Relationship between physical and mechanical properties of jointed rocks in Central Iran (Bafgh Block)

S. H. Beheshti[1], A. Yarahmadi Bafghi[1], A. Ghorbani[1]*, M. R. Rezvanianzadeh[2]

1- Dept. of Mining and Metallurgy Engineering, Yazd University, Yazd, Iran

2- Nuclear Science and Technology Research Institute, Atomic Energy Organization of Iran, Tehran, Iran

* Corresponding Author: *aghorbani@yazd.ac.ir*

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Abstract

Central Iran is one of the active mining zones of Iran and has great mining potential. Large iron mines such as Choghart, Chadormalu, Sechahoon, Chahgaz, Lake Siah, Mishdavan, etc. are located in this zone. Other metals also exist in this zone Like lead and zinc in Koushk, Chahmir, and Taj-Kooh mines. Also, non-metallic deposits such as Fahraj limestone mines and building stone mines such as Bishedar marble, Taft travertine, Shirkooh granite, etc. are being extracted in this zone. Considering mineral resources and current explorations, the mines continue to develop and one of the important topics in the exploration and exploitation phase is the study of geomechanical conditions in the zone under study.

The relationship between the physical and mechanical properties of rocks makes it possible to predict the strength of the intact rock which can be used in preliminary designing of the mine at less cost and less time and just with some simple tests on exploratory boreholes and surface samples. It can also be used in mines under extraction to gain more comprehensive knowledge of the mechanical properties of mine rocks. In this study, mechanical properties such as uniaxial compressive strength, point load, indirect tensile strength (Brazilian) as well as physical properties of rock such as density, porosity, compressive wave velocity (P-wave), and electrical resistivity were measured on selected samples taken from Choghart, Sechahoon, Lakeh Siah, Koushk, Bishehdar marble, Taft travertine, Ravar sandstone and the cores of 5 geotechnical boreholes from the Anomaly VI of Central Iran Iron Ore and 4 geotechnical boreholes of Chahgaz iron ore mine. The purpose of these measurements is to investigate the relationship between mechanical and physical properties of the samples, especially electrical resistivity. In the first step, 300 surface and depth samples were collected from the mines mentioned above. After preparing the cores, effective porosity and density were recorded according to the standards (weighing the saturated and dry sample method). Also, the electrical resistivity was calculated by measuring the voltage and electrical current in the samples. The results demonstrated that there is a high correlation between P-wave velocity and electrical resistivity in all the samples. Furthermore, both parameters of P-wave velocity and electrical resistivity are dependent on porosity, and electrical resistivity like P-wave velocity has a good relationship with the mechanical properties of sedimentary rocks and volcano-sediments. Hence, the special electrical resistivity can be used as a non-destructive test to estimate the mechanical properties of rocks. Additionally, the presence of metal ores in the samples in low percentages does not cause errors in estimating physical and mechanical parameters as long as density is less than 2.8 gr/cm3. For samples with high metal content, induced polarization measurements can reduce the uncertainty of the electrical resistivity.

1. INTRODUCTION

Estimating the mechanical properties of rocks is important in any engineering project. The most common mechanical parameters are uniaxial compressive strength (UCS) and tensile strength of rock (σt), and in cases where the dimensions of the sample do not allow uniaxial strength test, the point load index is checked. Numerous studies have been performed to establish experimental relationships between UCS, tensile strength, and point load index with ultrasonic pulse velocity (UPV), density, and porosity. (D'Andrea et al. 1965, Gaviglio 1989, Cargill and Shakoor 1990, Chau and Wong 1996, Brovtsyn and Chershneva 2000, Kahraman 2001a, 2001b, Sharma and Singh 2007, Kahraman and Yeken 2008, Sarno 2010, Kurtulus and Et al. 2010, Yağız 2011, Rajabzadeh et al. 2012, Sheraz et al. 2014, Kurtulus et al. 2016, Jamshidi et al. 2016, Jamshidi et al. 2018, Arshad Nejad 2018, Arshad Nejad 2020, etc.). However, limited studies have been performed on the relationship between electrical resistivity as one of the physical parameters of rock and the mechanical properties of rock. Most researchers have used P-wave velocity to estimate the mechanical properties owing to the dependence of ultrasonic pulse velocity (UPV) on the mechanical properties of the rock. Whereas, the electrical resistivity can estimate mechanical parameters too because it is dependent on the characteristics of the porous medium such as porosity, texture, amount of clay (alteration), and the number of metal ores. (Llera et al. 1990, Matsui et al. 2000, Roberts et al. 2000, Roberts et al. 2001a, Awang and Gye-Chun 2016, Kahraman and Yeken 2010, Iebrahim Sertçelik et al. 2018).

In this research, the relationship between the mechanical and physical properties (especially electrical resistivity) of sedimentary rock samples and volcano-sediments of Central Iran are investigated.

2. SAMPLING AND TESTING METHOD

In these experiments, the following samples were investigated: 32 igneous and metamorphic samples taken from Sehchahoon iron ore mine, 9 samples from Bishedar marble, 22 samples from metamorphic and igneous rocks of Choghart iron ore mine, 24 samples from sedimentary and igneous rocks (ore and including rock) of Lakeh Siah iron ore mine, 2 samples from Ravar sandstones selected from exploratory boreholes of 300 and 400 meters depth, 6 travertine samples from Taft building stone mines (Aliabad), one massive sulfide sample from Kushk mine, 57 metamorphic and igneous samples from cores of 4 geotechnical boreholes behind the walls of Chahgaz iron ore mine and 145 acidic tuff samples from cores of 5 geotechnical boreholes existing in Anomaly VI of central Iran iron ore (Figure 1).

