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A Combination of GPR Survey and Laboratory Rock Tests for Evaluating an Ornamental Stone Deposit in a Quarry Bench

Mohamed Elkarmoty*, Camilla Colla, Elena Gabrielli, Stefano Bonduà, Roberto Bruno

Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Bologna 40131, Italy

Abstract

The paper examines methods of assessing the critical fractures and quality of an ornamental stone deposit. Fracture status was evaluated by an in-situ Ground Penetrating Radar (GPR) test. The resulting 3D GPR model allowed exploration of the extension, shape, and orientation of the detected fractures surfaces. It also identified a rock stratum with a noticeably lower load of critical fractures compared to the other strata. Physico-mechanical properties were investigated by laboratory tests allowing classification of the deposit into quality categories, which provided a promising correlation with the GPR survey results.

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Keywords: ornamental stones; quarrying; evaluation; fractures; GPR; laboratory tests; physico-mechanical properties

1. Introduction

Research on ornamental stone evaluation, production, and processing have witnessed sustainable trends in recent years. Ornamental stone products have a wide range of uses for construction and prestigious purposes. Evaluation of ornamental stone deposits is a decision making tool not only for quarrying, but also for classifying deposit quality. The aesthetical appearance of ornamental stones and the commercial size of ornamental stone blocks are very significant marketing factors [1]. Rock mass fractures hamper the cutting of commercially viable ornamental stone blocks. Fractures are also the main cause of production waste. For this reason, fracture status evaluation is a critical assessment factor during the exploration stage.

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* Corresponding author. Tel.: +39-388-465-9785.
E-mail address: mohamed.elkarmoty2@unibo.it

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Since ornamental stones are non-renewable resources of considerable economic value, a non-destructive non-invasive fracture detection tool is recommended. We have selected Ground Penetrating Radar (GPR) [2] from among several fracture detection methods (Fig. 1) as a geophysical electromagnetic data acquisition tool for this research. GPR has been widely used to detect fractures in rock mass in quarries [3–8]. In this paper, we investigate the use of a low frequency GPR antenna to detect critical (large aperture) fractures inside a discontinuous heterogeneous rock mass in a sandstone quarry. The objective of using low frequency antenna is to obtain as deep a subsurface image as possible, since penetration depth is inversely proportional to wave frequency.

Selective extraction from an ornamental stone deposit first requires preliminary deposit classification into quality categories based on effective mechanical and physical properties [9, 10]. Since physico-mechanical properties, such as uniaxial compressive strength, porosity, etc., have a role in imposing restrictions on the uses of the ornamental stones products, laboratory tests to determine these were performed on representative samples from the quarry bench under study. The results of the laboratory tests and the GPR survey were then combined to evaluate the deposit on the micro and macro scales. The macro scale was investigated with GPR to detect critical fractures in the whole surveyed bench volume while the micro scale was investigated by means of physico-mechanical laboratory tests on representing samples from the bench.

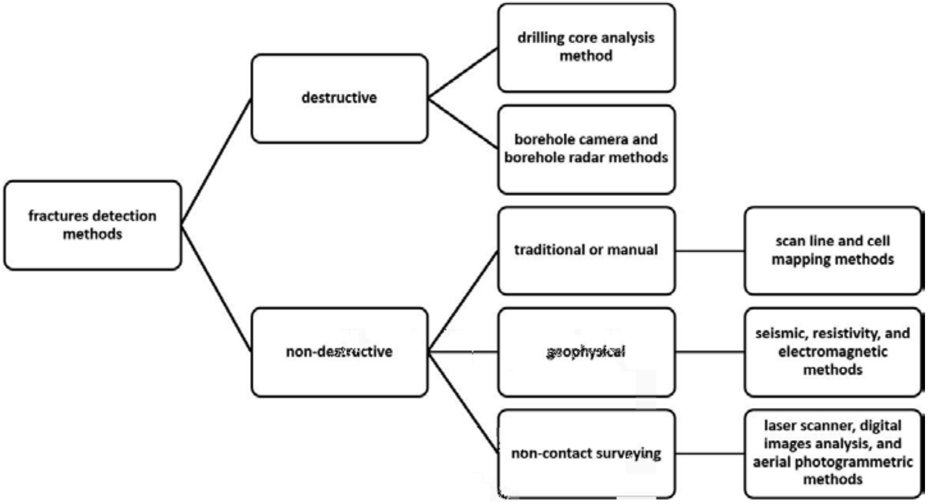

Fig. 1. A classification survey of fracture detection methods [11–17].

