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Geomechanical Properties of the Soft Rocks from Vale das Fontes Formation (Lower Jurassic, Lusitanian Basin, Portugal): An Exploratory Study

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Geomechanical Properties of the Soft Rocks from Vale das Fontes Formation (Lower Jurassic, Lusitanian Basin, Portugal): An Exploratory Study

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Abstract

This study examines the geomechanical properties of soft rocks from the Vale das Fontes Formation, a significant source rock in the Lower Jurassic Lusitanian Basin, Portugal. The study aims to establish a consistent relationship between uniaxial compressive strength, Young's modulus, and Poisson's ratio with mineralogical composition and porosity. The results indicate that samples are mainly characterised by calcite (ranging from 59.2% to 96.9%), followed by quartz (2.0% to 14.7%) and phyllosilicates (ranging from 0.0% to 22.0%). Porosity ranges from 0.4% in sample 6 to 15.1% in sample 7. The uniaxial compressive strength, Young's modulus, and Poisson's ratio results show the influence of mineralogy and porosity. The compressive strength values (21.40 MPa, sample 7 - 155.98 MPa, sample 1) increase as the combined calcite and quartz content increases (73.8%, sample 8 - 99.5%, sample 6) and as the porosity decreases (15.1%, sample 7 - 0.4%, sample 6). Samples characterised by high calcite and quartz contents (99.2%, sample 1 and 99.5%, sample 6) reflect high values of Young’s modulus (30269 MPa, sample 1 and 39468, sample 6) and Poisson’s ratio (0.26, sample 1 and 0.20, sample 6). On the other hand, samples represented by high porosity values (15.1%, sample 7 and 11.7%, sample 8) reflect low values of Young's modulus (1927 MPa, sample 7 and 5120 MPa, sample 8) and Poisson's ratio (0.14, sample 7 and 0.06 sample 8).

Keywords

Soft rocks, geomechanical properties, potential reservoir shale rock, Vale de Fontes Formation, Portugal.

1. Introduction

The current increase in energy consumption and the challenges of meeting this high demand through renewable sources create a concerning energy scenario. Therefore, to promote energy sustainability, exploring new sources that align with the European Union's goals outlined in the 2015 Paris Agreement is central, particularly achieving carbon neutrality by 2050 (UN 2023).

Natural gas has become increasingly competitive in the energy market because it is one of the most environmentally friendly fossil fuels and an excellent alternative energy source (Mohammad et al. 2021). Additionally, there has been considerable interest in exploring and developing unconventional reservoirs, particularly shale gas. In contrast to conventional reservoirs, unconventional reservoirs require stimulation due to their low permeability (e.g., Zou et al. 2016; Chen et al. 2019; Tan et al. 2019; Liu et al. 2020). As a result, studying the mechanical properties of unconventional reservoir rocks has become a challenging key field of research. The aim is to develop geomechanical models that can minimise the hazards and risks associated with unconventional reservoir rock behaviour under different environmental conditions and predict their response to specific loads (Liu et al. 2020; Kuang et al. 2023). Additionally, weak rocks or rock masses showing damage characteristics, such as jointing, faulting, or solution cracks, are commonly described as soft rocks (e.g., Potter et al. 1980; Oliveira 1993; Sadowski 2020). According to Manchao and Xiaoming (2020), soft rocks have distinguished low strength, lithology, fabric and physico-chemical properties. They can be classified into several categories (Manchao and Xiaoming 2020): expansible soft rock, high-strength soft rock, jointed soft rock, and their combinations. Their geomechanical behaviour represents geological materials between soil and rock (e.g., Sadowski 2020; Tao et al. 2020).

The Lower Jurassic of the Lusitanian Basin, particularly the Vale das Fontes Formation, is currently recognised for its organic-rich carbonates and shales (Duarte and Soares 2002; Oliveira et al. 2006; Duarte et al. 2010, 2012; Silva et al. 2011, 2015; Silva and Duarte 2015). This study highlights the Vale das Fontes Formation as an unconventional gas reservoir for the first time. Nevertheless, it is pertinent to note that the Jurassic in Portugal has been submitted to several studies since the 19th century. The first relevant stratigraphic study of the Jurassic of Portugal was developed by Choffat (1880). Later, the first biostratigraphical study of the Lower Jurassic of the Lusitanian Basin was reported by Mouterde (1955). More recently, studies focusing on organic geochemistry have been conducted to evaluate the Lower Jurassic´s potential as an oil source rock (e.g., Oliveira et al. 2006; Duarte et al. 2010, 2012; Silva et al. 2011; Ribeiro et al. 2013; Brito et al. 2017, 2023, and references therein). However, there is a significant lack of research on the petrophysics and geomechanics of these soft rocks in the Lusitanian Basin, which are essential for understanding unconventional reservoir rocks. This study aims to contribute to an exploratory understanding of the geomechanical properties of the Vale das Fontes Formation while offering practical guidance for future research in this area.

2. Geological setting

The Lusitanian Basin is located on the western margin of the Iberian Peninsula and is associated with the opening of the North Atlantic Ocean. It is part of a group of Atlantic Marginal Basins that began to form at the end of the Triassic during the rifting phase. The basin has a NE-SW orientation, covering an area of approximately 22.000 km^2. It is approximately 300 km long and 150 km wide, including offshore areas, with a maximum sediment thickness of 5 km (e.g., Wilson 1988; Soares et al. 1993; Pinheiro et al. 1996; Alves et al. 2002; Azerêdo et al. 2003; Kullberg et al. 2013). The Lusitanian Basin is privileged for its geologically significant and well-preserved outcrops, particularly those of the Lower Jurassic, materialised by carbonate ramp deposits (e.g., Duarte 1997, 2004; Duarte and Soares 2002; Duarte et al. 2010, 2014, 2022; Silva et al. 2011, 2015) (Fig. 1).

The present study focused on the Pliensbachian Vale das Fontes Formation due to its geological features, well-defined stratigraphic control of the sedimentary succession, organic-rich marl and limestone layers, and exceptional outcrops exposure throughout the Lusitanian Basin (details in Duarte and Soares 2002; Oliveira et al. 2006; Duarte et al. 2010; Silva et al. 2011).

2.1. Vale das Fontes Formation: Studied outcrops

The Vale das Fontes Formation is a marly-dominated unit composed of alternating decimetric to metric marls interspersed with centimetric limestone layers. This formation is notable for its record in benthic and nektonic macrofauna and exhibits a significant variation in thickness, reaching a maximum of approximately 90 m in the São Pedro de Moel region (Duarte and Soares 2002; Duarte et al. 2010; Silva et al. 2015).

The Vale das Fontes Formation is dated from the Pliensbachian (from the Jamesoni to Margaritatus ammonite zones), and it is subdivided into three members (Duarte and Soares 2002; Duarte et al. 2010): Marls and limestones with *Uptonia* and *Pentacrinus* (MLUP), Lumpy marls and limestones (LML), and Marly limestones with organic-rich facies (MLOF). Among the different types of marl-limestone alternations that typify each of the members, as well as their paleontological content, organic-rich facies, like black shales, are observed in all of them (see references cited above).

Three different outcrops have been selected to provide a spatial view of the formation (details in Temporão de Sousa 2014): Peniche (Praia do Portinho da Areia Norte), Brenha (Estrada N109), and Coimbra (Bairro do Loreto and Bairro de São Miguel; Figs. 1 and 2).

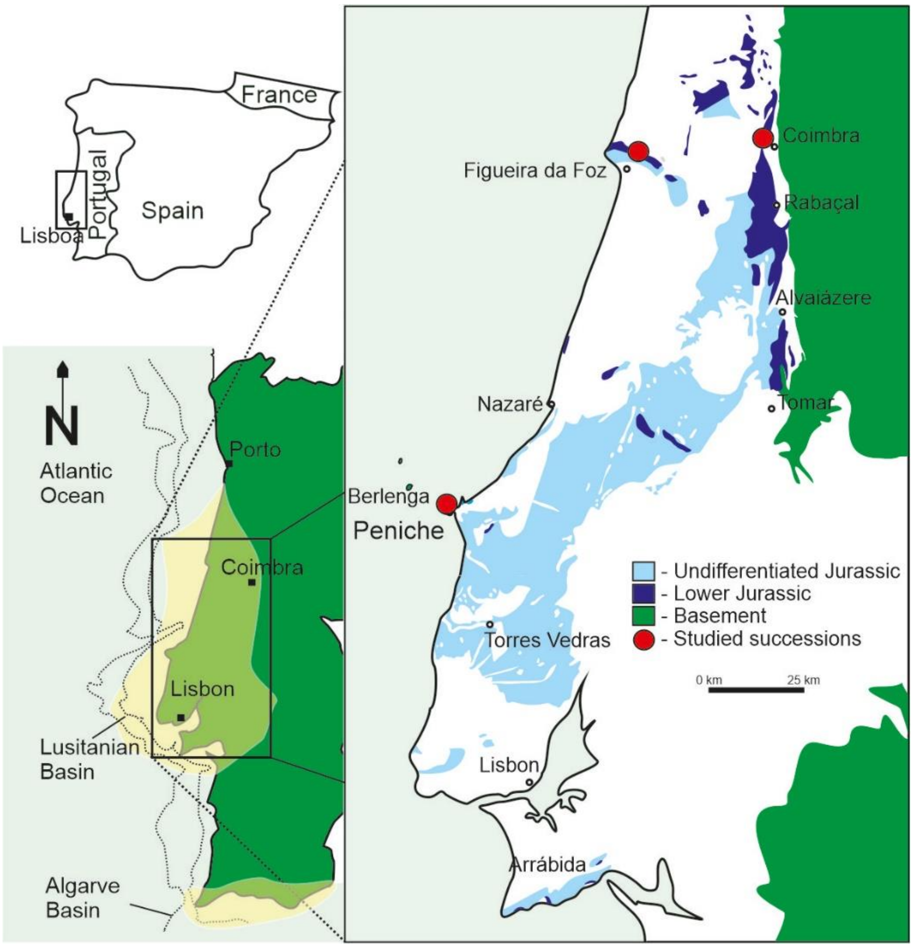

Fig. 1 The Lower Jurassic of the Lusitanian Basin and location of three studied successions: Peniche, Brenha (Figueira da Foz region), and Coimbra (modified from Duarte et al. 2010)

In the northern part of the Peniche Peninsula, at Portinho da Areia Norte Beach, there is the Peniche section, well-defined by the three members that constitute the Vale das Fontes Formation (Fig. 2a), showing an approximate thickness of 90 m (Duarte and Soares 2002; Oliveira et al. 2006).

The Brenha section (Fig. 2b), located along the N109 road, presents a continuous succession of the Vale das Fontes Formation with a thickness of approximately 80 m of this unit in this region (Duarte and Soares 2002; Silva 2007; Silva et al. 2007, 2010).

The Coimbra area exhibits a discontinuous number of outcrops (Fig. 2c), and the thickness of the Vale das Fontes Formation in this region was not expected to exceed 60 m (Duarte and Soares 2002; Silva 2007; Silva et al. 2007, 2010).

Fig. 2 Sampling sites in the three outcrop sections of the Vale das Fontes Formation: a) MLOF at Peniche; b) MLUP to MLOF at Brenha; c) MLUP at Coimbra

3. Materials and Methods

This study comprised samples collected from the three distinct sections described above. A total of 9 marl and limestone samples were collected: 6 from the Peniche section, 2 from the Brenha Section, and 1 from the Coimbra section (Fig.3), with a view to a mineralogical analysis by X-ray diffraction, porosity, uniaxial compressive strength, Young's modulus, and Poisson's ratio analyses. All laboratory work was conducted at the Petrophysical Institute Foundation (Fundación Instituto Petrofisico) based in Madrid (Spain). The rock testing methodologies recommended by CFCFF (1996) and ISRM (1981, 2007, 2015) were followed.

Fig. 3 Selected samples for petrophysical and geomechanical tests (after Temporão de Sousa 2014)

X-ray diffraction

For the X-ray diffraction analysis, an X-ray diffractometer using a mortar grinder (RM 200) was used to grind 2 to 4 grams of sample. After grinding, the samples were passed through a 53 µm sieve, allowing for excellent particle size distribution and ensuring that all the crystals were oriented in all possible directions during the analysis. This analysis used the Rietveld method, using Empyrean equipment from PANalytical.

Preparation of samples for geomechanical tests

Samples were prepared for geomechanical testing according to ASTM standards D5407-99 and D2664-04. Initially, all samples were washed using a Soxhlet extraction system combined with a Dean-Stark apparatus to remove potential hydrocarbons and salts. Subsequently, the samples were dried in an oven at 60°C for 24 hours until the difference between successive weights was less than 0.01 g.

