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The Importance of Welded Tuff Stones in Construction Industry According to Their Physico-Mechanical Properties

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Abstract

The welded tuff stones of volcanic origin are used as building stones in the construction sector as cladding stone for walls. It provides a beautiful and mystique view to the monuments. It has been widely used since the ancient times. Tuff stone cladding by mechanical anchorage is very common practice in recent years. In this study, physico-mechanical properties of welded tuff stones of Nevsehir and Isparta region are investigated according to European norms and Turkish standards. In addition, mineralogical characteristics of the rocks and chemical analysis of Isparta tuff stone are presented. The welded tuff stones having high porosity can be used for also heat and sound insulation in buildings by wall cladding using cement mortar adhesives or mechanical anchorage. Therefore, it has an important place in the building industry. The effect of water absorption on durability and strength, thaw and freeze resistance and abrasion values are examined. The results indicated that the welded tuff stones can be used for heat and sound insulation for buildings.

Key Words: *Welded tuff stones, Physico-mechanical properties, Heat insulation, Sound insulation, Mechanical anchorage, Water absorption, Thaw -freeze.*

Kaynaklanmış Tüflerin Fiziko-Mekanik Özeliklerine Göre Bina Yapımında Kullanımının Önemi

Özet

Volkanik kökenli kaynaklanmış tüfler yapı sektöründe duvar kaplaması ve yapı taşı olarak sıklıkla kullanılmakta ve yapılara estetik ve mistik bir görünüm kazandırmaktadır. Antik çağlardan beri yaygın olarak kullanılmıştır. Mekanik ankraj yöntemleriyle kaynaklanmış tüflerin dış cephe kaplaması olarak kullanımı son yıllarda yaygınlaşmıştır. Bu çalışmada Isparta ve Nevşehir bölgesi kaynaklanmış tüflerin fiziko-mekanik özellikleri Türk standartları ve Avrupa Birliği standartlarına göre belirlenmiştir. Bunun yanında kayaçların minerolojik özellikleri incelenmiş ve Isparta bölgesi tüf taşının kimyasal analizleri yapılmıştır. Yüksek gözenekliliğe sahip; çimento, yapıştırıcı veya mekanik ankraj yolu ile binaların dış cephelerine montajlanmış kaynaklanmış tüfler ısı ve ses yalıtımı sağlarlar. Bu nedenle yapı sektöründe çok önemli bir yere sahiptirler. Tüf Taşlarının su emme oranları basınç dayanımları, gözeneklilikleri, donma çözünme dayanımları ve aşınma dayanımlarının birbirleriyle ilişkileri incelenmiştir. Sonuç olarak kaynaklanmış tüf taşlarının ısı ve ses yalıtımı sağlayabilen yapı taşı olarak kullanılabilir olduğu belirlenmiştir.

Anahtar kelimeler: Kaynaklanmış Tüf Taşları, Fiziko Mekanik Özellikler, Isı Yalıtımı, Ses Yalıtımı, Mekanik Ankraj, Su Emme, Donma Çözünme

1. Introduction

Welded tuff is a building construction material used in the construction industry for many years. They are used mostly in the construction sector in building industry for wall cladding in outside exterior of buildings, at floor covering, and in masonry walls for decorative purposes due to having a wide range of colors. Decorative usage of welded tuffs carving especially outside walls of monuments is very common [1]. It gives a natural and mystique view to the monuments. Automated carving techniques increased the usage of tuffs in the sector by increasing the interest of architectures.

Nevsehir is the name of a city lies in Cappadocia region [2]. There are some very large caves carved out of welded tuffs. They are used to store wine, potatoes oranges and lemons and they have an ideal climate for food storage. These underground storage caves have internal natural temperatures of +10/+14 which does not change during summer and winter and high moisture content coming from welded tuffs. Welded tuffs have antibacterial property so the fruits and vegetables can be kept and preserved for a long time (without getting wrotten). History of the Anatolian natural stone operations goes back to ancient Greek, Roman and Ottoman Empire times. Also, many stone quarries opened during the recent Turkish Republic since the use of natural stones in building sector increased in recent years due to heat saving by insulation. One aspect of energy efficiency is the improved insulation of buildings by using stones of a low thermal conductivity [1]. In cold climates this results in reduced heating requirements, whilst in equatorial regions air conditioning energy consumption is decreased. Thermal conductivity of rocks changes with rock type since rocks have variable and different mineral constituents. Secondly the porosity, natural water content and density is also very important property, which affects the thermal conductivity [3]. Cladding walls of a mosque with tuffstone in Isparta city is shown in Fig.1