All samples were taken from the mine walls and cores extracted in the laboratory with a diameter of 54±2 mm according to ASTM 1984, ASTM 2001, ISRM 2007 standards except for samples taken from Chahgaz, Ravar, and Anomaly VI (Figure 2).

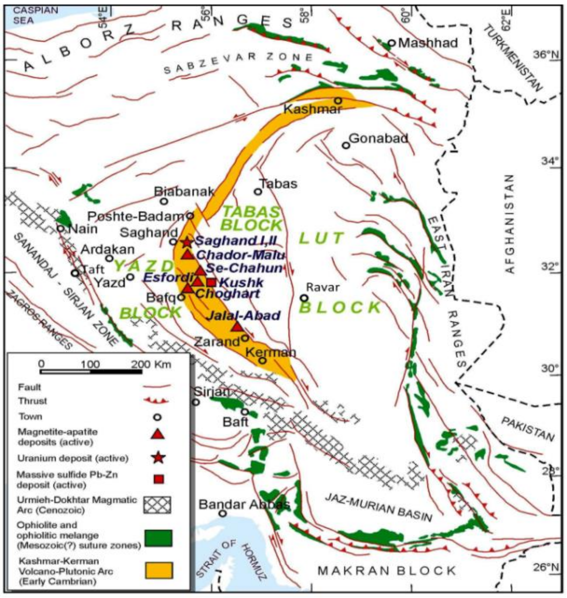

Figure 1. Central Iran and sampling zones (Torab and Lehmann 2007). These areas include the mines of Choghart, Koushk, Anomaly VI, Sehchahoon, Lake Siah, Chahgaz, and Bishehdar which are bounded between Ravar in the east and Taft in the west. These areas are located on the Kerman-Kashmar igneous rock arch.

After sampling and preparing the cores, the two ends of the sample were cut and parallelized with an accuracy of 0.25 degrees (15´). Then, the two ends of the sample were abraded with an accuracy of 0.02 mm by using silica powder. At the next stage, the dimensions of the samples were measured according to ISRM 2007 standard and were weighed after placing the samples in an oven at 105 ° C for 24 hours. Afterward, the P-wave velocity was measured using a UPV device with 55 kHz frequency transducers according to ISRM 1981 and ASTM 1978 standards (Figure 3a). After measuring the P-wave velocity in dry samples, they were placed in distilled water at 25° C temperature ambient air for at least 24 hours according to the ISRM 2007 standard. Effective porosity was calculated by measuring the difference between saturated and dry weight. P-wave velocity was also measured for the saturated samples. The electrical resistivity was measured after immersing the samples in a solution of water and salt with a conductivity of 1 Siemens per meter (S/m) for 14 days (Figure 3b). The medical conductive electro gels (AgCl) were used to connect the electrode and rock in a better way and a quick clamp with a constant force of 1000 N was used for the rock pressure to be constant.

Table 1. Lithology of samples and number of tests performed

Sampling location	Rock type	Lithology	No	ne	γ	Vp	ρ	CGS	UCS	σt	PLI
Anomaly VI	Volcano-sediment	Acidic Tuff	145	145	145	145	145	25	28	190	77
Choghart	Metamorphic	Metasomatitis	21	22	22	22	22	19	7	16	11
	Igneous	Magnetite ore	1								
Sehchahoon	Metamorphic	Metasomatitis	25	32	32	32	32	30	1	32	21
	Igneous	Magnetite ore	7								
Lekeh Siah	Sedimentary	Dolomite	12	24	24	24	24	24	8	18	30
	Igneous	Hematite ore	12								
Chahgaz	Metamorphic	Metasomatitis	53	57	57	57	53	38	21	-	-
	Igneous	Magnetite ore	4								
Bishehedar Marble	Sedimentary	Marble	9	9	9	9	9	9	1	9	7
Taft Travertine	Sedimentary	Travertine	6	6	6	6	6	6	-	4	4
Koushk	Volcano-sediment	Massive Sulfide	1	1	1	1	1	1	-	2	-
Ravar	Sedimentary	Sandstone	2	2	2	2	2	2	1	2	2

ne: Effective porosity, γ: Density, VP: P-wave Velocity, ρ: Electrical Resistivity, CGS: Magnetic Susceptibility, UCS: Uniaxial Compressive Strength,
σt: Indirect tensile strength (Brazilian Test), PLI: Point Load Index.

After measuring the physical properties, mechanical tests such as UCS according to ASTM 1984 standard with a loading intensity of 0.5 kN/s, indirect tensile test (Brazilian) with ASTM D3967, ISRM, and point load index were performed with ISRM standard.