Porosity

Effective porosities were determined using a Micromeritics AccuPyc™ 1340 pycnometer. These samples were then used to study geomechanical properties through the unconfined compressive strength test.

Uniaxial compressive strength test

This test was conducted using the MTS – Rock Mechanics Test System Model 815, which allows the determination of the uniaxial compressive strength of a cylindrical sample with a height equal to twice its diameter. In addition to assessing mechanical strength, this test allows the determination of the rock's elastic constants (Young's modulus and Poisson ratio) by measuring the axial and lateral deformations of the sample during the loading process (e.g., CFCFF 1996; Barton 2006; Gonzalez de Vallejo and Ferrer 2011; Zhang 2017; Ribeiro e Sousa et al. 2020; Tao et al. 2020). Young's modulus, also known as elastic modulus, measures how much a material can deform under tension or compression and indicates its hardness. On the other hand, Poisson's ratio measures how much a material expands or contracts in directions perpendicular to the direction of the load.

4. Results

The nine analysed samples are limestones and marly limestones; consequently, the mineral composition was dominated by calcite (a minimum of 59.2%), followed by quartz and phyllosilicates (mainly clay minerals). Some samples contained small amounts of albite (Samples 7 and 8) and magnetite (Sample 6) (Table 1).

Table 1 X-ray diffraction results

Sample	Location	Member	X-ray				
			Calcite (%)	Quartz (%)	Phyllosilicates (%)	Magnetite (%)	Albite (%)
1	Peniche	MLUP	95.6	3.6	0.8	-	-
2	Peniche	MLUP	79.7	11.6	8.6	-	-
3	Coimbra	MLUP	88.7	9.1	2.2	-	-
4	Peniche	LML	96.9	2.0	1.1	-	-
5	Peniche	LML	90.8	5.0	4.2	-	-
6	Brenha	LML	94.2	5.3	-	0.5	-
7	Peniche	MLOF	64.6	14.7	14.4	-	6.3
8	Peniche	MLOF	59.2	14.6	22.0	-	4.3
9	Brenha	MLOF	85.2	7.8	7.1	-	-

MLUP – Marls and limestones with *Uptonia* and *Pentacrinus*; LML – Lumpy marls and limestones; MLOF – Marly limestones with organic-rich facies.

Table 2 shows the porosity results, ranging from 0.4% to 15.1%, along with Young's modulus (1827 MPa – 9468 MPa) and Poisson's ratio (0.06 - 0.26) obtained from the uniaxial compressive strength. These values are critical for understanding the mechanical behaviour of materials under load.

Table 2 Porosity and geomechanical parameters

Sample	Location	Member	Porosity (%)	Geomechanical parameters: Maximum load (KN)	Compressive strength (MPa)	Young's modulus (MPa)	Passion ratio
1	Peniche	MLUP	4.6	194.15	155.98	30269	0.26
2	Peniche	MLUP	6.8	163.21	130.33	23212	0.22
3	Coimbra	MLUP	7.3	92.01	74.25	23745	0.16
4	Peniche	LML	6.0	89.38	71.34	38379	0.16
5	Peniche	LML	7.9	62.52	50.21	25981	0.22
6	Brenha	LML	0.4	188.67	150.67	39468	0.20
7	Peniche	MLOF	15.1	26.76	21.4	1927	0.14
8	Peniche	MLOF	11.7	45.20	36.4	5120	0.06
9	Brenha	MLOF	6.0	152.64	124.88	25624	0.21

MLUP – Marls and limestones with *Uptonia* and *Pentacrinus*; LML – Lumpy marls and limestones; MLOF – Marly limestones with organic-rich facies.

5. Discussion

The results of the present study's rock geomechanical properties showed a strong dependence on mineralogical composition and porosity.

The geomechanical results showed that the compressive strength index values (Fig. 4a) increased with the combined content of calcite and quartz. Generally, calcite is more brittle than quartz due to its crystalline structure, making it more susceptible to fracture. As a result, compressive strength values are typically lower for calcite. However, this trend does not apply to the samples analysed (Tables 1 and 2 and Fig. 4b). Specifically, samples 1 and 4 had the highest calcite content at 95.5% and 96.9%, respectively (Table 1). Despite this high calcite content, sample 1 exhibited the highest compressive strength value at 155.98 MPa (Table 2), whilst sample 4 had one of the lowest at 71.34 MPa (Table 2).

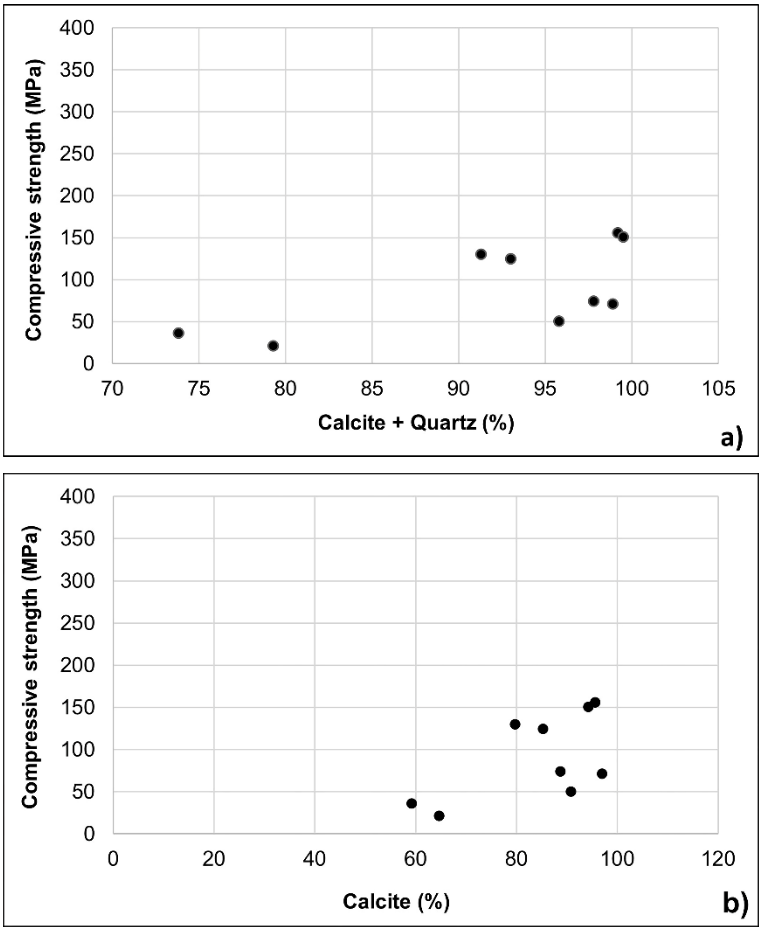

Fig. 4 Uniaxial compressive strength as a function of (a) calcite + quartz and (b) calcite

In addition, quartz is known for having higher hardness and compressive strength than calcite. It is generally expected that samples with a higher quartz content should have higher compressive strength values. However, the samples analysed did not support this (Tables 1 and 2 and Fig. 5a). Samples 7 and 8 had the highest quartz contents of 14.7% and 14.6%, respectively (Table 1). Yet, they recorded the lowest compressive strength values of 21.4 MPa and 36.4 MPa (Table 2). It is clear that the phyllosilicate content also plays a relevant effect on the compressive strength values of the analysed samples (Fig. 5b). It is well known that phyllosilicates typically exhibit elastic and/or plastic behaviour and are, therefore, less brittle and exhibit low compressive strength values. Thus, the compressive strength values of samples 7 and 8 were low (21.4 MPa and 36.4 MPa respectively, Table 2), despite their high quartz content (14.7% and 14.6% respectively, Table 1), due to their high phyllosilicates content (14.4% and 22.0%

respectively, Table 1). In addition, samples 5 and 6 were characterised by similar quartz content of 5.0 % and 5.3%, respectively (Table 1), but their compressive strength values are markedly different. Sample 5 showed a significantly lower compressive strength value (50.21 MPa, Table 2), while sample 6 achieved 150.67 MPa (Table 2). Therefore, it is clear that this difference in compressive strength values, identified between samples 5 and 6 (50.21 MPa and 150.67 MPa, respectively, Table 2), is closely related to the phyllosilicates content, meaning that sample 5 displayed a phyllosilicates content of 4.2% and in sample 6 they were not identified (Table 1). Finally, samples 1 and 6 displayed the highest compressive strength values (155.98 MPa and 150.67 MPa, respectively, Table 2), the highest combined percentages of calcite and quartz, at 99.2% and 99.5%, respectively (Table 1), and the lowest phyllosilicates content, at 0.8% for sample 1 and 0% for sample 6 (Table 1).

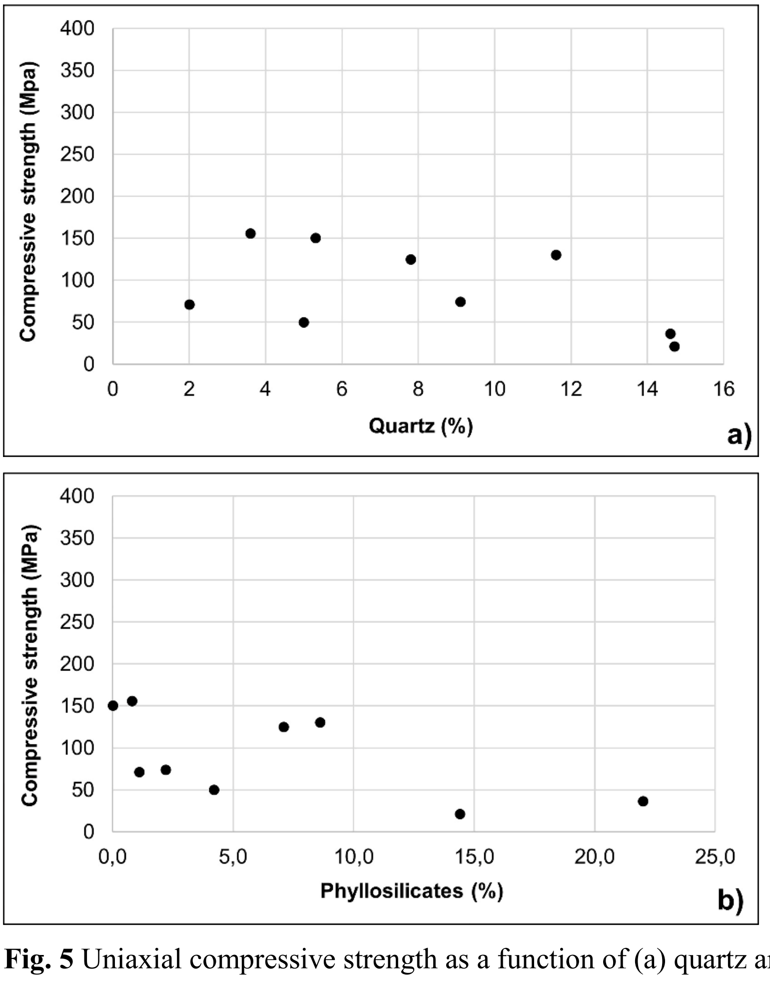

Fig. 5 Uniaxial compressive strength as a function of (a) quartz and (b) phyllosilicates

Figure 6 shows a general trend of increasing compressive strength values as porosity decreases. Samples displaying high porosity values, such as samples 7 and 8 (15.1% and 11.7% respectively, Table 2), exhibited low compressive strength values (21.4MPa and 36MPa respectively, Table 2) due to pore collapse and, therefore, they are less resistant. However, the relationship between compressive strength and porosity must also consider the mineral composition. For example, sample 1 exhibited a compressive strength of 155.98 MPa, while sample 6 had a compressive strength of 150.67 MPa (Table 2). Therefore, one would typically expect lower porosity in the former than in the latter. Nevertheless, sample 1 exhibited a porosity of 4.6%, which is significantly higher than the 0.4% of sample 6. This unexpected result can be related to the higher phyllosilicate content in sample 1 (0.8%) compared to sample 6, which has no phyllosilicates.