Figure 1. Cladding walls of a mosque with tuffstone in Isparta city

The durability of natural stones are determined from physico-mechanical tests and their usage area is established. Improving cutting technology of natural stones from blocks in factories is important for reducing the cost of processing. If the cost of producing the tuff stone is reduced, than according demand and supply law, the demand will increase, this will cause the expanding area of usage and availability in the market for tuff stones. Architects and engineers should know physico-mechanical properties of stones for a better design [4]. The parameters which effects rock strength are mainly porosity, grain size that constitutes texture and mineralogy. Regarding mineralogy quartz is the strongest mineral. Calcite is the second strongest mineral, where as ferrous minerals and clay bands make the rocks weaker. In Turkey ferrous red lines and clay filling of cracks can make beige limestone marbles weaker than marbles without fillings. It’s shown that the increase in quartz content makes the rocks stronger [3,5]. Also finer grained rocks are more stronger [3,6]. It is observed that finer size crystals make metamorphic crystalline marbles much stronger than large size crystals. There is an inverse proportion between porosity and strength. The higher the porosity content makes the rock weaker [3, 5, 7].

Welded tuffs are light colored and light weight sedimentary porous volcanic ash in various sizes deposited after volcanoes erupted. They deposited on top of each other depending on the time of eruption by climatic effects [1]. In the literature, they are named as volcanic tuff, tuff stone, welded tuff, sedimentary stone and they belong to natural stone category [8, 9].

The use of welded tuffs in the building sector has an economic advantage besides its visual richness [9]. The most important of these is its higher rate of heat and sound insulation in buildings when the building is covered by exterior wall cladding. Therefore tuff stone is a good heat insulator due to having a high degree of porosity. The amount of heat energy conserved by using tuff stone in external walls of buildings is determined by Ozkahraman and Bolatturk, [10].

Clauser and Huenges [11], illustrated thermal conductivity for volcanic and sedimentary rocks as shown in Fig. 2. At the top of the triangle quartz has the highest thermal conductivity. At the bottom thermal conductivity decreases from right to left, where at the right non quartz minerals like carbonate has higher thermal conductivity than at the left where tuff has the lowest thermal conductivity due to air and water filling the pores of the tuff. The position of a rock's name in the triangle indicates its thermal conductivity [11].

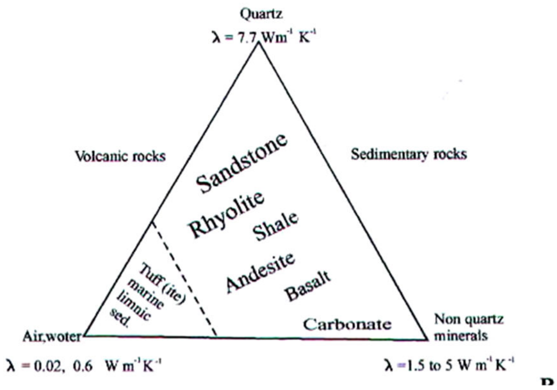

Figure 2. Thermal conductivity diagram of volcanic and sedimentary rocks [10].

2. Experiments for determining physico-mechanical properties

The physico-mechanical properties of Nevsehir and Isparta region welded tuffs are determined according to European norms (EN), Turkish standards (TS) and American standard testing methods (ASTM) as shown in Table 1, [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23].