Figure 2. Samples prepared for physical and mechanical studies

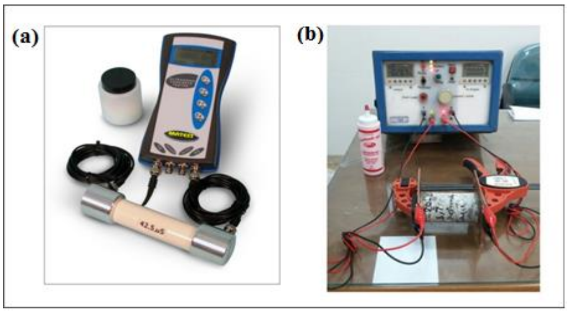

Figure 3. Equipment for measuring the P-wave (a) and electrical resistivity (b)

3. RESULTS

3.1. Statistical Analysis

Figure 4 shows the samples' range of physical properties including P-wave velocity, electrical resistivity, porosity, and density

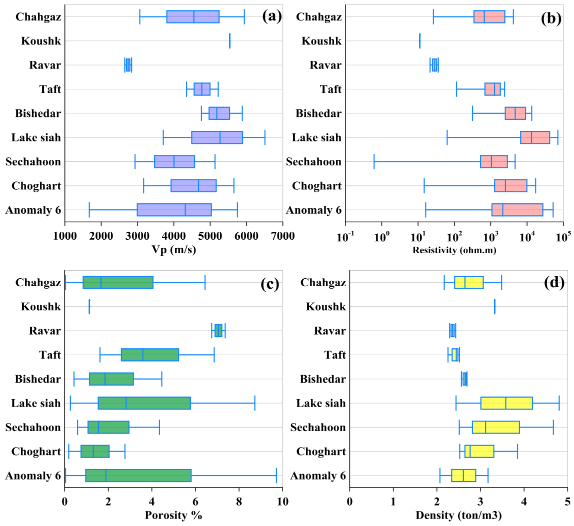

Figure 4. The range of physical properties of the samples studied

The average porosity of the samples is about 1.8% and the standard deviation is 1.7% with a lognormal distribution. The maximum and minimum porosity measured is 0.04% and 9.71% respectively (Figure 4. c). The average density of the samples is 2.71 ton/m3 with a standard deviation of 0.47 and a normal distribution. The lowest density is related to an altered tuff sample of Anomaly VI and the maximum density to a hematite sample from Lake Siah (Figure 4.d). Also, the average P-wave velocity in dry samples is about 4440 m/s, the lowest of which was for a porous tuff sample in Anomaly VI and the highest was for a hard dolomite sample recorded in the Lake Siah (Figure 4. a). In terms of electrical resistivity, the average was about 2900 ohmmeters. The highest electrical resistivity was for the same high-velocity sample measured in the Lakeh Siah mine and the lowest was for a sample of sulfide rock from Koushk which contained 65% of sulfide metal ores as well as a sample of magnetite iron ore from Sechahoon (Figure 4. b). It should be noted that before electrical resistivity measurements, samples were saturated with pore water with electrical conductivity of 1 S/m. The electrical resistivity, as expected, shows a lognormal distribution (Figure 5.a). The histogram shows the density of all samples which follows a bimodal distribution. An average value of 4.5 g/cm3 is related to samples containing metal minerals (Figure 5.d). P-wave velocity also follows a bimodal distribution (Figure 5.b). The statistical population with a smaller P-wave velocity is related to the fractured and altered samples of Anomaly VI and Sechahoon (Figure 5.b and Figure 6).

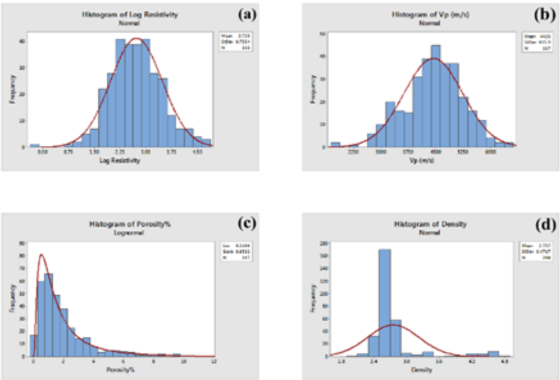

Figure 5. Statistical distribution of physical properties of the studied samples

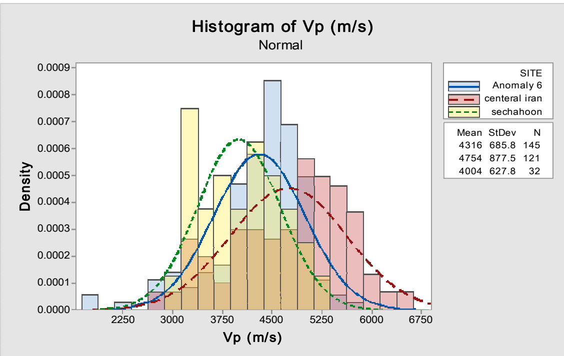

Figure 6. Statistical distribution of P-wave velocity of Anomaly VI, Sechahoon and other mines