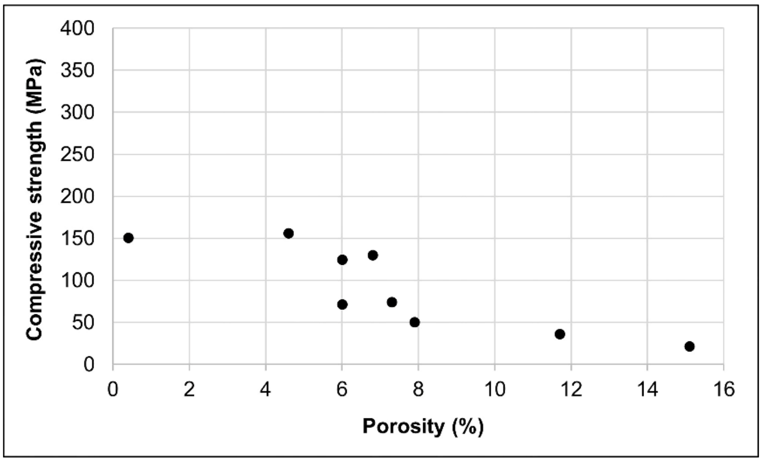

Fig. 6 The relationship between compressive strength and porosity

The Young´s modulus and the Poisson´s ratio strongly depended on mineral composition and porosity. Young's modulus measures the hardness of a rock, which, in this case study, increases as the combined calcite and quartz content increases (Fig. 7a). Sample 6 had the highest combined content of calcite and quartz at 99.5%, corresponding to the highest Young's modulus value of 39468 MPa (Table 2, Fig. 7a). In contrast, the lower Young's modulus values of 1927 MPa (sample 7, Table 2) and 5120 MPa (sample 8, Table 2) were observed in samples with higher phyllosilicate contents (14.4% and 22.0%, respectively Table 1, Fig. 7b). Phyllosilicates typically exhibit elastic and plastic behaviour, making them less susceptible to brittle deformation.

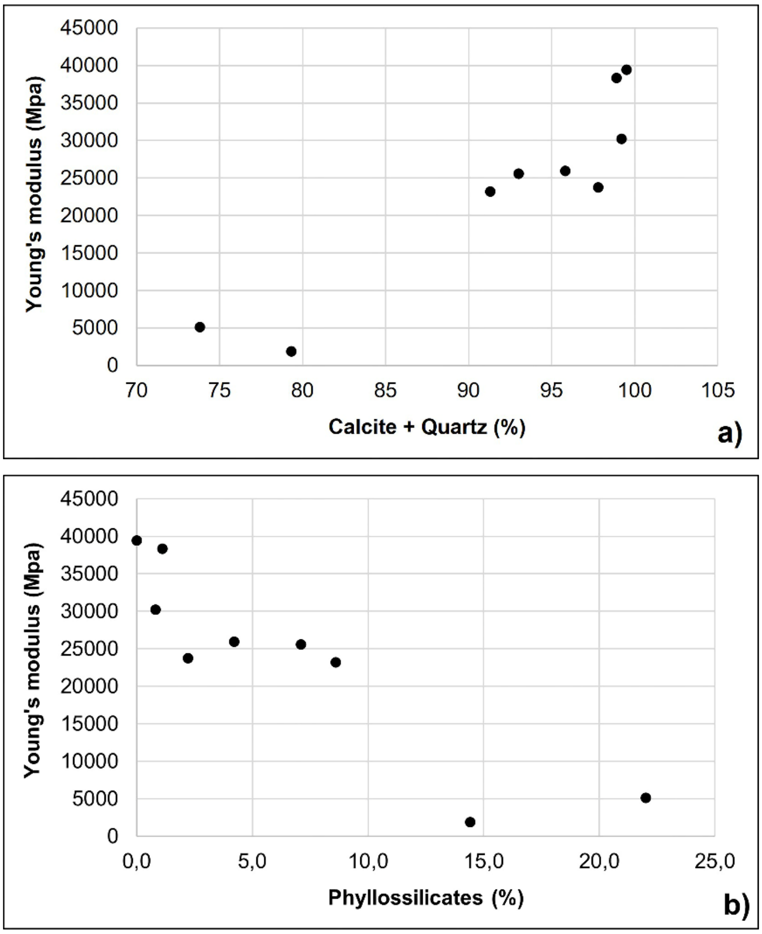

Fig. 7 Young's modulus behaviour as a function of (a) calcite + quartz and (b) phyllosilicates

Poisson's ratio shows an increasing trend with increasing calcite and quartz contents (Fig. 8a). In contrast, due to their elastic or plastic behaviour, Poisson's ratio decreased with increasing phyllosilicate content (Fig. 8b). For example, sample 1 showed a high Poisson´s ratio value of 0.26 (Table 2), and the phyllosilicate content was 0.8% (Table 1). In contrast, sample 8, which showed a high phyllosilicate content of 22.0% (Table 1), reported a low Poisson ratio of 0.06 (Table 2). This suggests lateral deformation may become less significant than axial deformation as the phyllosilicate content increases, reducing Poisson's ratio.

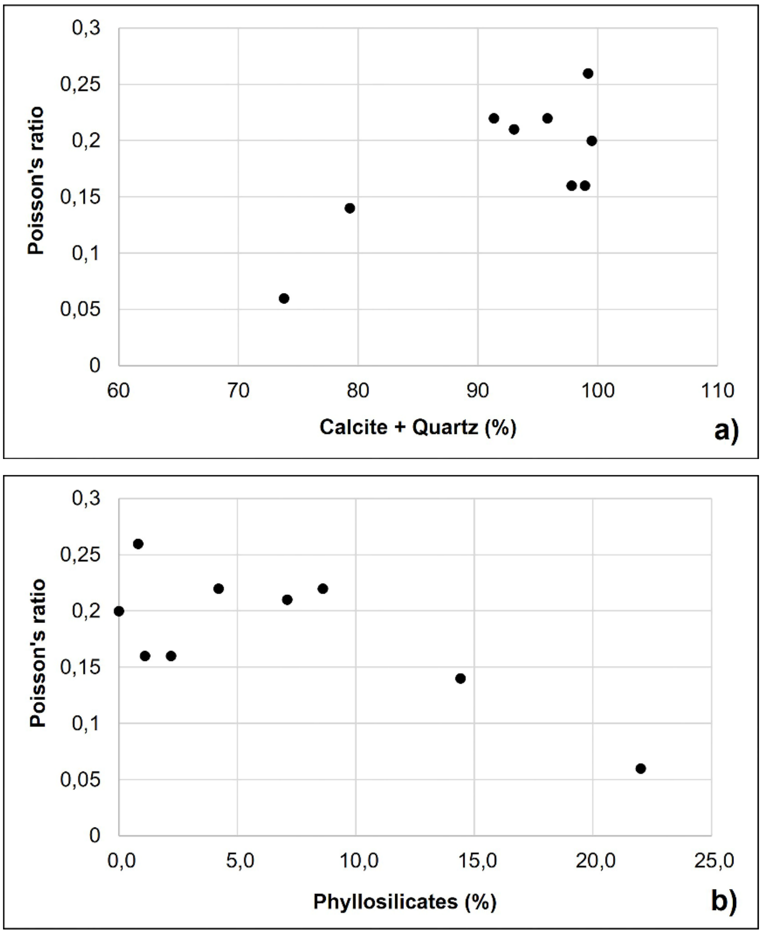

Fig. 8 Poisson's ratio behaviour as a function of (a) calcite + quartz and (b) phyllosilicates

Additionally, porosity affects the mechanical behaviour of the rock as the volume of voids in the internal pore structure contributes to increased deformation when subjected to load or stress. Thus, samples with greater porosity are more flexible, resulting in lower values for both Young's modulus and Poisson´s ratio, as shown in Fig. 9a and 9b. For example, sample 6 showed a low porosity value of 0,4% (Table 2), resulting in high values of Young´s modulus of 39468 MPa and Poison's ratio of 0.2 (Table 2). In contrast, sample 7 showed a high porosity value of 15.1% (Table 2), leading to low values of Young´s modulus of 1927 MPa and Poisson's ratio of 0.14 (Table 2).

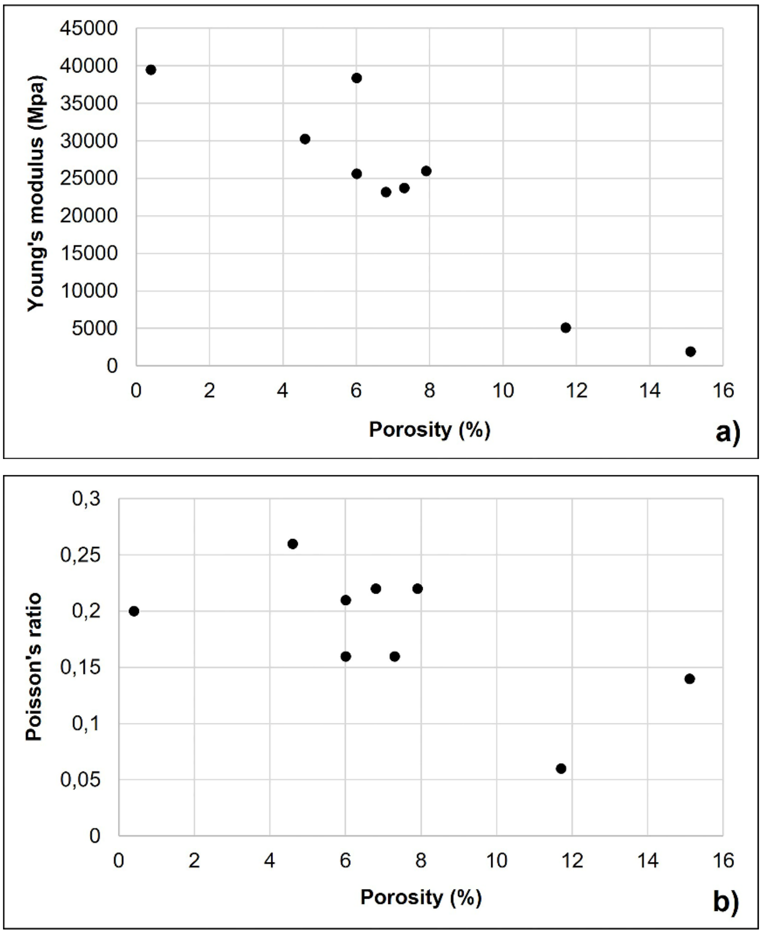

Fig. 9 Influence of porosity on (a) Young's modulus and (b) Poisson's ratio

6. Conclusions

The exploratory study of the geomechanical properties of the Vale das Fontes Formation leads to the following concluding remarks:

1) The X-ray results indicate that calcite is the most representative mineral in the Vale das Fontes Formation, followed by quartz and phyllosilicates. The porosity of the studied samples varies between 0.4% (sample 6) and 15.1% (sample 7), with an average value of 7.3%.

2) The geomechanical properties of rocks are strongly dependent on their mineralogical composition and porosity:

- Rock samples with a high content of brittle minerals, such as calcite and quartz, present high compressive strength values. Thus, samples 1 and 6, which are characterised by the higher calcite and quartz contents of 99.2% and 99.5%, report the highest compressive strength values of 155.98 MPa and 150.67 MPa, respectively.

- Phyllosilicate-rich samples exhibit plastic and/or elastic behaviours and, therefore, less brittleness, resulting in lower compressive strength. In the present study, the lower compressive strength values of 21.4 MPa and 36.4 MPa are reported in the samples with the highest phyllosilicate contents, sample 7 (14.4%) and sample 8 (22.0%).

3) Results show that compressive strength values generally increase as porosity decreases. Therefore, samples 1 and 6 report the highest compressive strength values of 155.98 MPa and 150.67 MPa, respectively. These samples have the lowest porosity values of 4.6% (sample 1) and 0.4% (sample 6).

4) Young's modulus and Poisson's ratio show average values of 23.747 MPa and 0.18, respectively. Both parameters show an increase with decreasing calcite and quartz content, whereas an increase in phyllosilicate content leads to a decrease in these values. In addition, samples with higher porosity of 15.1% and 11.7% are reported for samples 7 and 8, show increased flexibility, which is associated with a decrease in both Young's modulus (1927 MPa, sample 7 – 5120 MPa, sample 8) and Poisson's ratio (0.14, sample 7 – 0.06, sample 8).

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Declarations

Conflict of interest: The authors declare no competing interests.

Data availability: All data generated or analysed during this study are included in this published article**.**

Code Availability: Not applicable.

References

Alves TM, Gawthorpe RL, Hunt DW, Monteiro JH (2002) Jurassic tectono-sedimentary evolution of the Northern Lusitanian Basin (offshore Portugal). Marine and Petroleum Geology 19(6): 727-754.

Azerêdo AC, Duarte LV, Henriques MH, Mannupella G (2003) Da dinâmica continental no Triássico aos mares do Jurássico Inferior e Médio. Cadernos de Geologia de Portugal, Instituto Geológico e Mineiro, 43p.

Barton N (2006) Rock quality, seismic velocity, attenuation and anisotropy. Taylor & Francis, London, 729p.