2. Site characteristics

The study was carried out in a sandstone quarry in Firenzuola, Italy. The site of both the GPR survey and rock samples collection was a newly created quarry bench. The product and the geologic formation of the Firenzuola sandstone quarries are historically known as “Pietra Serena di Firenzuola” [18]. Firenzuola sandstones belong to the Marnoso-arenacea geologic formation, known in English as clay-sandstone formation [19]. The out-cropping strata of the bench under study are of this geologic formation (Fig. 2.a). Stratification runs parallel to the bench surface.

Sandstones are characterized by several colors due to differences in their mineralogical composition, which in turn gives rise to differing physical and mechanical properties [20]. The out-cropping strata in the bench face in question are divided into two lithologic parts. The first is a yellow-to-yellowish gray sandstone series of strata. Under this is a gray sandstone stratum.

The bench is characterized by large aperture sub-vertical fractures (about 2.0 cm) that propagate randomly in the rock mass strata (Fig. 2.b). Some large–aperture outcropping fractures are clearly seen to extend through all outcropping strata in the bench face while other fractures stop at the top surface of the gray sandstone stratum, as shown in Fig. 3. This observation is limited to the large aperture fractures visible to the naked eye in the outcropping gray sandstone strata from Fig. 3.

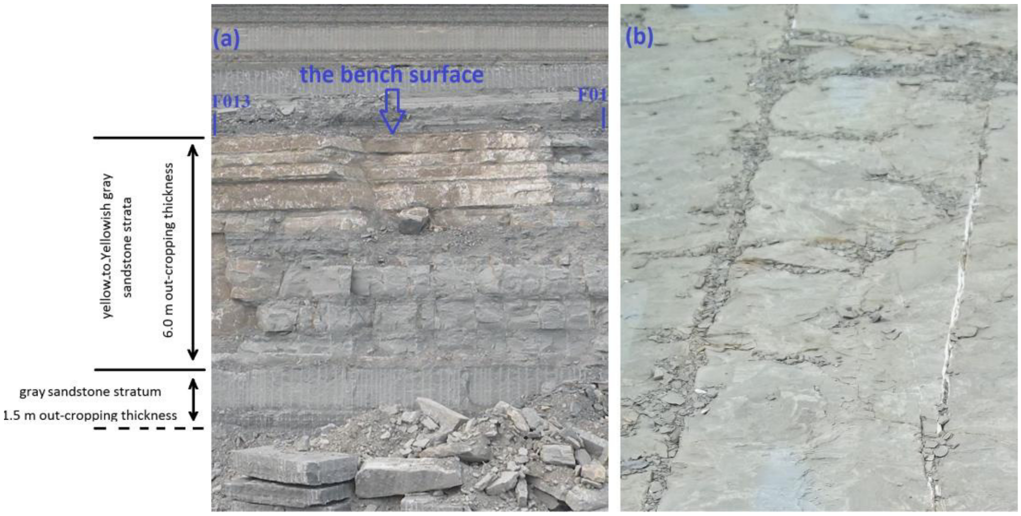

Fig. 2. (a) Front view of the bench face, F01 and F013 are the first and last GPR survey lines in the X direction (see sec. 3.1.1. and fig. 4); (b) some out-cropping fractures in the bench surface.