3.2. Relationship Between P-Wave Velocity And Density

Figure 7.a shows the relationship between P-wave velocity and density. Comparing previous studies (sedimentary rocks) with this study shows that this relationship is not only established for sedimentary type, but also for volcano-sediment rocks provided that the density is less than 2.8 g/cm3. The important point is that the dispersion of these results is the same in the previous and the current study. Measurement of surface electrical conductivity, which represents clay alteration in the sample (not reported here), showed that for densities less than 2.8 g/cm3, the alteration decreases to a lower density with a linear function. This indicates that alteration has increased porosity and consequently decreased density (Figure 7.c). Another point is that many of the samples used in this study have metal minerals, especially hematite and magnetite (Figure 8). Figure 7.b shows the same relationship between P-wave velocity and density. In this figure, the magnetic susceptibility of the samples is shown with a color scale. It should be noted that magnetic susceptibility can be directly related to magnetite content of sample. According to Figure 7.b, the presence of metallic minerals in rocks will not change the P-wave - density relationship of the compression waves as long as the density of rocks remain at the level of the density of rocks without metal minerals (2.8 g/cm3). Salisbury et al. (1997) (Figure 7.d), investigated the relationship between P-wave velocity and density of sulfide ore samples at a lateral pressure of 200 MPa. For high-grade metal minerals such as iron ore or high-grade sulfides, they concluded that most minerals are denser than their host rocks. The P-wave velocity of ore is close to that of their host rocks (overlapping) (Malmir et al. 2012; Schetselaar and Bellefleur 2019). They also concluded that changes in P-wave velocity in different rocks from unconsolidated and sedimentary rocks to mafic igneous rocks (peridotite, eclogite) vary drastically (Figure 7.e). These studies showed that the acoustic impedance (product of density and P-wave velocity) of some ores such as pyrite, magnetite and hematite is much higher than conventional host rocks (Figure 7.f). Minerals of base metals such as sphalerite, chalcopyrite and galena have lower acoustic impedance than mafic-ultramafic rocks. Nevertheless, deposits of these minerals are commonly found in felsic rocks such as granitoids or sedimentary rocks, and again there is a sharp contrast in acoustic impedance. Accordingly, they predicted that seismic exploration of ore deposits containing a large part of these minerals would be possible. Here, diversity of lithology is less than the studies mentioned above, but their results are confirmed (Figure 7.e). However, as stated above, when the percentage of mineral in the ore is low, the P-wave velocity is similar to the P-wave velocity of the host rocks.

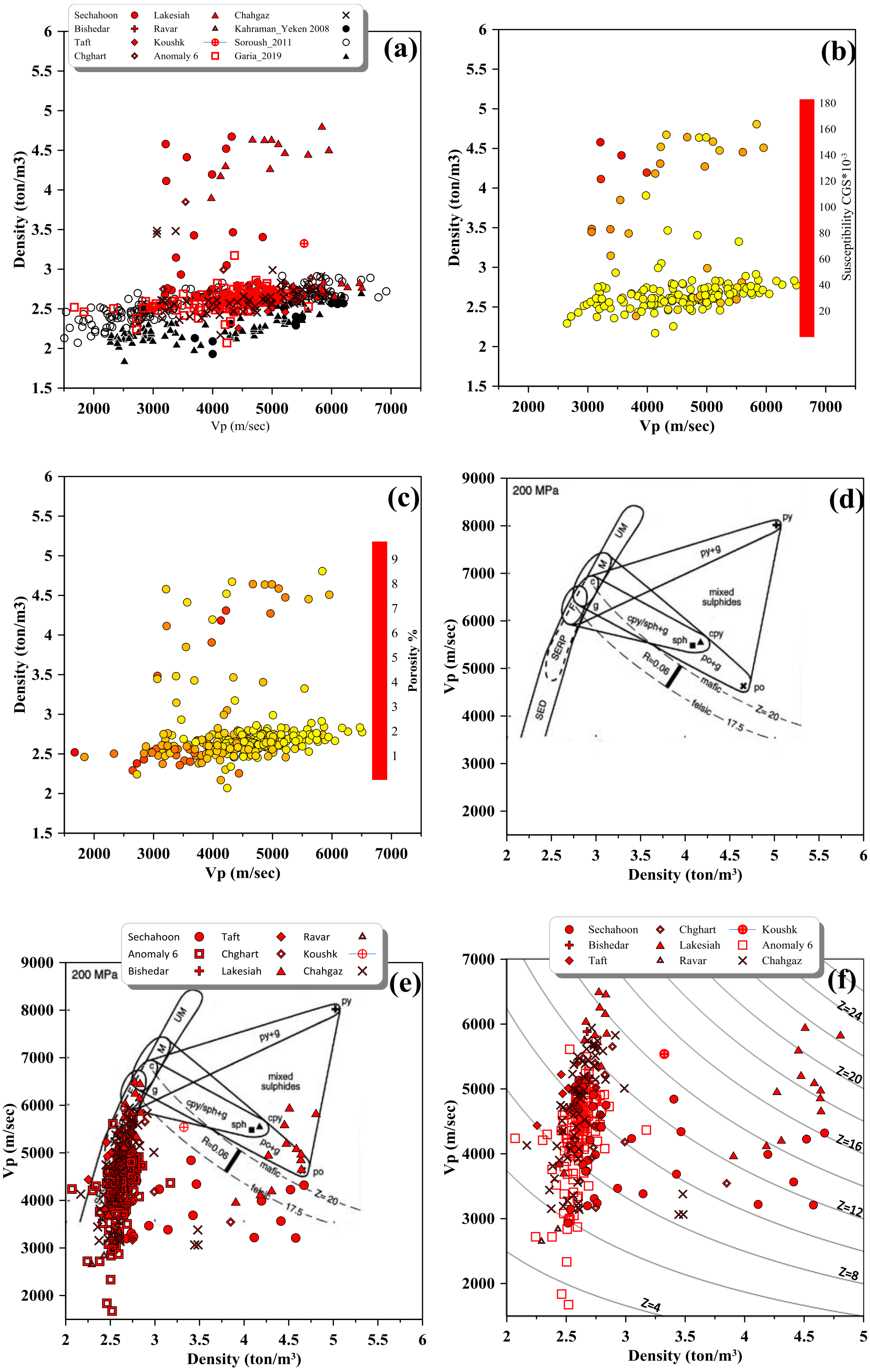

Figure 7. a: Relationship between P-wave velocity and density (○Soroush et al. 2011; ● Kahraman and Yeken 2008; and ▲ Results of Garia et al. 2019);b: relationship between p-wave velocity, density, and susceptibility; c: the relationship between p-wave velocity, density and porosity; d: P-wave velocities and densities of sulfide ores and silicate host rocks at a pressure of 200 MPa (Salisbury et al. 1997) (pyrite (py), chalcopyrite (cpy), sphalerite (sph) and pyrrhotite (po) Also includes silicate rocks along the Nafe-Drake curve including sedimentary rocks (SED), serpentinite (SERP), felsic (F), mafic (M), ultramafic (UM) and carbonate (C)); e: Adaptation of the relationship between P-wave velocity and density of these studies with the design presented by Salisbury et al. (1997); f: Relationship between P-wave velocity and density and acoustic impedance (Z sound impedance multiplied by 10^3 kg/m2.sec)