Brito M, Rodrigues R, Baptista R, Duarte LV, Azerêdo AC, Jones CM (2017) Geochemical characterization of oils and their correlation with Jurassic source rocks from the Lusitanian Basin (Portugal). Marine Petroleum Geology 85: 151-176.

Brito M, Rodrigues R, Baptista R, Duarte LV, Azerêdo AC, Jones CM (2023) Jurassic Petroleum Systems in the Lusitanian Basin, Portugal: new insights based on oil-source rock correlations. Journal of Petroleum Geology 46(4): 463–485.

CFCFF (Committee on Fracture Characterization and Fluid Flow) (1996) Rock fractures and fluid flow: contemporary understanding and applications. National Research Council, National Academy Press, Washington DC, 551p.

Chen T, Feng X, Cui G, Tan Y, Pan Z (2019) Experimental study of permeability change of organic-rich gas shales under high effective stress. Journal of Natural Gas Science and Engineering 64(6): 1-14.

Choffat LP (1880) Étude Stratigraphique et Paléontologique des Terrains Jurassiques du Portugal. Première Livraison Le Lias et le Dogger au Nord du Tage. Lisbonne: Imprimerie de l'Académie Royale des Sciences, 72p.

Duarte LV (1997) Facies analysis and sequential evolution of the Toarcian-Lower Aalenian series in the Lusitanian Basin (Portugal). Comunicações do Instituto Geológico e Mineiro 83: 85-94.

Duarte LV (2004) The geological heritage of the Lower Jurassic of Central Portugal: selected sites, inventory and main scientific arguments. Rivista Italiana di Paleontologia e Stratigrafia 110(1): 381-388.

Duarte LV, Comas-Rengifo MJ, Silva RL, Paredes R, Goy A (2014) Carbon isotope stratigraphy and ammonite biochronostratigraphy across the Sinemurian-Pliensbachian boundary in the western Iberian margin. Bulletin of Geoscience 89: 719–738.

Duarte LV, Silva RL, Azerêdo AC, Comas-Rengifo MJ, Mendonça Filho JG (2022) Shallow-water carbonates of the Coimbra Formation, Lusitanian Basin (Portugal): contributions to the integrated stratigraphic analysis of the Sinemurian sedimentary successions in the western Iberian Margin. Comptes Rendus Géoscience 354(s3): 89–106.

Duarte LV, Silva RL, Mendonça Filho JG, Poças Ribeiro N, Chagas RBA (2012) High-resolution stratigraphy, Palynofacies and source rock potential of the Água de Madeiros Formation (Upper Sinemurian) of the Lusitanian Basin, Portugal. Journal of Petroleum Geology 35(2): 105-126.

Duarte LV, Silva RL, Oliveira LCV, Comas-Rengifo MJ, Silva F (2010) Organic-Rich facies in the Sinemurian and Pliensbachian of the Lusitanian Basin, Portugal: Total Organic Carbon distribution and relation to transgressive-regressive facies cycles. Geologica Acta 8(3): 325-340.

Duarte LV, Soares AF (2002) Litostratigrafia das séries magro-calcárias do Jurássico inferior da Bacia Lusitânica (Portugal). Comunicações do Instituto Geológico e Mineiro 89: 135-154.

Gonzalez Vallejo L, Ferrer M (2011) Geological Engineering. CRC Press, Taylor & Francis Group, London, 725p.

ISRM (International Society for Rock Mechanics) (1981) Rock Characterization, Testing and Monitoring: ISRM Suggested Methods. In: Brown ET (ed) Suggested Methods Prepared by the Commission on Testing Methods. Oxford, Pergamon Press, 200p.

ISRM (International Society for Rock Mechanics) (2007) The complete ISRM suggested methods for characterization, testing and monitoring: 1974-2006. In: Ulusay R, Hudson JA (eds) Suggested methods prepared by the Commission on Testing Methods. ISRM, Ankara, 628p.

ISRM (International Society for Rock Mechanics) (2015) The ISRM suggested methods for rock characterization, testing and monitoring: 2007-2014. In: Ulusay R (ed) Suggested methods prepared by the Commission on Testing Methods. ISRM & Springer, Berlin, 280p.

Kuang N, Zhou J, Xian X, Zhang C, Yang K, Dong Z (2023) Geomechanical risk and mechanism analysis of CO_2 sequestration in unconventional coal seams and shale gas reservoirs. Rock Mechanics Bulletin 2(4): 100079.

Kullberg JC, Rocha RB, Soares AF, Rey J, Terrinha P, Azerêdo AC, Callapez P, Duarte LV, Kullberg MC, Martins L, Miranda R, Alves C, Mata J, Madeira J, Mateus O, Moreira M, Nogueira CR (2013) A Bacia Lusitaniana: estratigrafia, paleogeografia e tectónica. In: Dias R, Araújo A, Terrinha P, Kullberg JC (eds) Geologia de Portugal, Volume II – Geologia Meso-cenozóica de Portugal. Escolar Editora, Lisboa, III.3: 195-347.

Liu B, Wang S, Ke X, Fu X, Liu X, Bai Y, Pan Z (2020) Mechanical characteristics and factors controlling brittleness of organic-rich continental shales. Journal of Petroleum Science and Engineering 194: 107464.

Manchao H, Xiaoming S (2020) Engineering view of soft rocks. In: Kanji M, He M, Ribeiro e Sousa L (eds) Soft Rock Mechanics and Engineering. Springer, Chapter 2, pp 7–17.

Mohammad N, Ishak WWM, Mustapa SI, Ayodele BV (2021) Natural gas as a key alternative energy source in sustainable renewable energy transition: a mini review. Frontiers in Energy Research 9: 625023.

Mouterde R (1955) Le Lias de Peniche. Comunicações dos Serviços Geológicos de Portugal 36: 87-115.

Oliveira LCV, Rodrigues R, Duarte LV, Lemos V (2006) Avaliação do potencial gerador de petróleo e interpretação paleoambiental com base em biomarcadores e isótopos estáveis do carbono da secção Pliensbaquiano-Toarciano inferior (Jurássico inferior) da região de Peniche (Bacia Lusitânica, Portugal). Boletim de Geociências da Petrobrás 14(2): 207-234.

Oliveira R (1993) Weak rock materials. In: Cripps JC, Coulthard JM, Culshaw MG, Forster A, Hencher SR, Moon CF (eds) The engineering geology of weak rock: Proceedings of the 26th Annual Conference of the Engineering Group of the Geological Society (Leeds, United Kingdom, 9-13 September 1990). Engineering Geology Special Publication, Balkema, Rotterdam, Chapter 8, pp 5–15.

Pinheiro LM, Wilson RCL, Pena dos Reis R, Whitmarsh RB, Ribeiro A (1996) The Western Iberia Margin: a geophysical and geological overview. In: Whitmarsh RB, Sawyer DS, Klaus A, Masson DG (eds) Proceedings of the Ocean Drilling Program. Scientific Results 149(1): 3-23.

Potter PE, Maynard JB, Pryor WA (1980) The sedimentology of shale: a study guide and reference source. Springer Verlag, New York, 306p.

Ribeiro e Sousa L, Sousa RL, Cuiying Z, Karam K (2020) Evaluation of geomechanical properties of soft rock masses by laboratory and in situ testing. In: Kanji M, He M, Ribeiro e Sousa L (eds) Soft Rock Mechanics and Engineering. Springer, Chapter 8, pp 187–234.

Ribeiro NP, Mendonça Filho JG, Duarte LV, Silva RL, Mendonça JO, Silva TF (2013) Palynofacies and organic geochemistry of the Sinemurian carbonate deposits in the western Lusitanian Basin (Portugal): Coimbra and Água de Madeiros formations. International Journal of Coal Geology 111: 37-52.

Sadowski GR (2020) The geology of soft rocks. In: Kanji M, He M, Ribeiro e Sousa L (eds) Soft Rock Mechanics and Engineering. Springer, Chapter 3, pp 19–35.

Silva F (2007) A Formação de Vale das Fontes no sector norte da Bacia Lusitânica. Caracterização, avaliação e distribuição do conteúdo em matéria orgânica. Master's Dissertation, Universidade de Coimbra, 93p.

Silva F, Duarte LV, Oliveira LCV, Rodrigues R, Comas-Rengifo MJ (2007) Caracterização do Carbono Orgânico Total e pirólise *Rock-Eval* no intervalo Sinemuriano superior – Pliensbaquiano do sector norte da Bacia Lusitânica (Portugal). In: Gomes EP, Alencoão AM (eds) Procedings of XV Semana de Geoquímica no VI Congresso Ibérico de Geoquímica. Vila Real, Geoquímica Orgânica 12: 564-567.

Silva F, Duarte LV, Oliveira LCV, Rodrigues R, Comas-Rengifo MJ (2010) Contribution to the knowledge of petroleum generative potential of Late Sinemurian – Pliensbachian of the Lusitanian Basin – northern sector (Portugal). II Central & North Atlantic Conjugate Margins Conference, Re-Discovering the Atlantic, New winds for an old sea – Extended Abstracts. Lisbon 1: 256-260.

Silva RL, Duarte LV (2015) Organic matter production and preservation in the Lusitanian Basin (Portugal) and Pliensbachian climatic hot snaps. Global and Planetary Change 131(1-3): 24–34.

Silva RL, Duarte LV, Comas-Rengifo MJ (2015) Facies and carbon isotope chemostratigraphy of Lower Jurassic carbonate deposits, Lusitanian Basin (Portugal): Implications and limitations to the application in sequence stratigraphic studies. In: Ramkumar M (ed) Chemostratigraphy: Concepts, Techniques, and Applications. Elsevier, Amsterdam, pp 341–371.

Silva RL, Duarte LV. Comas-Rengifo MJ, Mendonça Filho JG, Azerêdo AC (2011) Update of the carbon and oxygen isotopic records of the Early-Late Pliensbachian (Early Jurassic, ~187Ma): Insights from the organic-rich hemipelagic series of the Lusitanian Basin (Portugal). Chemical Geology 283(3-4): 177-184.

Soares AF, Rocha RB, Elmi S, Henriques MH, Mouterde R, Almeras Y, Ruget C, Marques J, Duarte LV, Carapito C, Kullberg JC (1993) Le sous-bassin nord-lusitanien (Portugal) du Trias au Jurassique moyen: histoire d'un "rift avorté". Comptes Rendus de L' Academie des Sciences de Paris 317(II): 1659-1666.

Tan Y, Pan Z, Feng X, Zhang D, Connell LD, Li S (2019) Laboratory characterisation of fracture compressibility for coal and shale gas reservoirs rocks: A review. International Journal of Coal Geology 204(07): 1-17.

Tao Z, Zhou C, Ribeiro e Sousa L, Feifei Z (2020) Site investigation for soft rock mass. In: Kanji M, He M, Ribeiro e Sousa L (eds) Soft Rock Mechanics and Engineering. Springer, Chapter 7, pp 163–186.

Temporão de Sousa JP (2014) Proposta metodológica para avaliação preliminar de jazigos de shale gas: aplicação à Formação de Vale das Fontes, Bacia Lusitânica (Portugal). Master's Dissertation, Instituto Superior de Engenharia do Porto, 194p.

UN (United Nations) (2023) United Nations Framework Convention on Climate Change: Conference of the Parties serving as the meeting of the Parties to the Paris Agreement. (Document FCCC/PA/CMA/2023/L.17). United Arab Emirates, first global stocktake, 21p.

Wilson RCL (1988) Mesozoic development of the Lusitanian Basin, Portugal. Revista de la Sociedad Geologica de España 1(3-4): 393-407.

Zhang L (2017) Engineering properties of rocks. 2nd edition. Elsevier, Butterworth-Heinemann, Oxford. 394p.

Zou C, Dong D, Wang Y, Li X, Huang J, Wang S, Guan Q, Zhang C, Wang H, Liu H, Bai W, Liang F, Lin W, Zhao Q, Liu D, Yang Z, Liang P, Sun S, Qiu Z (2016) Shale gas in China: Characteristics, challenges and prospects (II). Petroleum Exploration and Development 43(2): 182-196.

Table 1

Sample	Location	Member	X-ray				
			Calcite (%)	Quartz (%)	Phyllosilicates (%)	Magnetite (%)	Albite (%)
1	Peniche	MLUP	95.6	3.6	0.8	-	-
2	Peniche	MLUP	79.7	11.6	8.6	-	-
3	Coimbra	MLUP	88.7	9.1	2.2	-	-
4	Peniche	LML	96.9	2.0	1.1	-	-
5	Peniche	LML	90.8	5.0	4.2	-	-
6	Brenha	LML	94.2	5.3	-	0.5	-
7	Peniche	MLOF	64.6	14.7	14.4	-	6.3
8	Peniche	MLOF	59.2	14.6	22.0	-	4.3
9	Brenha	MLOF	85.2	7.8	7.1	-	-

MLUP – Marls and limestones with *Uptonia* and *Pentacrinus*; LML – Lumpy marls and limestones; MLOF – Marly limestones with organic-rich facies.