Table 1. The standards used in the corresponding Physico-mechanical tests [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]

The Standard Number	Name of the test
TS EN 699, EN 12504-2	Schmidt hammer hardness value
TS EN 1936, ASTM D 5550 -06	Dry density
TS EN 1936	Specific gravity of solid part
TS EN 13755	Water absorption at atmospheric pressure (By weight and by volume)
DIN 52108, EN 14157	Resistance to abrasion (By Böhme method)
TS EN 1936	Total and apparent porosity
TS EN 1926, ASTM-C-170	Uniaxial compressive strength
TS EN 13161	Flexural strength under concentrated load
TS EN 14579	P-Wave velocity, (m/s)
TS EN 12371	Freezing and thawing strength and strength change after freezing and thawing cycles (Determination of frost resistance)
TS 850; ASTM E 1461-01	Determination of insulation properties and thermal conductivity; Standard Test Method for Thermal Diffusivity of Solids by the Flash Method
TS EN 12407	Petrographic examination

Eight different Nevsehir welded tuff samples and Isparta welded tuff are used in the tests that are collected from operated quarries in Nevşehir and Isparta region in Turkey. The appearance of a porous tuffstone in Isparta Region (light yellow) is shown in Fig. 3. and Nevsehir tuff stones named Nevsehir white, Desert Yellow, Erciyes Dark and Antique Brown, Nevsehir Red, Cappadocian rose, Asmali Grey and Nevsehir Goreme is shown in Fig. 4a, b. The tuff stones are cut into slabs as dimension stone in factories as shown in Fig. 5.

Figure 3. The appearance of a Tuffstone in Isparta Region (Light yellow)

Figure 4a. Nevsehir tuff stones named Nevsehir white, Desert Yellow, Erciyes Dark and Antique Brown (from top to bottom).

(a) **(b)**

(c) **(d)**

Figure 4b. Tuff stones named Nevsehir Red (a), Cappadocian rose (b), Asmali Grey (c), Nevsehir Goreme (d).

Figure 5. Produced slabs in stock at Boltas company

The physico-mechanical tests were Schmidt hammer hardness, uniaxial compressive strength, flexural strength, seismic velocity, water absorption, density, specific gravity of solid part, porosity, abrasion resistance and freezing and thawing strengths. Also freezing and thawing strength reduction after freezing is given to show the stones ability for freezing cycles. The results of physico-mechanical tests are shown in Table 2a. and 2b. In addition mineralogical and petrographical chemical properties are determined by inspections on polarized microscope. The chemical analysis of Isparta tuff stone is given in Table 3. The discussion of the results is given in Section 3 and conclusions are given in Section 4.

Table 2a. Physico-Mechanical Properties of Antique Brown, Nevsehir Red, Asmali Gray, Erciyes Black

Parameters	Units	Antique Brown	Nevsehir Red	Asmali Gray	Erciyes Black
Hardness	(Mohs)	3	3	3	2-3
Schmidt hammer rebound value	-	23	24	31	19
Dry density (unit volume weight),	(gr/cm^3)	1.715	1.730	1.711	1.200
Specific gravity of solid part	(gr/cm^3)	2.549	2.590	2.545	2.453
Water absorption at atmospheric pressure (By weight)	(%)	13.26	16.50	14.27	31.30
(By volume)	(%)	22.74	28.55	24.40	37.56
Total porosity	(%)	32.7	33.2	32.8	51.1
Uniaxial compressive strength	(kg/cm^2)	440	380-470	340-400	65-110
Flexural strength	(kg/cm^2)	110	110	70	50
P-Wave velocity	(m/s)	3000	2700	1950	2250
P- wave velocity decrease after freezing	(%)	3.6	3.5	4.2	4.1
Weight reduction after freezing and thawing cycles	(%)	0.24	0.21	0.19	0.55
Strength reduction after freezing	(%)	4	4.1	4.05	3.95
Abrasion resistance (By Böhme method)	($cm^3/50cm^2$)	18.0	27.0	36.3	89.3
Coefficient of thermal conductivity, k (λ)	(W/m.K)±	0.5	0.47	0.51	0.3

Table 2b. Physico-Mechanical Properties of Nevsehir White, Cappadocian Rose, Desert Yellow, Nevsehir Goreme, Isparta Tuff Stone