Figure 8. Samples containing magnetite and hematite minerals including samples of Ravar sandstone (Ra70, Ra91), samples of Lake Siah hematite mineral (61 to 69, 75, 87 and 88) and samples of Lake Siah dolomites (33,76, 77,92,93)

3.3. Relationship Between P-Wave Velocity And Porosity

Examination of the P-wave velocity - porosity relationship on volcano-sediments and sedimentary rocks shows that P-wave velocity decreases when porosity increases (Figure 9). This is the same as studies conducted on carbonate rocks by others such as Wilkens and Salisbury, 1996; Kahraman and Yeken, 2008. One of the reasons for the scattering of points in figure 9 is metal minerals. For example, Lake Siah samples have hematite and magnetite metal minerals, and Sechahoon samples have magnetite minerals with metamorphic texture. In this diagram, Lake Siah samples are the upper limit and Sechahoon samples are the lower limit of the P-wave velocity.

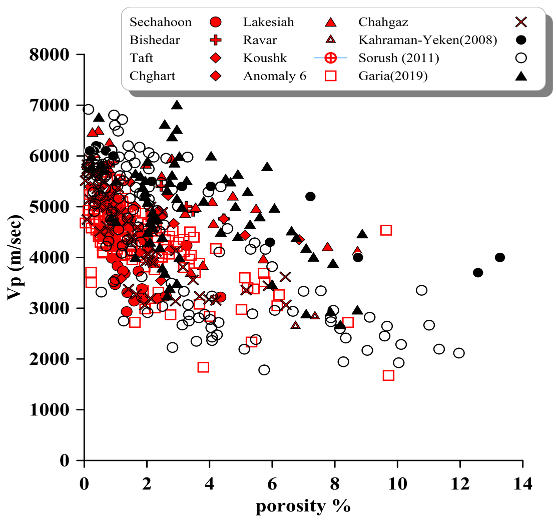

Figure 9. Relationship between P-wave velocity and porosity

3.4. Relationship Between Electrical Resistivity And Porosity

The physical properties of the samples demonstrated that there is an exponential relationship between electrical resistivity and porosity (Figure 10). Concerning iron ore mines, Lake Siah data constitute the highest exponential curve and the lowest limit is related to the exponential curve of Chahgaz data. Most curves have a parallel decreasing trend except for Choghart and Sechahoon data in which the decreasing trend is much sharper. The data of Taft travertine (sedimentary type) that is out of the range mentioned above, form the upper limit of these almost parallel curves and are consistent with other studies such as Matsui et al. 2017 who based their studies on a set of sedimentary, igneous and metamorphic rocks. It should be noted that the electrical conductivity of rocks is controlled by three parameters: pore water salinity (conductivity), conductive solid minerals such as clays that cover the surface of insulative minerals and electronic conductivity that is created by metal minerals (Telford et al., 2005). Porosity is just one of the parameters that show the effect of porous space connected and filled with electrolytes (Archie, 1941). These curves show the dependence of electrical resistivity on texture.

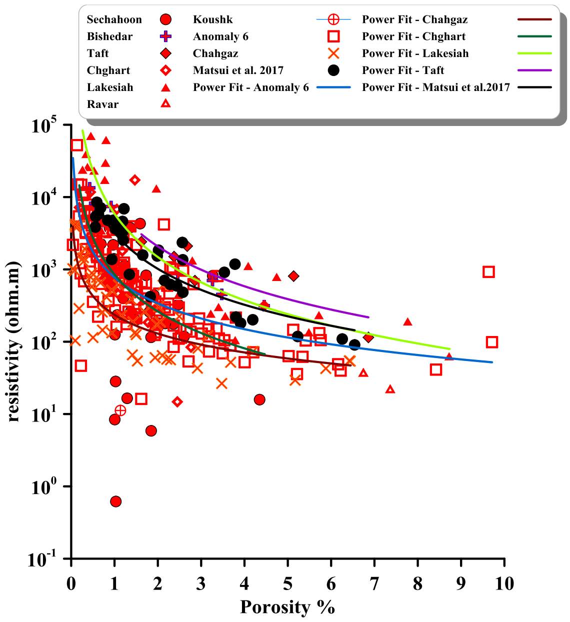

Figure 10. Relationship between electrical resistivity and porosity

3.5. Relationship Between Electrical Resistivity And Density

Density vs. electrical resistivity of samples shows that there is a significant relationship between these two parameters for data with a density of less than 2.8 g/cm3. The samples with higher density contain metal minerals and show no correlation with electrical resistivity (Figure 11). In this research, the density vs. electrical resistivity for samples with a density of less than 2.8 g/cm3 was compared with the research of Menier et al. 2020. It can be concluded that the samples used in this study did not have high alteration (Figure 11). Comparing P-wave velocity vs. density with electrical resistivity vs. density determined that in samples containing a large number of metal minerals, neither P-wave velocity nor electrical resistivity is estimated correctly.