Sample	Location	Member	Porosity (%)	Geomechanical parameters			
				Maximum load (KN)	Compressive strength (MPa)	Young's modulus (MPa)	Passion ratio
1	Peniche	MLUP	4.6	194.15	155.98	30269	0.26
2	Peniche	MLUP	6.8	163.21	130.33	23212	0.22
3	Coimbra	MLUP	7.3	92.01	74.25	23745	0.16
4	Peniche	LML	6.0	89.38	71.34	38379	0.16
5	Peniche	LML	7.9	62.52	50.21	25981	0.22
6	Brenha	LML	0.4	188.67	150.67	39468	0.20
7	Peniche	MLOF	15.1	26.76	21.4	1927	0.14
8	Peniche	MLOF	11.7	45.20	36.4	5120	0.06
9	Brenha	MLOF	6.0	152.64	124.88	25624	0.21

MLUP – Marls and limestones with *Uptonia* and *Pentacrinus*; LML – Lumpy marls and limestones; MLOF – Marly limestones with organic-rich facies.

Fig.1

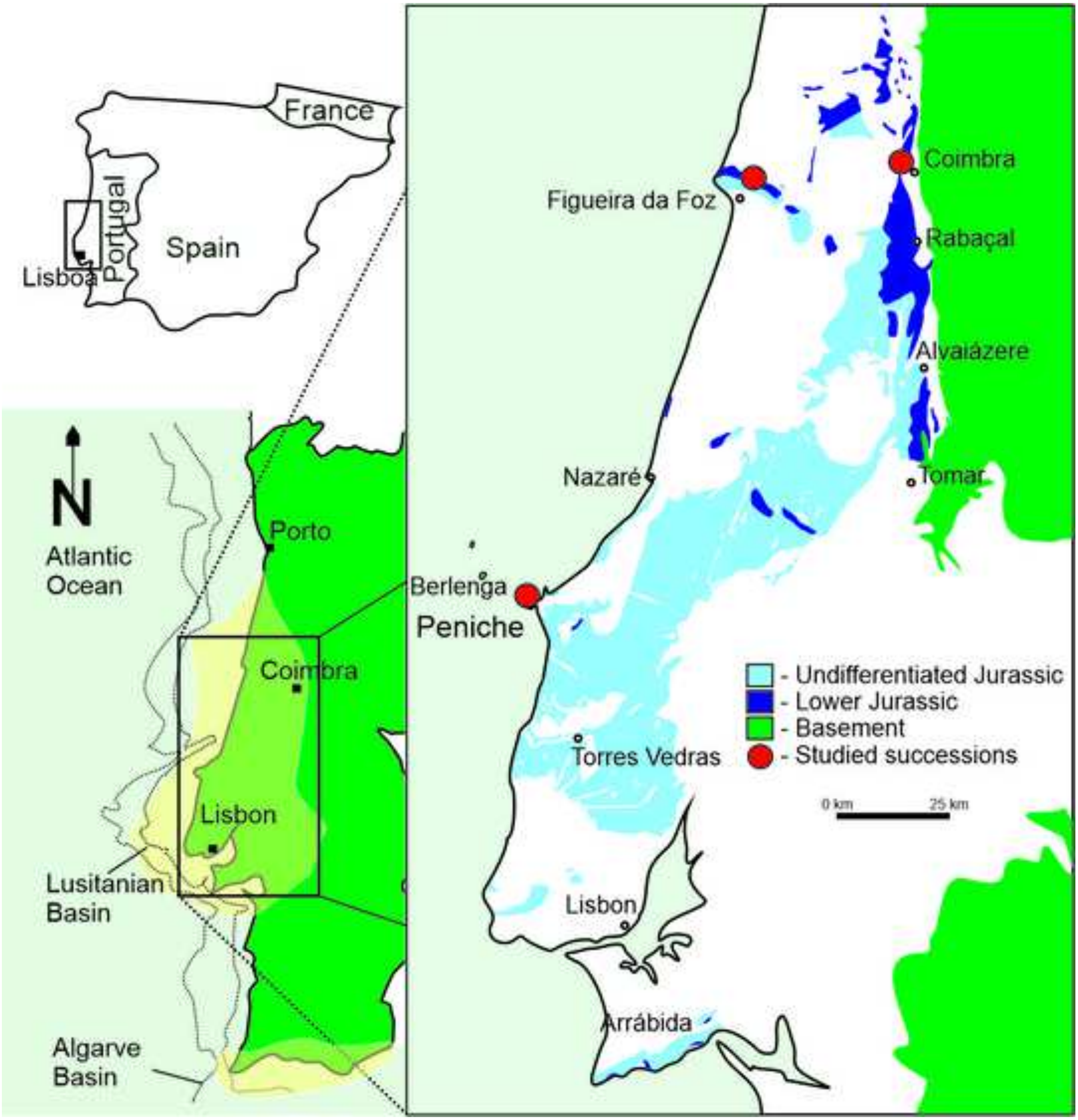

France
Portugal
Spain
Lisboa
N
Atlantic Ocean
Porto
Coimbra
Lisbon
Lusitanian Basin
Algarve Basin
Coimbra
Figueira da Foz
Rabaçal
Alvaiázere
Nazaré
Tomar
Berlenga
Peniche
Torres Vedras
Lisbon
Arrábida
- Undifferentiated Jurassic
- Lower Jurassic
- Basement
- Studied successions
0 km
25 km

Fig.2

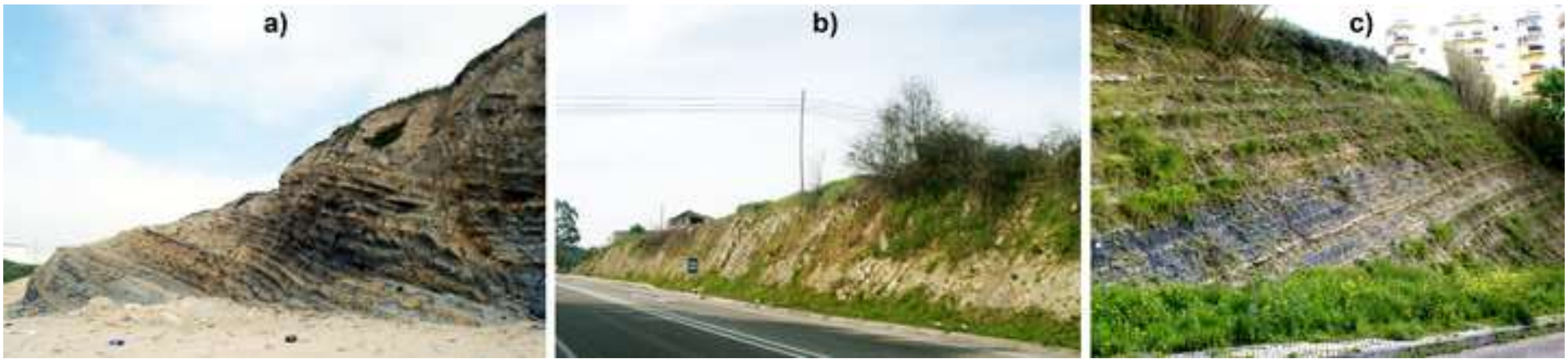


Fig.3

Fig.4(a)

Click here to access/download;Figure;Fig. 4(a).tif

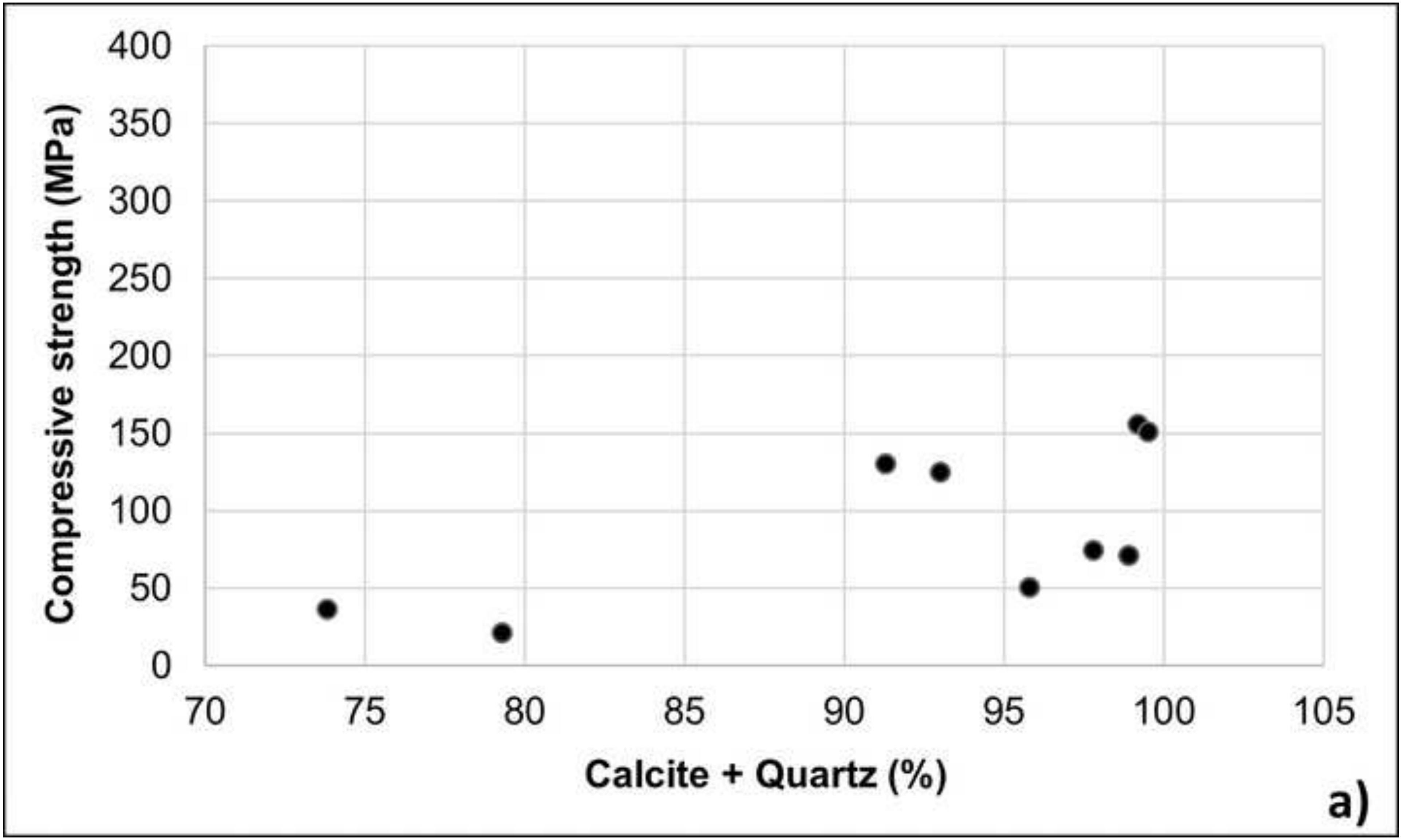
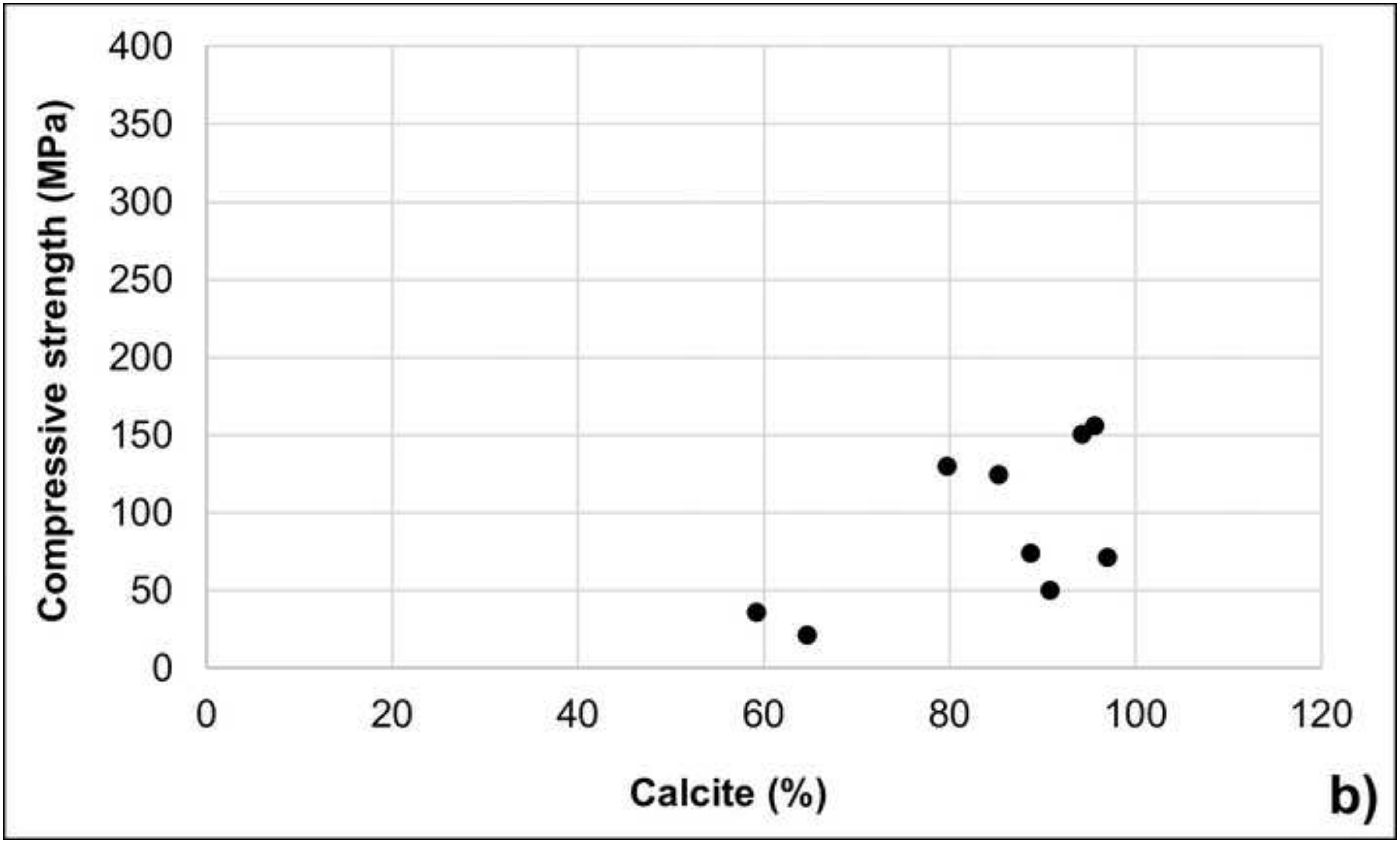