Parameters	**Units**	**Nev. White**	**Cappadocian Rose**	**Desert Yellow**	**Nev. Goreme**	**Isparta Tuff Stone**
Hardness	(Mohs)	2-3	2	2	3	2
Schmidt hammer rebound value	-	5	12	13	12	18
Dry density (unit volume weight),	(gr/cm^3)	1.371	1.516	1.087	1.420	1.400
Specific gravity of solid part	(gr/cm^3)	2.560	2.674	2.500	2.58	2.38
Water absorption at atmospheric pressure (weight)	(%)	20.00	15.21	39.34	17.51	20
(volume)	(%)	27.42	23.10	42.77	24.14	28
Total porosity	(%)	46.5	43.3	56.5	45	40
Uniaxial compressive strength	(kg/cm^2)	50-60	90-95	25-30	102	60-120
Flexural Bending strength	(kg/cm^2)	40	60	75	72	55
P-Wave velocity	(m/s)	2100	2200	1800	2400	2300
P- wave velocity decrease after freezing	(%)	6.0	3.9	6.1	4.2	5
Weight reduction after freezing and thawing cycles	(%)	0.77	0.53	0.64	4.09	1.5
Strength reduction after freezing	(%)	5.0	5.40	5.2	0.5	23
Abrasion resistance (by Böhme method)	($cm^3/50cm^2$)	49.8	32.3	92.0	38	15.5
Coefficient of thermal conductivity, k (λ)	(W/m.K)±	0.39	0.35	0.25	0.37	0.2 – 0.4

Table 3. Chemical Properties of Isparta Tuff Stone

Elements	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	LOI
Values, %	4.41	58.31	16.01	2.95	1.13	1.67	5.2	7.65

3. The relations between physico–mechanical properties

The presence of pores in the texture of a rock causes deformability which eventually reduces its strength [3]. This happens even in a small increase in volume of pores. The total porosity is an essential parameter for strength which is a resistance to deformation and eventual collapse under applied loads must be given consideration in petrological descriptions [3].

Porosity reduces density. Therefore apparent and grain density values are important parameters that should be given under physical properties of rocks together with porosity values. A high-density rock is usually less porous [3]. The experimental error should be reduced when cutting samples into cubes by increasing rock lumps and samples taken as a representative from the rock mass [3].

Determination of apparent density and porosity is given under I.S.R.M. Committee or Laboratory Tests, suggested Methods [23]. Grain density is known as specific gravity of solid part of the sample. Archimedes principle is used to determine bulk volume using, from the difference between saturated –surface dry and saturated –submerged sample weights. The dry weight of the sample is obtained by oven drying at a temperature of 105 °C.

The total pore volume made up from closed pores as well as open pores. Porosity calculated by pycnometer test by pulverizing rock. Its important that air bubbles should be extracted from the sample by stirring. The effective or apparent porosity is the term given to open and interconnected pore volume close to surface of the sample. During the water absorption test water is filled to these open pores in emercing the samples of rock in water.

3.1. The change in porosity with hardness and strength

The Schmidt hardness, compressive strength and P-wave velocity of welded tuffs are measured and given in Table 2a, b.

Schmidt hardness index versus porosity is shown in Fig.6. The correlation coefficient of the relationships is r = 0.84, indicating a strong relationship. In figures correlation coefficients (r) are calculated from R^2. The correlation coefficient, given by r, shows the strength of a correlation between two variables. The correlation coefficient has a maximum value of +1.

Compressive strength versus porosity is shown in Fig. 7. The correlation coefficient of the relationships is r = 0.97, indicating a very strong relationship.

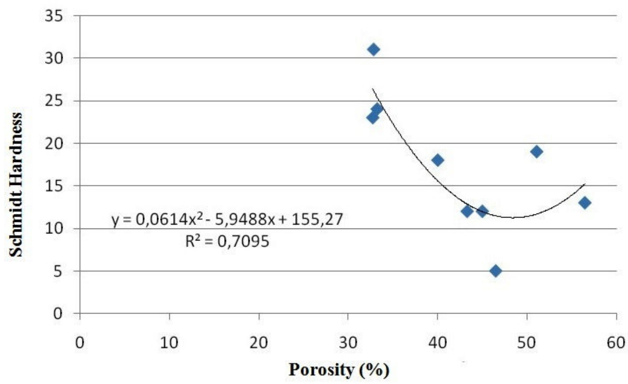

Figure 6. Schmidt hardness index versus porosity (%)

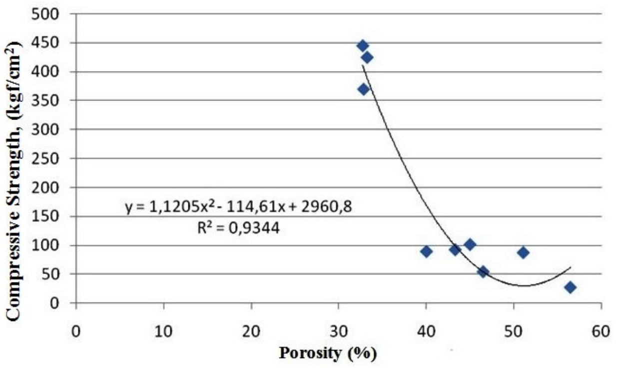

Figure 7. Compressive strength (kg/cm2) versus porosity (%)

Compressive strength versus porosity is shown in Fig. 7. The correlation coefficient of the relationships is r = 0.97, indicating a very strong relationship.