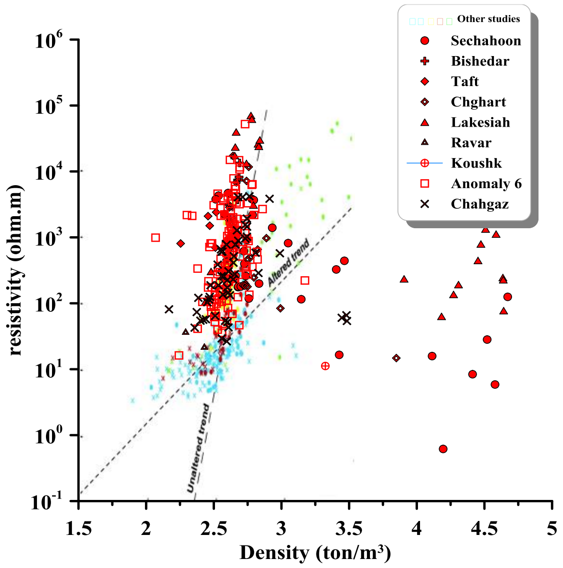

Figure 11. Relationship between density and electrical resistivity (compared with studies by Menier et al. 2020)

By increasing the metal content till density is more than 2.8 g/cm3, the possibility of connecting metal minerals (conductive minerals) and creating new paths for the passage of electrical current increases, and consequently the electrical resistivity decreases. This reduction in electrical resistivity may be misinterpreted with an alteration. Hence, the presence of metal minerals when density is more than 2.8 g/cm3 does not follow the usual trend in the passage of electrical current and passage of P-wave velocity thus leading to inappropriate interpretation. Measuring induced polarization which is sensitive to both conductive minerals and alteration can compensate for the limitations of the electrical resistivity method.[45],[46] The presence of sulfide minerals such as pyrite (for example in Koushk sample) increases the density and also decreases the electrical resistivity. This is because electrical current paths increase when there is more possibility of contact with sulfide conductive minerals.[39] Lake Siah samples contain prominent hematite minerals as well as magnetite minerals which has increased the density of the samples. Samples of Sechahoon also contain magnetite which is conductive and reduces the electrical resistivity of the sample. Lake Siah samples have higher electrical resistivity due to the presence of hematite minerals. Considering Figure 11, it seems that there is a direct relationship between the logarithm of electrical resistivity and the density of samples containing hematite and magnetite minerals in Lake Siah and Sechahoon. This relationship occurs in the density range of 4-5 g/cm3 (around the density of nearly pure hematite and magnetite) and its trend is close to the trend of samples containing low metal minerals with a density of less than 3 g/cm3.

3.6. Relationship Between Electrical Resistivity And P-Wave Velocity

The relationship between P-wave velocity and electrical resistivity indicates a correlation of 0.65 (Figure 12). This relationship shows a clear increase in electrical resistivity as P-wave velocity increases. Considering the discussion on the relationship between electrical resistivity vs. porosity and P-wave velocity vs. porosity as well as the correlation between porosity and both P-wave velocity and electrical resistivity, it seems that porosity is one of the important factors controlling these parameters (Figure 13).

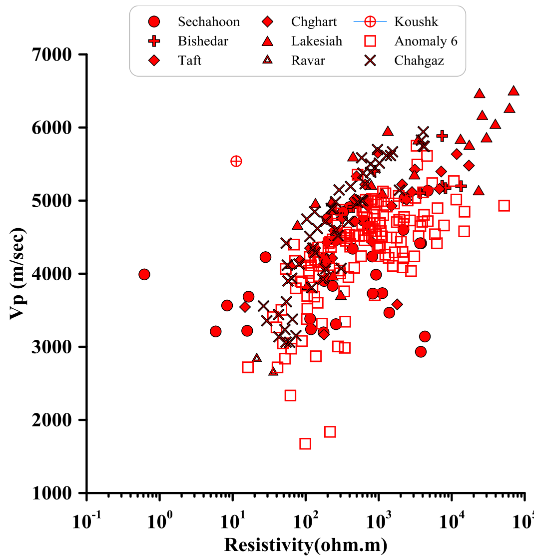

Figure 12. Relationship between P-wave velocity and electrical resistivity

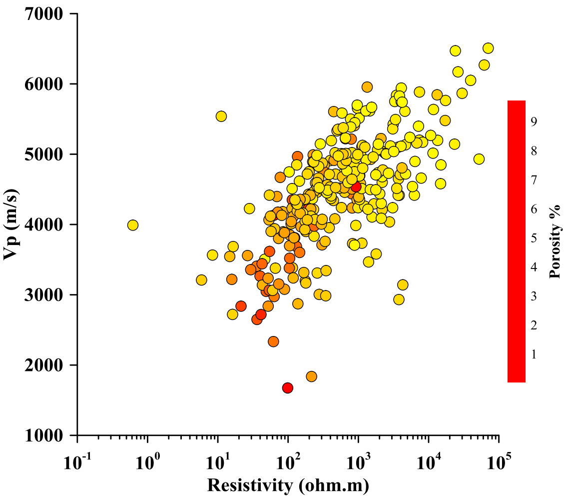

Figure 13. Relationship between P-wave velocity and electrical resistivity (porosity range indicated by color scale)