Fig.4(b)



Compressive strength (MPa)
400
350
300
250
200
150
100
50
0
0
20
40
60
80
100
120
Calcite (%)
b)

Fig.5(a)

Click here to access/download;Figure;Fig. 5(a).tif

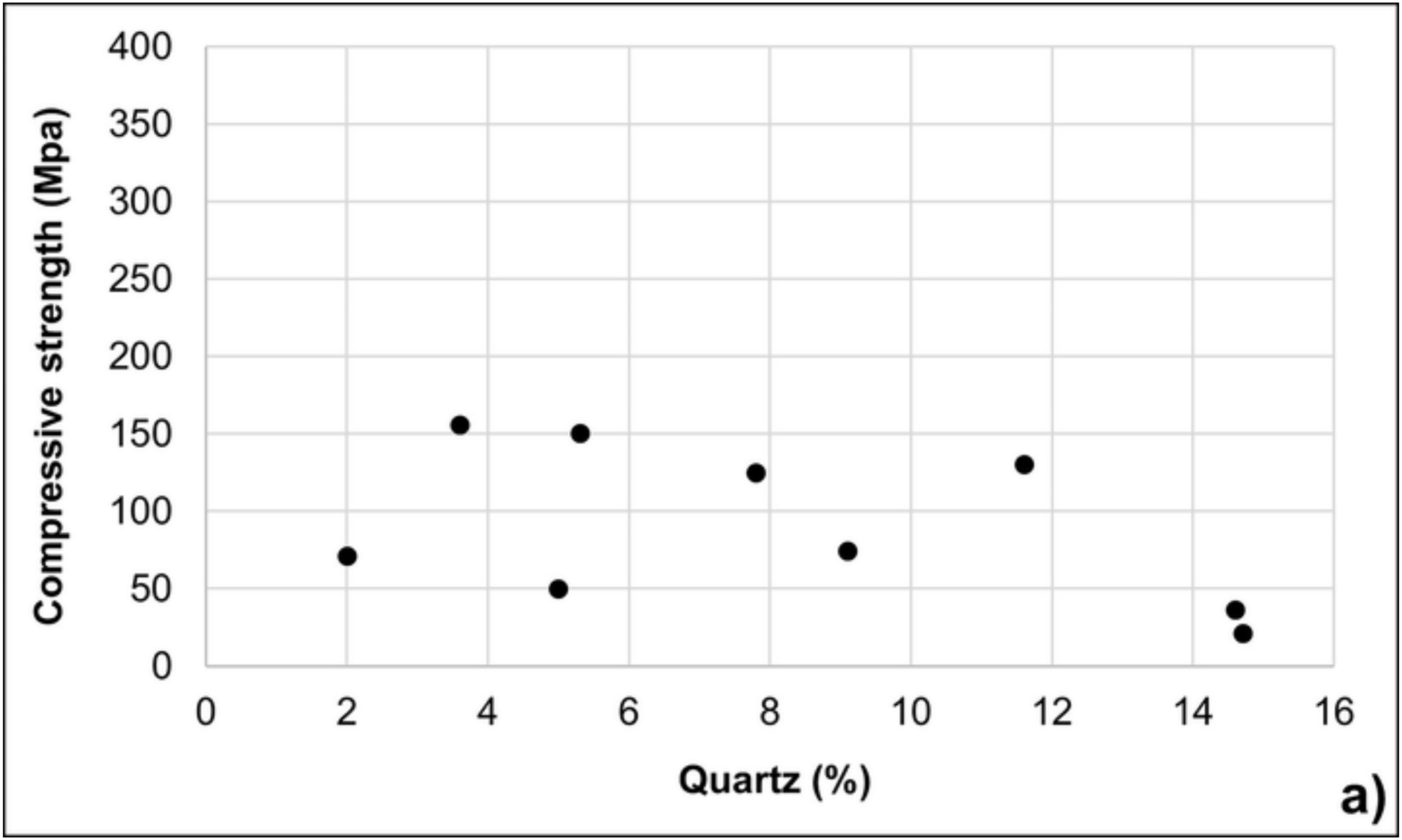


Fig.5(b)

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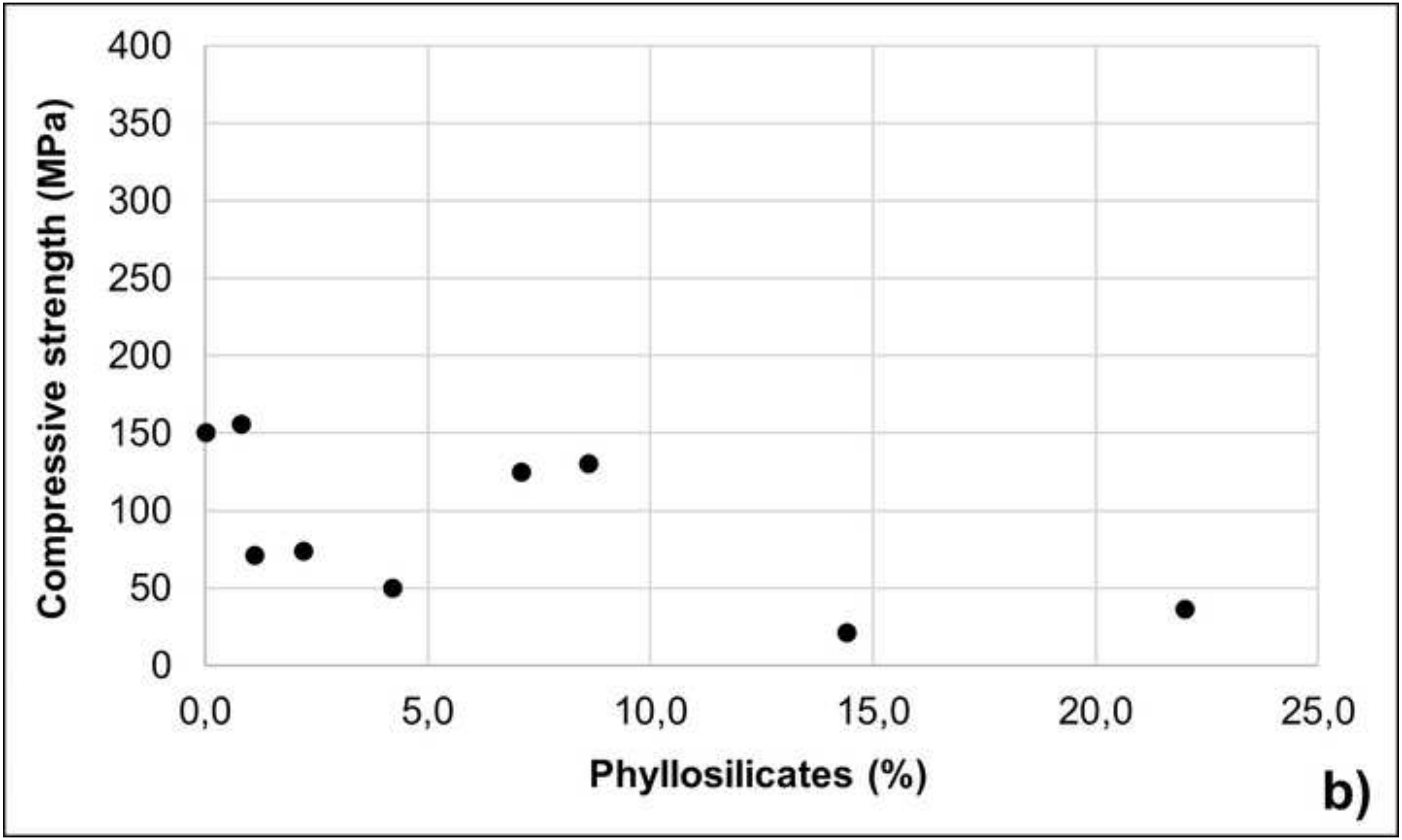


Fig.6

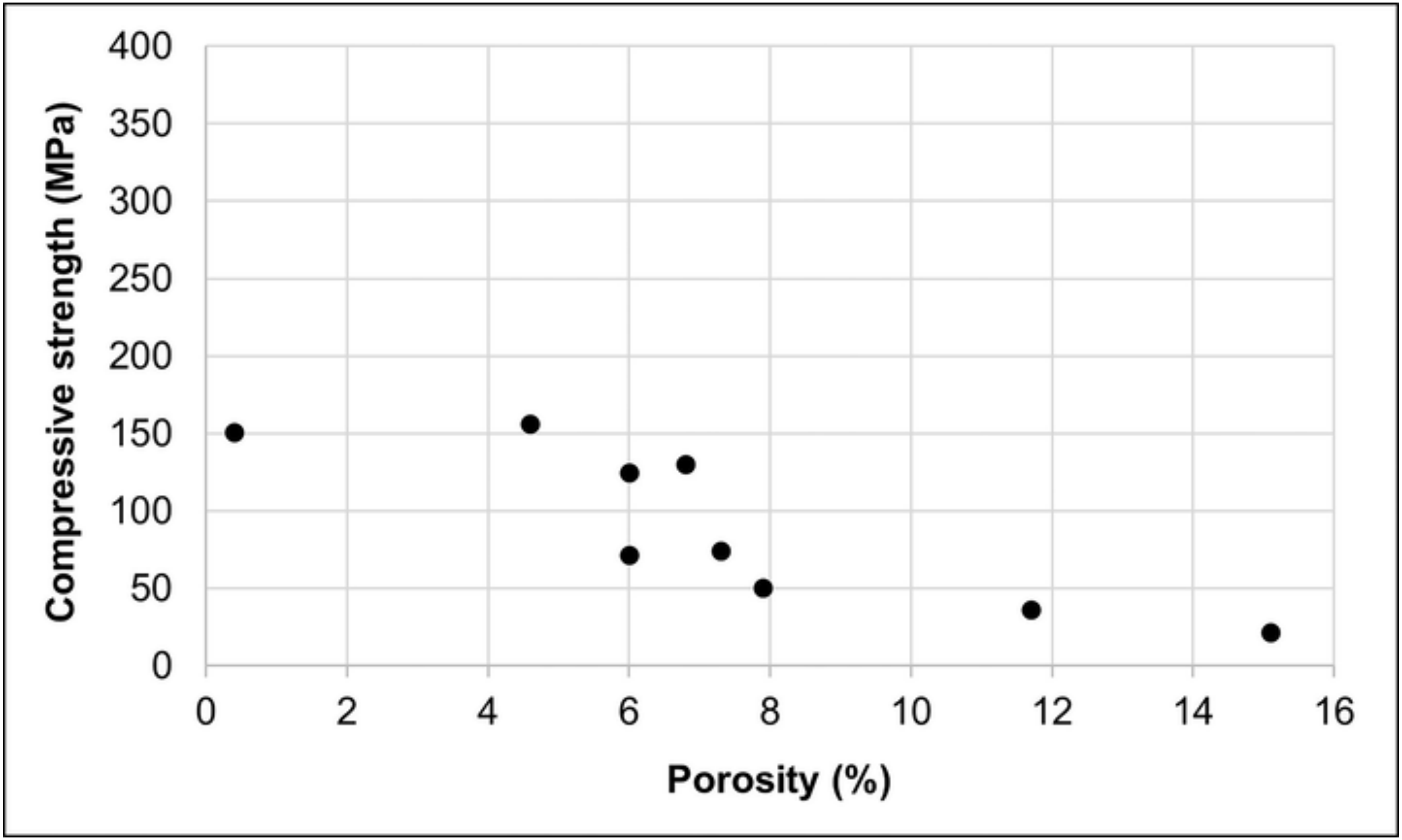

400
350
300
250
200
150
100
50
0
Compressive strength (MPa)
0
2
4
6
8
10
12
14
16
Porosity (%)