3.2. The change in porosity with P- Wave velocity

The p-wave velocity versus porosity is shown in Fig. 8. The correlation coefficient of the relationships is r = 0.61, indicating a moderate relationship. There exist an inverse relationship between porosity and P-wave velocity. Therefore as porosity increases P-wave velocity decreases. P-wave velocity values are low in porous rocks that mean it travels more slowly in porous rocks. So, sound isolation property of porous rocks is more than compact rocks. The determined porosity value of Desert yellow is 56.5 % against P-wave velocity of 1800 m/s. Similarly the porosity of Antique brown is 32.7 %, against P-wave velocity of 3000 m/s. Therefore as porosity increases P-wave velocity decreases. P-wave velocity values are low in porous rocks that mean it travels more slowly in porous rocks.

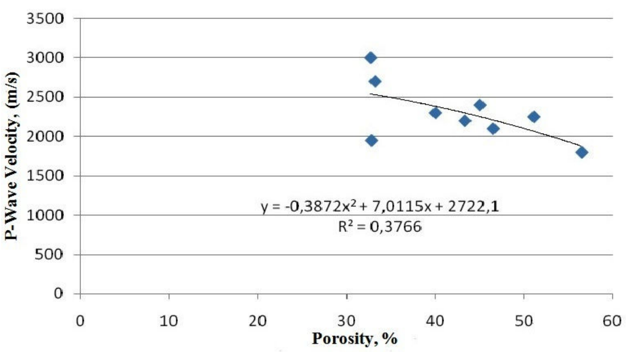

Figure 8. P-Wave velocity versus porosity

3.3. The change of thermal conductivity with porosity, P-Wave velocity, compressive strength and density

3.3.1. The change of thermal conductivity with porosity

Thermal conductivity change with porosity is studied for welded tuff samples that are collected from operated quarries in Nevşehir and Isparta region is given in Fig. 9. It is plotted from the values given in Table 2a, b. The porosity of Desert Yellow is 56.5 % against thermal conductivity value of 0.25 (W/m.K). The porosity of Antique Brown is 32.7 % against thermal conductivity value of 0.5 (W/m.K.). It is found that thermal conductivity reduces with increasing porosity. Therefore there is a indirect relationship between thermal conductivity value and percentage of porosity. This means that heat insulation increases with the increase in porosity. The relationship has a correlation coefficient of r =0.89

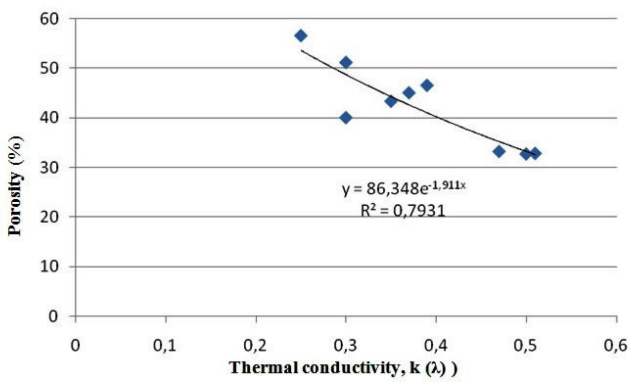

Figure 9. Porosity (%)versus Thermal conductivity, k(λ)

3.3.2. The change of thermal conductivity with P-Wave velocity

Thermal conductivity versus P-wave velocity relation is shown in Fig. 10. The correlation coefficient of the relationships is r = 0.56, indicating a moderate relationship. It is found that thermal conductivity increases with increasing P-wave velocity values. Therefore there is a direct relationship between thermal conductivity value and P-wave velocity values.