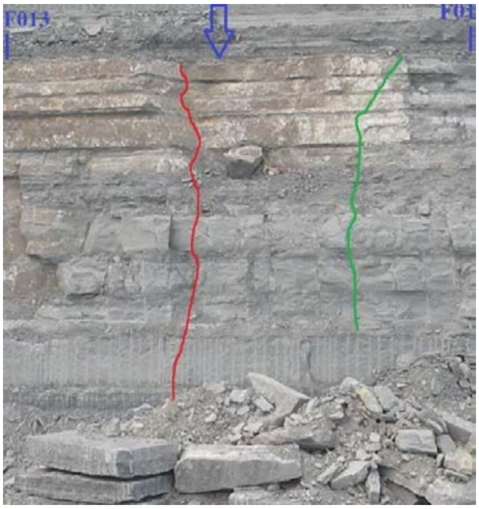

Fig. 3. Tracing of a fracture surface extending through all the outcropping strata of the bench face (red) and a fracture surface stopping at the top surface of the gray sandstone stratum (green).

3. Methods and results

3.1. GPR exploration

3.1.1. Method

The GPR survey aims (i) to detect large aperture fractures at the greatest depth possible, (ii) explore fracture surface orientation and shape, and (iii) check the correlation between the out-cropping fractures on the bench face and the interior volume of the rock mass. The bench surface was surveyed by a GPR unit, using a 70 MHz monostatic antenna of manufactured by Geophysical Survey Systems Inc. (GSSI). The antenna was adapted to a cart and linked to GSSI-SIR 3000 system. The GPR survey was carried out in a selected area exhibiting behavior typical for the stratigraphic and geo-structure features of whole the bench. Planning of the survey lines over the bench surface is shown in Fig. 4. The survey was carried out on an intensive GPR grid with a spacing of (1.0 m x 1.0 m) in order to enhance the interpolation of reflections in the 3D GPR model. The survey grid was 12.0 m x 7.0 m, leading to 21 survey lines. The survey grid was designed 8.0 m from the bench face in order to investigate the fractures in the interior rock mass of the bench. It should be noted that the rock mass was wet in the time of GPR surveying since it had rained on the previous days. Accordingly, the fractures apertures were filled with water allowing stronger reflections in the radargrams.

Standard signal processing functions were applied to the GPR data using the signal processing software package RADAN (GSSI). The processing functions and parameters employed are listed in Table 1. The theoretical basis of GPR signal processing are indicated in the bibliographic references [21, 22].

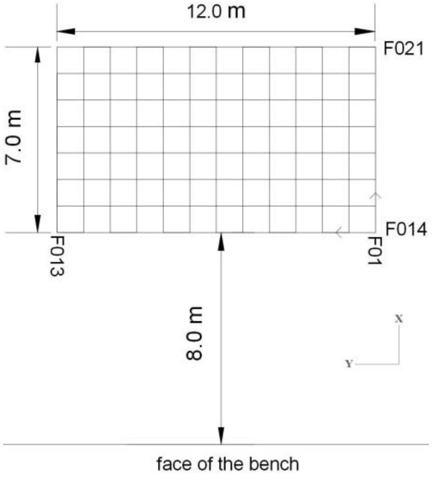

Fig. 4. Planning the GPR survey lines.

Table 1. GPR processing procedures used with RADAN software.

time zero	3.91 ns
low pass filter	140 MHz
high pass filter	15 MHz
range gain	linear
migration	constant velocity migration of 111.0 μm/s
deconvolution	operator length: 31, predication lag: 5, prewhitening: 10%
display gain	6

3.1.2. Results

After standard signal processing, the 21 two-dimensional radargrams were interpolated by RADAN (GSSI) and a 3D GPR model was built (Fig. 5). The 3D GPR model shows the vertical reflections of large aperture fractures extending up to the maximum penetration depth of 14.0 m, revealing how the surface fractures extended into the bench body (Fig. 6). The interior body of the rock mass presents predominantly the same behavior as the outcropping sub-vertical fractures.