Fig.7(a)

Click here to access/download;Figure;Fig. 7(a).tif

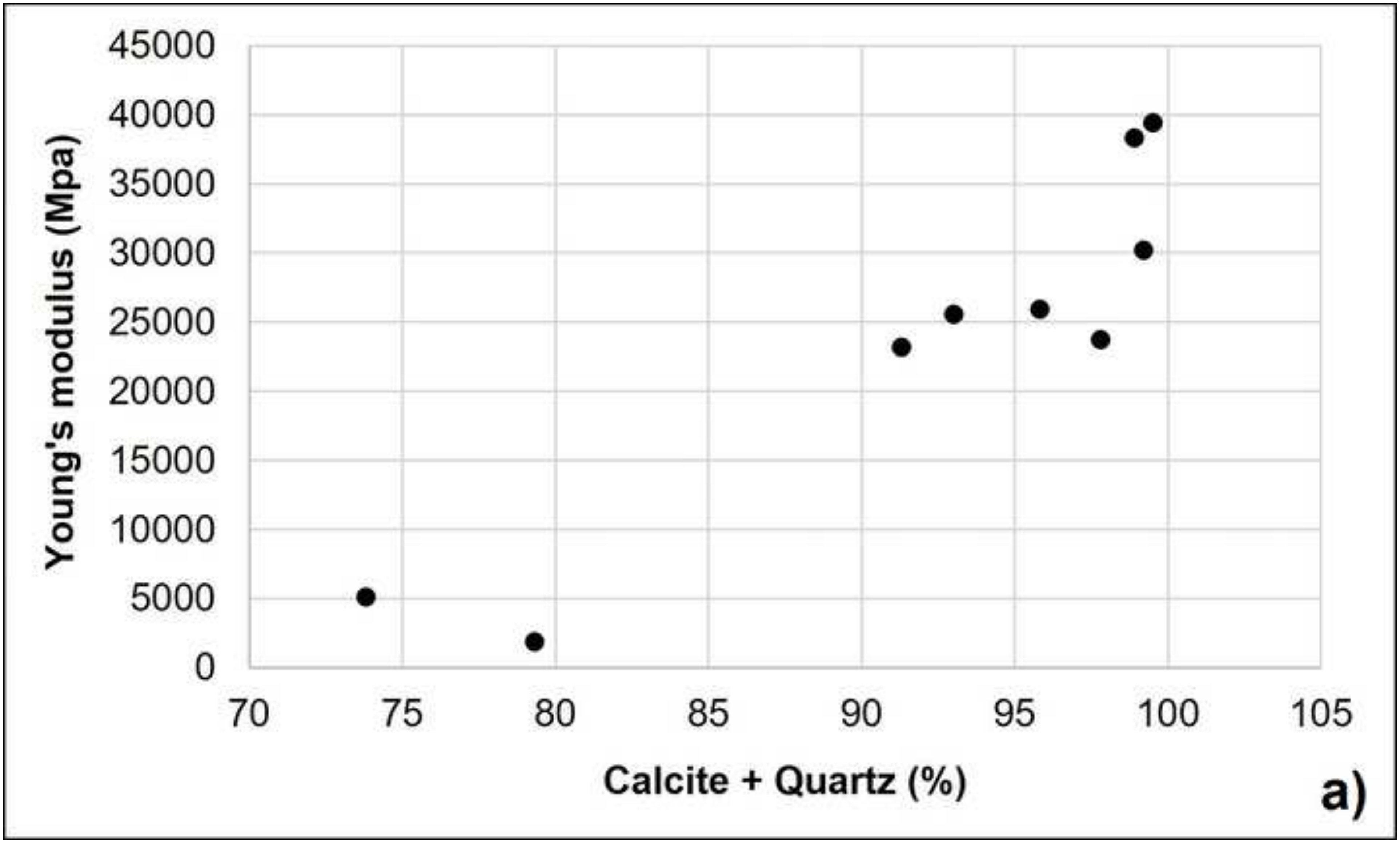
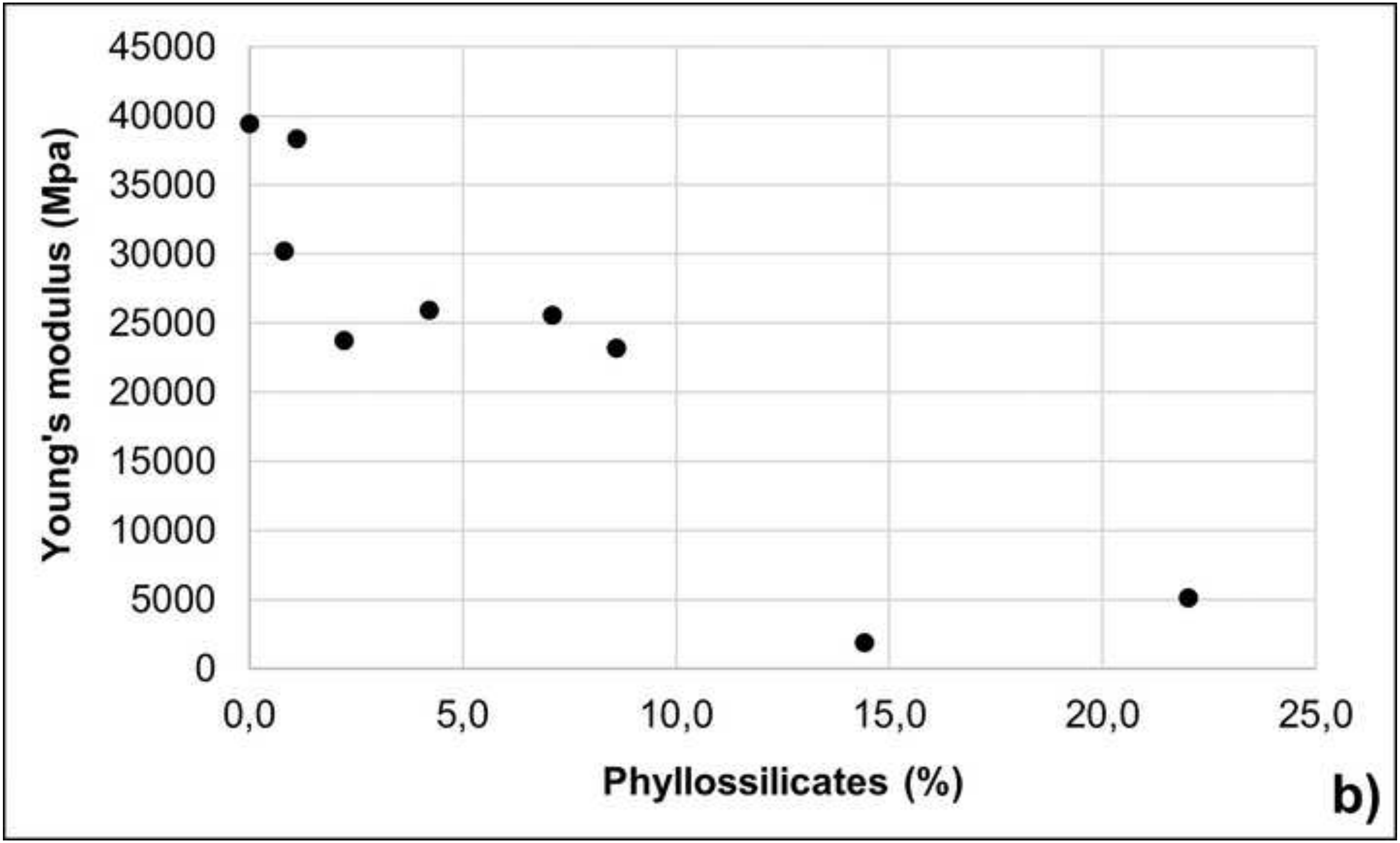


Fig.7(b)



Young's modulus (Mpa)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0,0
5,0
10,0
15,0
20,0
25,0
Phyllossilicates (%)
b)

Fig.8(a)

Click here to access/download;Figure;Fig. 8(a).tif

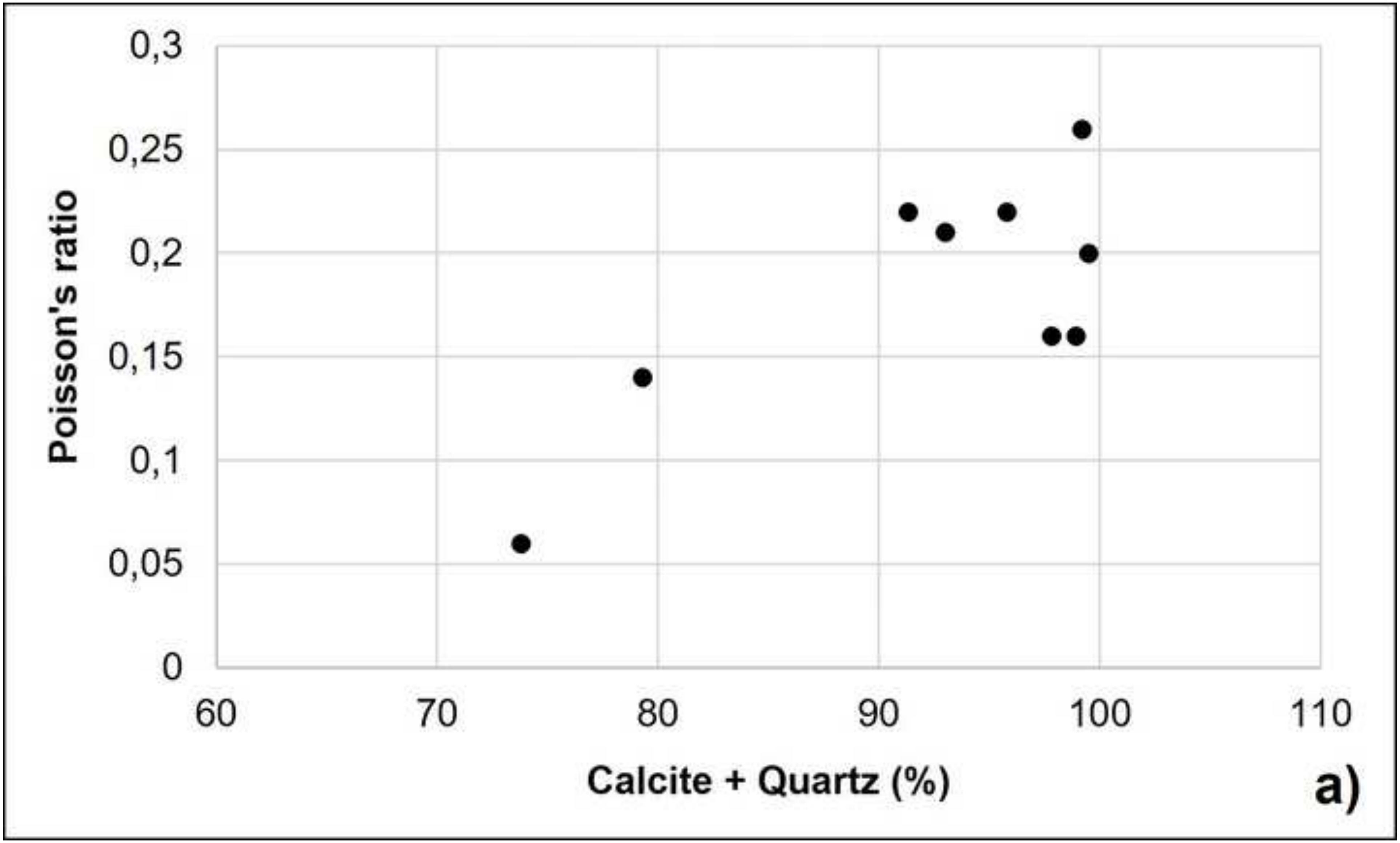


Fig.8(b)

