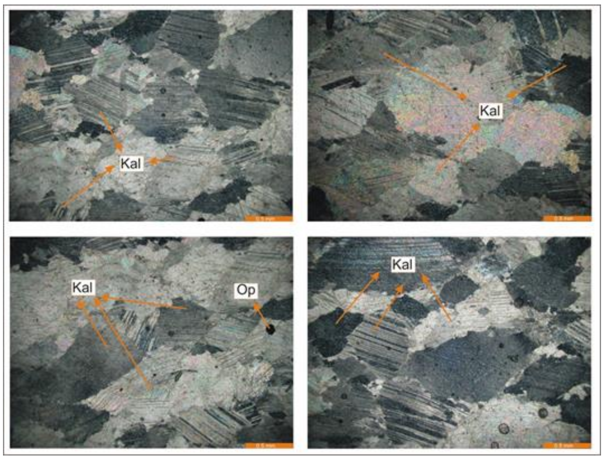

Fig 6. Microscopic appearance of rocks from the study area (Kal: calcite, Op: opaque minerals)

Table 5. SH measurement results

Value of R	Sample no	Value of R	Sample no
53	1	56	11
43	2	30	12
22	3	35	13
39	4	38	14
69	5	32	15
44	6	46	16
30	7	63	17
24	8	45	18
58	9	65	19
46	10	49	20

Table 6. Schmidt hardness values with different standards

Standards	Schmidt Hardness Values
ASTM, 2001	41.75
Sumner and Nel, (2002)	39.50
Deere and Miller, (1966)	42.25

Table 7. Uncorrected and corrected point load strength test values

Point Load Strength (Is) (Uncorrected)	Correction Factor (F)	Point load strength (Is$_{(50)}$) (Corrected)
2.89 MPa	0.97	2.80 MPa

In this study, by using Deere and Miller's (1966) chart, limestone's uniaxial compressive was calculated as 85 MPa (Fig 7). This value is used in the excavability classification system to compare with point load index test values.

3.4. Point Load Index (PLI) Results

1 and 2. Point load indices calculated using forms are given in Table 7. Additionally, according to point load index classification ISRM (1981), the average value of limestone point load strength is 2.80 MPa, which is in the strong class according to the classification (Table 8).

Table 8. Point load index test classification of rocks (ISRM 1981)

Descriptions	UCS (MPa)	PLI, Is$_{(50)}$ (MPa)
Extremely weak rock	0.25 – 1.0	--
Very weak rock	1.0 – 5.0	--
Weak rock	5.0 – 25	0.2 – 1
Medium strong rock	25 – 50	1 – 2
Strong rock	50 – 100	2 – 4
Very strong rock	100 – 250	4 – 10
Extremely strong rock	> 250	> 10

3.5. Excavability

When the study area is examined visually, only near joint surfaces discoloration is presented. The original mass structure is fully conserved. The geological hammer scratches hardly the surface. The rock material is struck by a hammer and observed as making a ringing sound. According to this classification described in ISRM (1981), the rock masses in the study area show slightly weathered rock features (Table 2).The RQD and Jv values of the rock mass in the study area and the engineering properties of the joints are presented in Table 9.The RQD value of limestone was calculated as 74, and the number of volumetric joints is calculated as 14 joints/m3 related to the formulas.

Evaluation of Rock Mass in Accordance with Excavability Classification Systems

Excavability evaluations of rock mass in the study area were utilized with classification systems suggested by Franklin et al. (1971); Pettifer and Fookes (1994); Tsiambaos and Saroglou (2009). According to Franklin et al. (1971) classification system; joint space, PLI (Is(50)) and UCS derived from the Schmidt hardness test are used as input parameters. Resultantly, the excavation classification was "pre-explosion" class (Fig 8).

In the excavability classification system suggested by Pettifer and Fookes (1994), joint space index (If) and point load index (Is$_{(50)}$) values are used as input parameters. The joint spacing index (If) is determined from equation (5) using the number of volumetric joints.

$$If=3/Jv \qquad (5)$$

According to Pettifer and Fookes' (1994) excavability classification system, the rock mass in the Bayburt-Tepetarla area is hard ripping (Fig 9).

Table 9. Engineering properties of joints in the limestone quarry

Properties	Slightly Weathered Limestone
Joint frequency (λ)	10
RQD (%)	74
Number of volumetric joints (Jv, joints/m^3)	14
Number of joints	3
Joint space (m)	0,48
Joint continuity (m)	0,95

Therefore, pre-explosion or loosening blasting should be applied to the study area to make the area easily ripped. Referring to the Tsiambaos and Saroglou (2009) excavability classification system study, Geological Strength Index and point load strength index ($Is_{(50)}$) values are used as input parameters. In the literature, there are two different charts depending on $Is_{(50)}$ <3MPa and $Is_{(50)}$ ≥3MPa conditions (Tsiambaos and Saroglou 2009). As the point load index value is lower than 3MPa, the appropriate chart was used for the study area (Fig 10).

3.6. Suggested Excavation Method and In-situ Practice Comparison

The proposals for slightly weathered limestone were matched against the excavation work in the study area to determine the applicability of excavation methods according to the excavability classification systems. The rock mass is subjected to pre-blasting operations (Figs 11a, b) and then it is broken with a hydraulic breaker (Figs 11c, d). Resultantly, the excavation method in the study area is compatible with analyzed excavability classification systems.