The waviness height of a fracture aperture can change with the variable stresses t which a rock mass is subjected [23, 24]. Moreover, Gudmundsson et al. [25] demonstrated that the variation of stiffness in the path of a fracture surface causes variation in aperture. A stratum with highly resistant mechanical properties may not fracture or in the event of fracture, these may be so narrow as to be undetectable by low antenna resolution. Our GPR results evidence that the majority of fracture reflections are discontinuous in a particular volumetric region between about 5.0 m to 10.0 m depth (Figs. 5 and 6). At the bench face (Fig.2-a), a gray sandstone stratum crops out at a depth of 6.0 m below the bench surface. In accordance with the above-mentioned interpretation of the discontinuous reflections of fractures in the 3D GPR model, it is posited that the relatively higher mechanical properties of the gray sandstone stratum are the reason why the gray sandstone stratum does not present with large aperture fractures. This interpretation is investigated by applying uniaxial compressive strength and deformation tests to samples collected from the bench strata (see section 3.2).

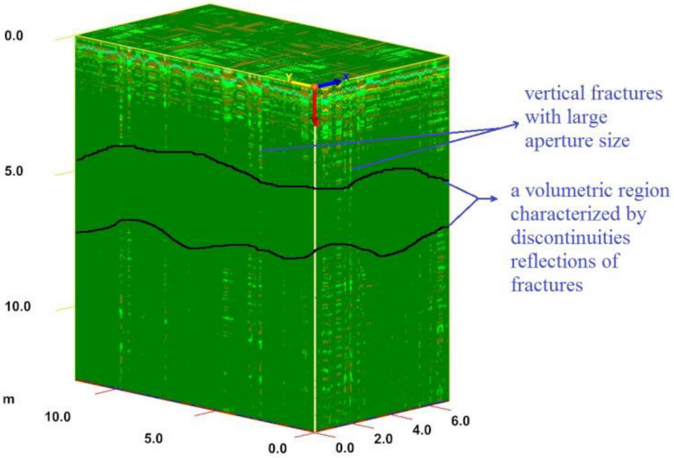

Fig. 5. The 3D GPR model with indications of some vertical fractures and the volumetric region of discontinuous reflections of fractures.

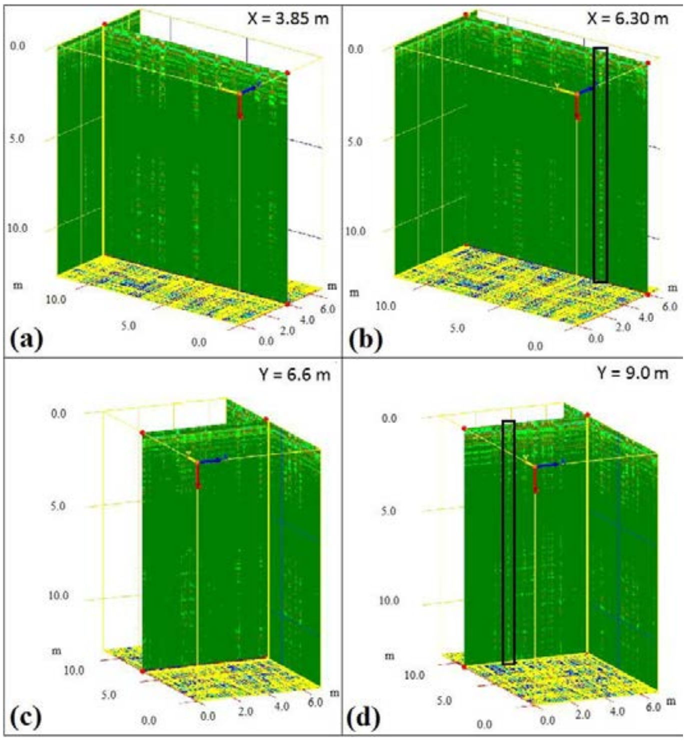

Fig. 6. Cross-sectional GPR slices, in x and y directions, from the 3D GPR model. The slices show that the volumetric depth region, between about 5.0 to 10.0 m, is characterized by discontinuous reflections of fractures, however there are few detected continuous reflections (highlighted by black rectangles).

3.2. Laboratory tests

3.2.1. Method

The laboratory tests were carried out on representative samples collected from the out-cropping strata on the bench face, following the methods suggested by the International Society of Rock Mechanics ISRM [26]. The samples are divided into two main groups according to their lithologic nature. Group (G) are samples collected from the gray sandstone stratum whilst group (Y) are samples collected from the yellow-to-yellowish gray sandstone strata. The samples were prepared as cylindrical specimens of 38 mm diameter and 76 mm height.