Table 2. Correlation (R2) between physical properties of Anomaly VI samples

	Vp	ρ	ne	γ
Vp	1	0.48	0.51	0.27
ρ	0.48	1	0.67	0.19
ne	0.51	0.67	1	0.29
γ	0.27	0.19	0.29	1

Table 3. Correlation (R2) between physical properties of Choghart samples

	Vp	ρ	ne	γ
Vp	1	0.52	0.54	0.07
ρ	0.52	1	0.70	0.62
nen	0.54	0.70	1	0.04
γ	0.07	0.62	0.04	1

Table 4. Correlation between physical properties of Sechahoon samples

	Vp	ρ	ne	γ
Vp	1	0.11	0.17	0.08
ρ	0.17	1	0.17	0.55
ne	0.17	0.17	1	0.08
γ	0.08	0.55	0.08	1

Table 5. Correlation (R2) between physical properties of Lake Siah samples (H: hematite, D: dolomite)

	Vp	ρ	ne	γ
Vp	1	0.70	0.60	H 0.60 D 0.77
ρ	0.70	1	0.81	H 0.54 D 0.65
ne	0.60	0.81	1	H 0.55 D 0.67
γ	H 0.6 D 0.77	H 0.54 D 0.65	H 0.55 D 0.67	1

Table 6. Correlation (R2) between physical properties of Chahgaz samples

	Vp	ρ	ne	γ
Vp	1	0.81	0.62	0.39
ρ	0.81	1	0.63	0.44
ne	0.62	0.63	1	0.37
γ	0.39	0.44	0.37	1

Table 7. Correlation (R2) between physical properties of Taft travertine and Bishedar marble samples

	Vp	ρ	ne	γ
Vp	1	0.50	0.58	0.44
ρ	0.50	1	0.88	0.32
ne	0.58	0.88	1	0.52
γ	0.44	0.32	0.52	1

According to the correlation coefficients of physical properties in each zone (Tables 2-7), there is a good correlation between P-wave velocity and electrical resistivity in all the zones except for Sechahoon which has both alteration and metal minerals. Also, both parameters of P-wave velocity and electrical resistivity are dependent on porosity. In all the samples, the relationship between density and other parameters has the least correlation.

3.6. Investigating The Relationship Between Mechanical Properties And Physical Properties

So far, a lot of research has been conducted on the use of P-wave velocity in estimating mechanical properties of rocks, and this parameter is known as a non-destructive test to estimate the mechanical properties. However, little research has been done to investigate the relationship between electrical resistivity and mechanical properties of rocks. According to the physical and mechanical experiments performed on 300 samples of this study (summarized in Table 8 and Figure 14), electrical resistivity like P-wave velocity is correlated with mechanical properties. Comparison of P-wave velocity and electrical resistivity with each of these mechanical properties indicates that electrical resistivity is also sensitive to mechanical properties; P-wave velocity is dependent on porosity (at least for densities less than 2.8 g/cm3); and correlation of electrical resistivity with porosity is higher than P-wave velocity. UCS (Figures 14a and 14b), Tensile strength (Figures 14c and 14d) and point load index (Figures 14e and 14f) increase when porosity decreases. On the other hand, when porosity decreases, P-wave velocity and electrical resistivity of the rocks increase. Considering the high correlation between electrical resistivity and porosity, electrical resistivity like P-wave velocity has the ability to estimate the mechanical properties of rocks. Table 8 shows the statistical relationships between P-wave velocity and electrical resistivity with UCS and tensile strength of samples in different zones. The coefficients of determination of UCS with physical properties are higher than coefficients of determination of indirect tensile strength (Brazilian test) and point load index with physical properties. This is due to the dispersion of the results obtained by the Brazilian method in estimating tensile strength and also the point load index in estimating UCS.