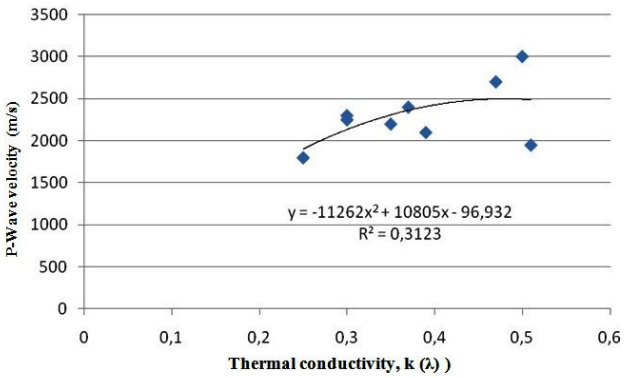

Figure 10. P-Wave velocity (m/s) versus Thermal conductivity, k(λ)

3.3.3. The change of thermal conductivity with compressive strength

Thermal conductivity versus compressive strength relation is shown in Fig. 11. The correlation coefficient of the relationships is r = 0.94, indicating a very strong relationship.

Thermal conductivity increases with increasing compressive strength since compressive strength of well compacted and low porosity rocks are higher. Therefore there is a direct relationship between thermal conductivity values and corresponding compressive strength values of the same rocks

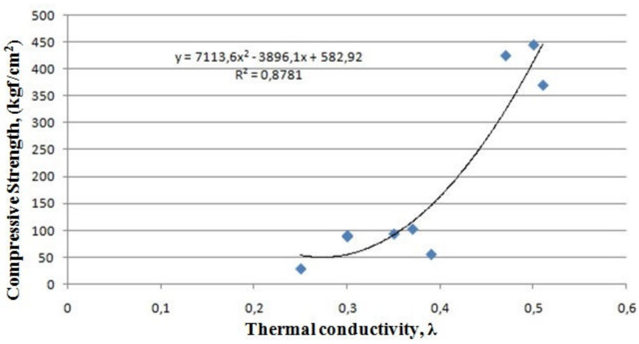

Figure 11. Compressive strength (kg/cm2) versus thermal conductivity, k(λ)

3.3.4. The change of thermal conductivity with density

Thermal conductivity versus density relation is shown in Fig. 12. The correlation coefficient of the relationships is r = 0.93, indicating a very strong relationship. There is a direct relationship between thermal conductivity and density since well compacted rocks have higher densities.

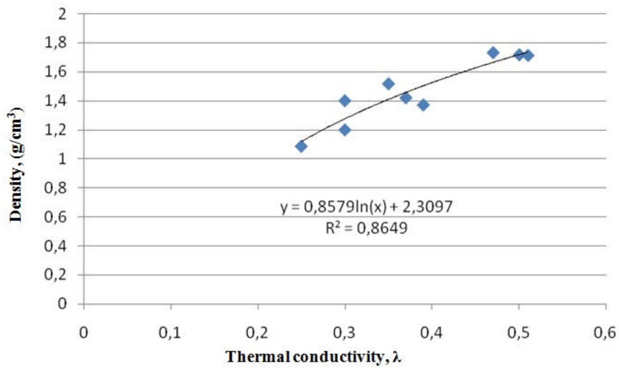

Figure 12. Density (g/cm3) versus thermal conductivity, k(λ)

3.4. The variation of water absorbsion with porosity

Water absorbsion by weight (%) versus porosity (%) relation is shown in Fig. 13. The correlation coefficient of the relationships is r = 0.96, indicating a very strong relationship.

Percentage of water absorbsion increases with increasing porosity indicating a direct relationship. The higher porosity means a higher water absorption.

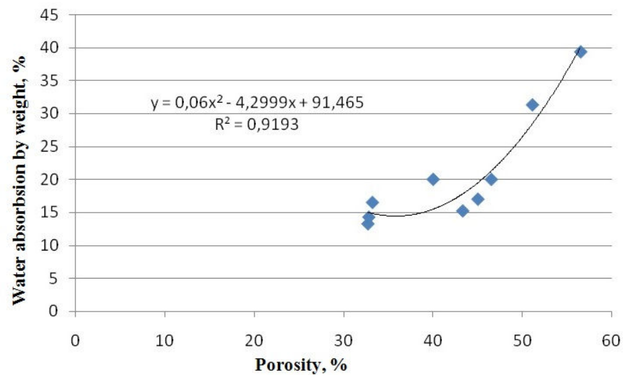

Figure 13. Water absorbsion by weight (%) versus porosity (%)