Density (ρ) and porosity (n) were measured by saturation and buoyancy techniques. The water absorption by weight (W) was also calculated. The p-wave velocity (v_p), in dry conditions, was measured with an ultrasonic instrument (a pulse generator of EPOCH1000 and 1 MHz transducers).

Uniaxial compressive strength (σ_c) was measured, under natural conditions, with a 500 KN load cell and an accuracy of 1%, by applying a continuous stress rate of 0.5 MPa/s. Uniaxial compressive strength was measured in one direction perpendicular to the bedding planes. A further deformation test was performed using strain gages, under natural conditions, on two representative samples of 38 mm diameter and 76 mm height, from both groups G and Y.

3.2.2. Results

The results of the laboratory tests are presented in Table 2. The G samples are characterized by noticeably higher density than the Y samples. The average porosity and water absorption by weight of the Y samples are 1.6 and 1.5 times higher than the G samples respectively.

The gray sandstone stratum is characterized by higher mechanical compressive strength (about 1.37 times on average) than the strata of the yellow-to-yellowish gray sandstone. Fig. 7 shows that the G sample is characterized by higher stiffness than the Y sample.

The mechanical laboratory results support the absence of fracture reflections in the 3D GPR model (Fig. 5 and 6) in keeping with the finding that the G samples have higher mechanical properties than the Y samples. Accordingly, it is highly probable that fracture apertures in the gray sandstone strata are too small to be detected by the used antenna frequency.

Table 2. Statistical breakdown of the physico-mechanical properties measured.

properties	group	no. of samples	minimum value	maximum value	average value
ρ (kg/m3)	Y	19	2460	2555	2515
	G	20	2505	2681	2580
n (%)	Y	19	5.72	9.24	7.26
	G	20	2.00	6.34	4.58
W (%)	Y	19	2.18	3.61	2.78
	G	20	0.74	2.76	1.80
Vp (m/s)	Y	19	2518	3410	2911
	G	20	2533	3919	3089
σc (MPa)	Y	19	69	94	86
	G	20	89	159	118

Fig. 8 shows correlations between several physico-mechanical properties. Porosity decreases linearly with the increase of compressive strength and p-wave velocity (Fig. 8 – a and b), while the density increases linearly with the increase of compressive strength and p-wave velocity (Fig. 8 – c and d). The coefficients of correlations in Fig. 8 show that the G samples are characterized by moderate to strong linear relations while the Y samples are characterized by weak linear relationships. This is evidently because the Y samples represent several stratum with slightly different lithological characteristics.

The laboratory tests show the gray sandstone stratum as characterized by more resistant physico-mechanical characteristics. As a result, the bench examined is classed as having good quality gray sandstone, intermediate quality yellowish gray sandstone, and poor quality yellow sandstone. The yellowish gray sandstone represents the rocks in the transition zone between gray sandstone and yellow sandstone (Fig. 8).

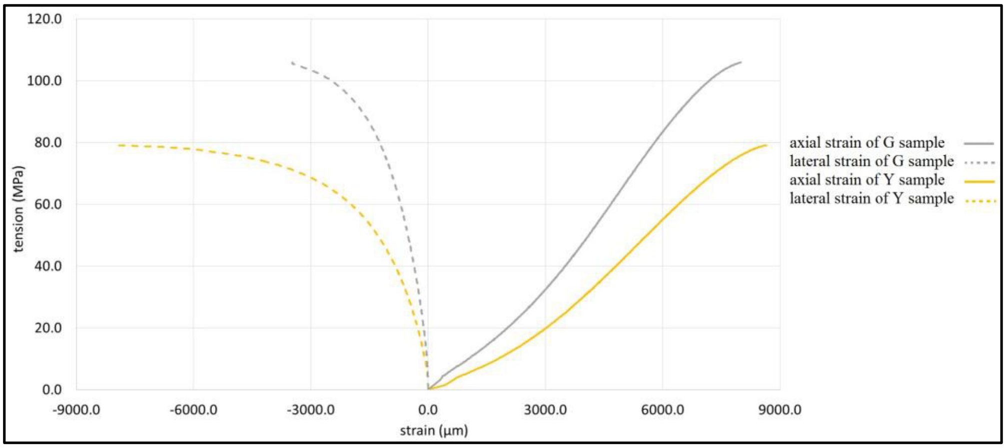

Fig. 7. The stress-strain curve of a G and Y sample.