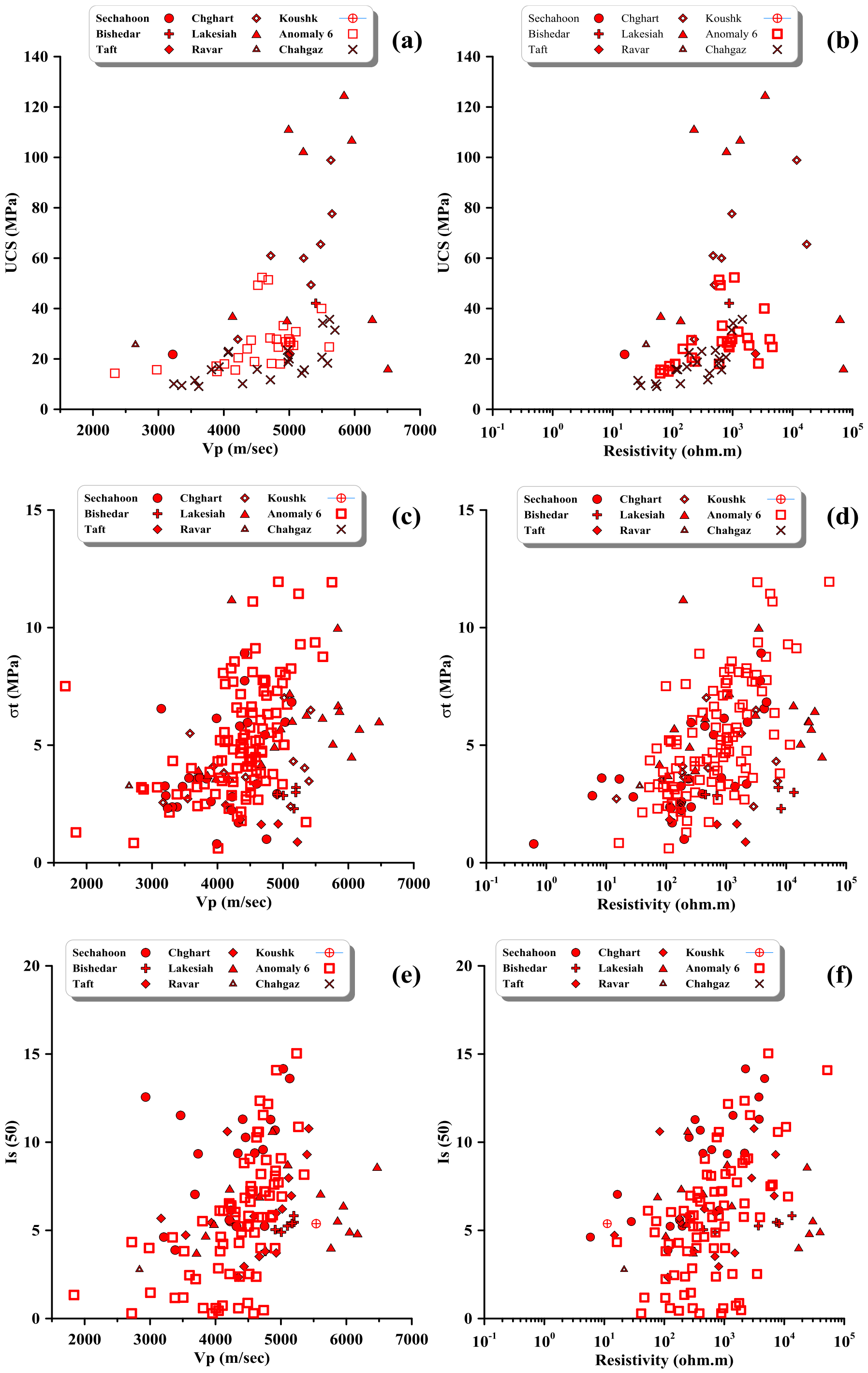

Figure 14. Relationship between mechanical properties and P-wave velocity and electrical resistivity, a and b) UCS, c and d) Tensile strength, e and f) point load index vs. P-wave velocity and electrical resistivity, respectively.

Table 8. Relationship between P-wave velocity and electrical resistivity with UCS and tensile strength in the studied areas

Sampling location	Test	Vp	R2	ρ	R2
Anomaly VI	UCS	Ucs = 0.0063 Vp - 5.065	0.52	Ucs =9.43 ρ0.14	0.53
	σt	σ t = 0.0026 Vp - 6.09	0.35	σ t =1.04 Ln ρ -1.48	0.41
Choghart	UCS	Ucs =2.16 e 0.0006Vp	0.73	Ucs =9.37Ln ρ -4.40	0.51
	σt	σ t = 0.0007 Vp +1	0.13	σt =0.8 Ln ρ +2.3	0.12
Lake Siah	UCS	Ucs = 0.027 Vp - 66.56	0.46	UCS =14.7 Ln ρ -32.6	0.82
	σt	σ t = 0.0009 Vp + 0.84	0.42	σt =0.23Ln ρ +3.63	0.23
Sechahoon	σt	σt = 0.0012 Vp - 1.17	0.11	σt =0.001 ρ +2.99	0.57
Chahgaz	UCS	Ucs = 3.30 e 0.0004Vp	0.50	Ucs = 11.89 e 0.0009 ρ	0.64
Bishehedar Marble and Taft Travertine	σt	σt = 0.0007 Vp - 1.41	0.07	σt =0.15Ln ρ +1.09	0.10

4. CONCLUSION

In this study, physical (density, porosity, P-wave velocity, and electrical resistivity of rocks saturated by water with conductivity of 1 S/m) and mechanical properties (UCS, indirect tensile strength, and point load index) of 300 samples taken from nine zones at Central Iran (Anomaly VI, Choghart, Sechahoon Koushk, Chahgaz, Lake Siah, Bishedar as well as two zones in Taft and Ravar in west and east of Central Iran respectively) were identified by performing more than 1800 tests and measurements. These samples are of volcanic, plutonic, metamorphic and sedimentary types.

It is noted that the samples contained different percentages of conductive metal minerals (such as magnetite) and non-conductive metal minerals (such as hematite). Measured magnetic susceptibility can indicate the presence of magnetic minerals, especially magnetite. The samples had different degrees of alteration and comparing results of this study with the results obtained from previous studies show that these samples are not highly altered. As in other studies, the effect of structure and texture (metallic minerals, alteration, microfractures) is also observed in the results of this study. It is suggested that a detailed investigation of the structure and texture of the samples; especially fracturing and alteration, be investigated in future studies.

The results demonstrated that samples with high content of metallic minerals (conductive or non-conductive) were not appropriately estimated by either P-wave velocity or electrical resistivity and may lead to misinterpretation of the data. It was proved that samples with a density of less than 2.8 g/cm3 can be used in estimating the physical and mechanical properties of the rocks.

According to the results, the linear relationship between the logarithm of electrical resistivity and P-wave velocity is affected by porosity. In other words, both parameters increase or decrease when porosity increases or decreases respectively. Given the negligible initial porosity of the samples, the increased porosity may be the result of fracturing and alteration.

The correlation of mechanical properties especially UCS with electrical resistivity on one hand, and control of both parameters of electrical resistivity and P-wave velocity by porosity on the other hand shows that electrical resistivity can also be used in estimating mechanical properties of rocks.

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