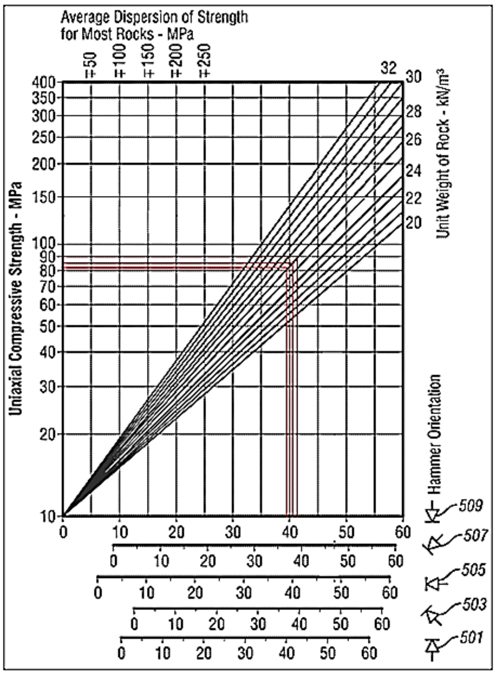

Fig 7. Correlation between UCS and SH tests (Deere and Miller 1966)

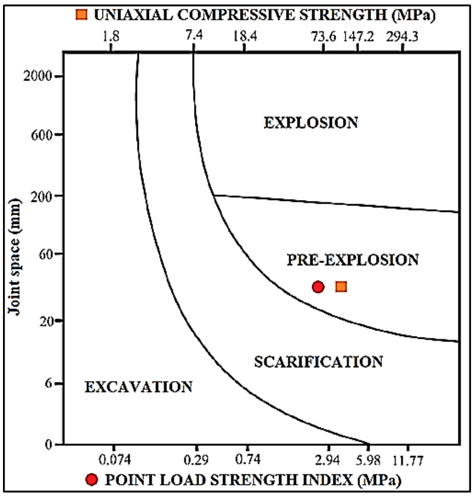

Fig 8. Excavability classification system evaluation suggested by Franklin et al. (1971)

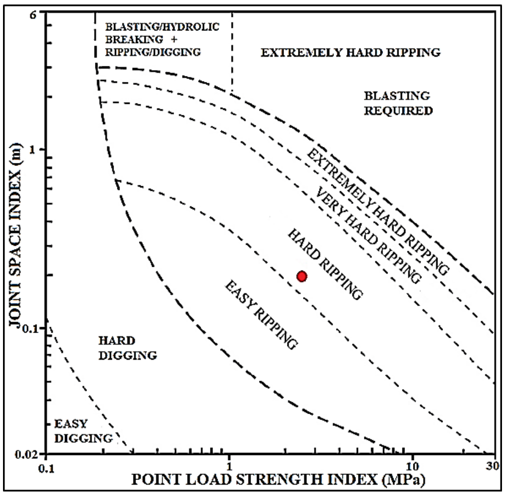

Fig 9. Excavability classification system evaluation was suggested by Pettifer and Fookes (1994).

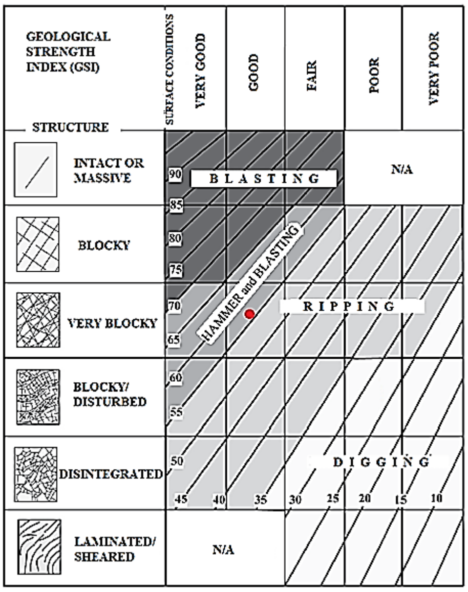

Fig 10. Tsiambaos and Saroglou (2009) suggestion to evaluating of excavability classification system (for $Is_{(50)}$<3MPa)

Fig 11. Excavation method currently applied at the study site and equipment used. (a) drilling holes for pre-excavation loosening blasting, (b) loosening blast, (c) excavation and size reduction with hydraulic breaker, (d) final product state

4. Conclusion

In this study, the excavability characteristics of slightly weathered limestone, from a limestone quarry in Bayburt province, were investigated. For this purpose, rock masses were classified by using excavability classification systems which are widely used in practice, and results were contrasted with in-situ excavation methods. The results obtained from the study are presented below.

- From the excavability classifications available in the literature, classification systems using UCS, PLS and weathering degree of rock mass parameters were used.
- In this study, Schmidt hardness values were used to calculate the uniaxial compressive strength value according to ISRM 1981 and ASTM 2001 methods.
- PLI and UCS test values are used in excavability classification diagrams to analyze the proposed classification systems.
- Based on the excavability classification system suggested by Franklin (1971), the slightly weathered limestone is in the “pre-explosion” class meaning “blasting for loosening".
- Based on the excavability classification system offered by Pettifer and Fookes (1994), the slightly weathered limestone is classified as "hard ripping" or "blasting is necessary".
- In the excavation operations carried out in the study area, slightly weathered limestone was blasted for

loosening and then excavated with a hydraulic breaker and/or bucket of excavator.

- The rock class and excavability found as a result of the study matched the method suggested by Tsiambaos and Saroglou (2009).
- As a result of the analyses, the parameters for getting more appropriate results of excavation classifications in surface are GSI (geological strength index), PLI (point load strength) index ($Is_{(50)}$ and rock mass degree of weathering.

The authors recommend the statistical evaluation of the results in future studies on this subject. It should be demonstrated that the results found are statistically correlated with each other.

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