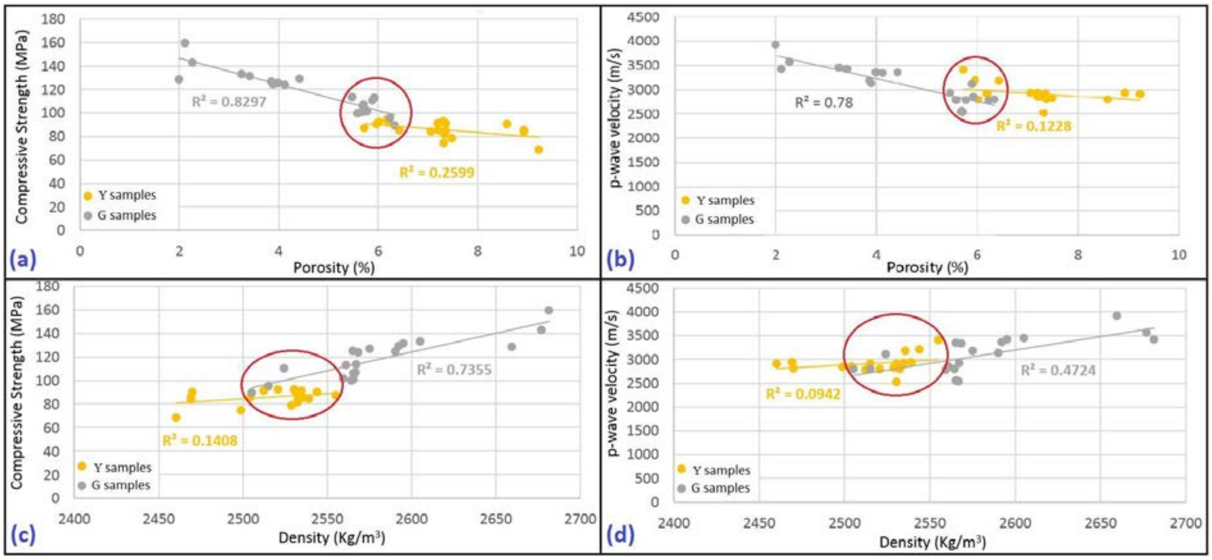

Fig. 8. Correlations between (a) compressive strength and porosity, (b) p-wave velocity and porosity, (c) compressive strength and density, and (d) p-wave velocity and density. The red circles refer to a lithological transition zone between the gray sandstone and yellow sandstone.

4. Conclusions

A 70 MHz GPR antenna was able to detect large aperture fractures in a sandstone bench of lithologically differing strata. Although the maximum penetration depth achieved (14.0 m) in the fractured rock mass examined was limited on account of signal attenuation, penetration depth using this antenna may be greater in the case of more continuous homogeneous rock bodies. Due to the limited resolution of low frequency antennas, an intensive GPR survey grid was used in this research to estimate, by interpolation, the reflections between the 2D cross-sectional radargrams. The use of a 3D GPR model led to the identification of a volumetric region of a rock stratum (gray sandstone) with a lower load of large aperture fractures than other neighboring strata of yellow-to-yellowish gray sandstone.

Together with the results of the GPR survey, the physico-mechanical properties obtained by laboratory tests, allowed the Authors to classify the deposit into quality categories. The gray sandstone was seen to have better physical and mechanical properties than the yellowish sandstone. Mechanical laboratory tests were also used to validate the fracture findings of the 3D GPR model, leading the Authors to conclude that the combination of non-destructive in-situ geo-physical and destructive laboratory geo-mechanical tests is a promising tool for a sustainable evaluation of ornamental stone deposits.

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