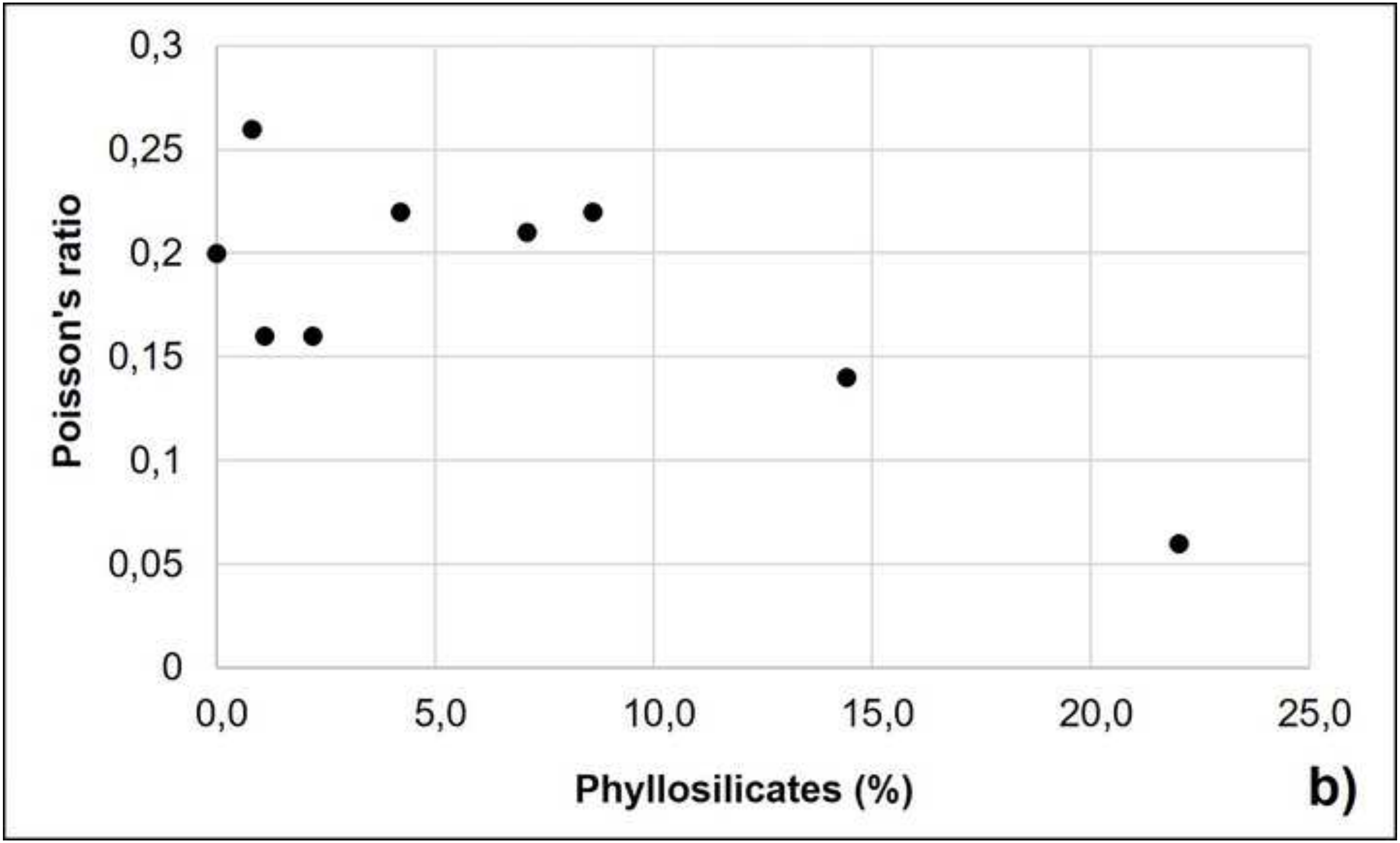

0,3
0,25
0,2
0,15
0,1
0,05
0
Poisson's ratio
0,0
5,0
10,0
15,0
20,0
25,0
Phyllosilicates (%)
b)

Fig.9(a)

Click here to access/download;Figure;Fig. 9(a).tif

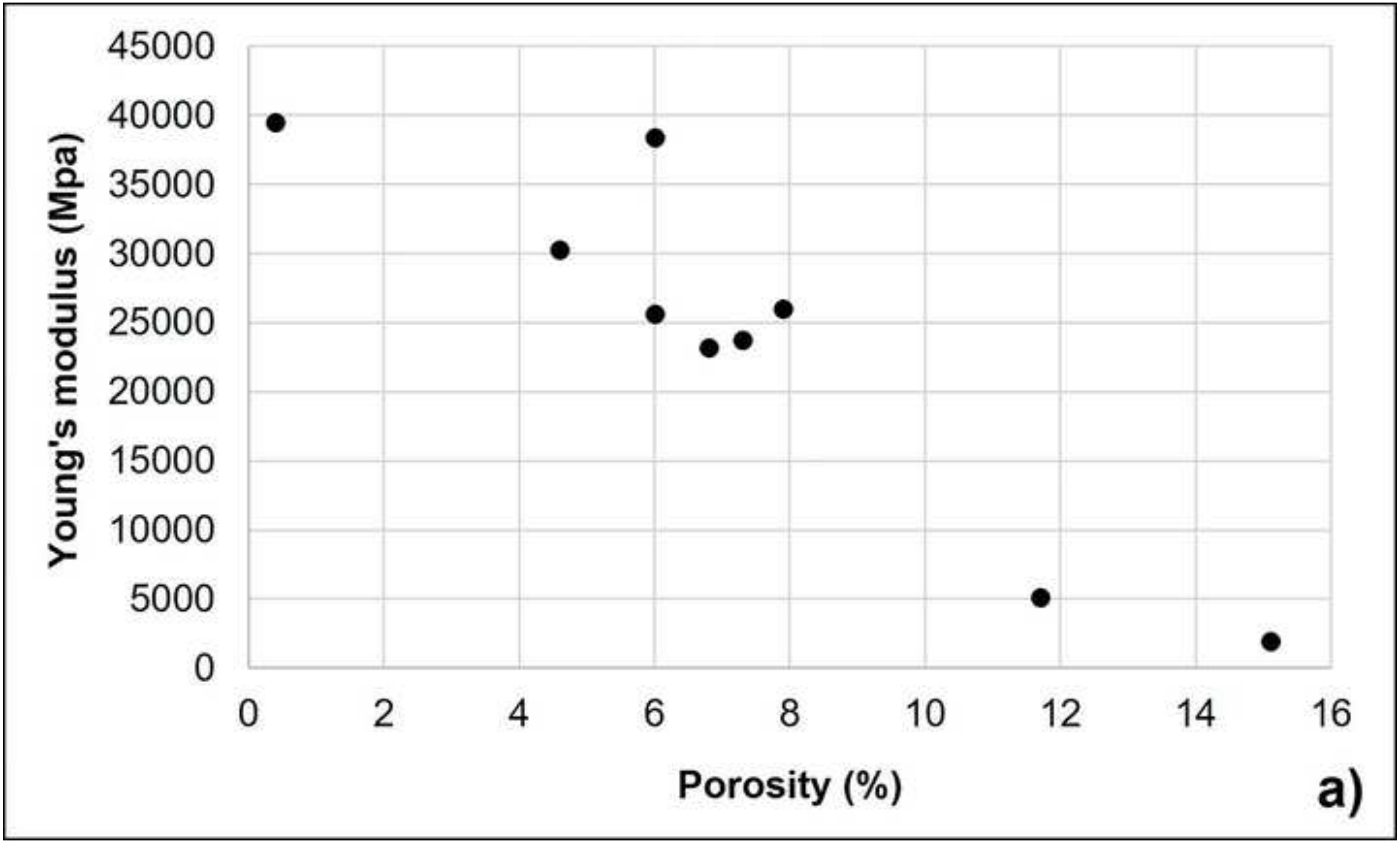
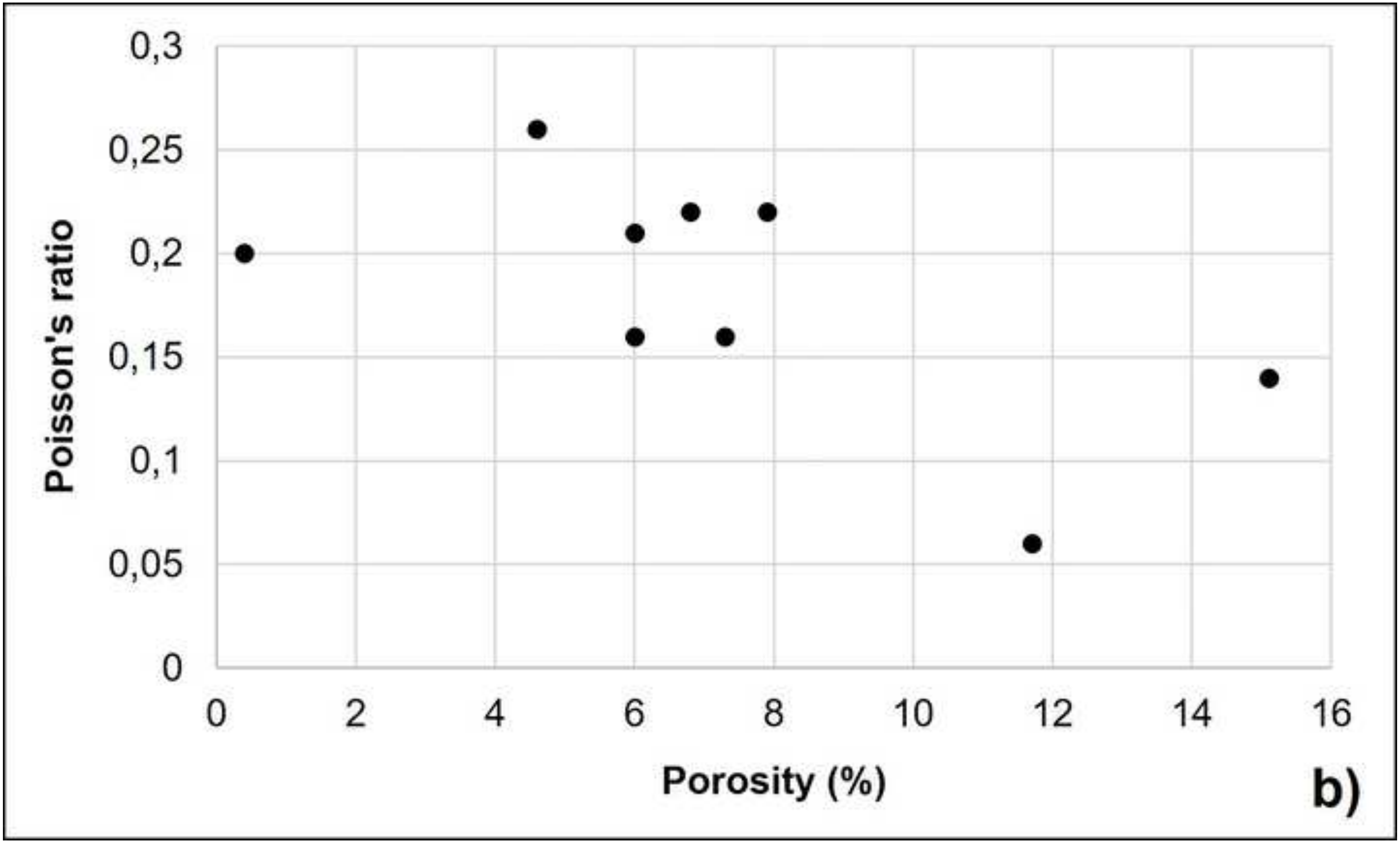


Fig.9(b)


0,3
0,25
0,2
0,15
0,1
0,05
0
Poisson's ratio
0
2
4
6
8
10
12
14
16
Porosity (%)
b)