3.5. The variation of P-wave velocity decrease due to freezing with porosity

P-wave velocity decrease after freezing (%) versus porosity (%) relation is shown in Fig. 14. The correlation coefficient of the relationships is r = 0.72, indicating a moderately strong relationship. This is due to crack formation inside tuff stones with freezing and thawing cycles. The freezing pore water increases pressure on the walls of pores causing fracture. The inside cracks and fractures reduces P-wave velocity.

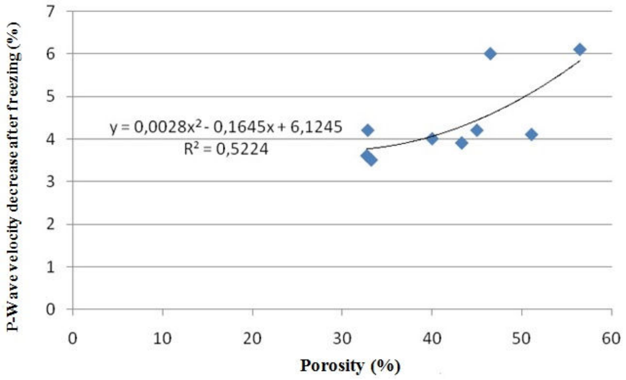

Figure 14. P-wave velocity decrease after freezing (%) versus porosity (%)

3.6. Mineralogical and Petrographical properties

The welded tuffs are light colored and light weight sedimentary porous volcanic ash in various sizes deposited after volcanoes erupted. They deposited on top of each other depending on the time of eruption, [1]. The porous structure is found to be due to phenocrystals by mineralogical and petrographical properties. The feldspars are decomposed by weathering action from phenocrystals and transformed to clay minerals by forming kaoline (china clay). The matrix which surrounds this phenocrystals has a unstable crystal structure. The porosity in this stones is produced by environmental effects according to mineralogical structure of the tuffs not from sudden cooling in magmatic stones or due to metamorphism. The zeolite mineral is 15 % by content [8]. There is high volume of pores present in zeolits and it make up 50 % of their total volume [23].

4. Conclusion

In this study, the relation between P wave velocity, thermal conductivity values and porosity is studied for welded tuff samples taken from different stone quarries at Nevsehir and Isparta region. The main results obtained from this research are;
Valuable information on usage of tuff stones as building stone in the construction sector is given. Welded tuff stones are a good heat insulator due to having a high degree of porosity compared to other natural stones (marble, granite etc.) as given in the Unver B, Agan C, 2009 [9]. Energy saving by heat insulation saves a lot of money and very important for countries which have limited energy resources [9]. For this reason building insulation must be applied to buildings. Distribution of energy consumption in various sectors in % is given in Table 4. [10, 25, 26, 27].

Table 4. Distribution of energy consumption in various sectors

Industry	Building sector	Transportation	Agriculture	Others
37	32	23	5	3

Energy conservation (saving) in buildings became important after 1973 when the energy crises begin. Heat insulation, also reduces air pollution products such as CO_2, CO, SO_2 and the dust particles [9].

The laboratory determined P-wave velocity of the rock samples which is a function of total porosity affects the thermal conductivity. So thermal conductivity values of natural stones found to be directly proportional to their P-wave velocities and there exists a good correlated relationship between them. So by measuring sonic velocity of a rock one can guess its thermal conductivity with a close approximation since sonic velocity can readily be determined. Also similar relationship exists between porosity and thermal conductivity since porosity is indirectly proportional to sonic velocity.

The physico-mechanical properties of 1. Antique Brown, 2. Asmali Gray, 3. Cappadocian Rose, 4. Nevsehir Red, 5. Nevsehir Goreme, 6. Nevsehir White, 7. Isparta Tuff Stone, 8. Erciyes Black and 9. Desert Yellow are shown in Table 2a and 2b. The tuffstones are listed from 1 to 9 according to their water absorption values. One being the least water absorption value (Antique Brown) to 9 which is the most water absorption value (Desert yellow). Similarly low numbers have higher uniaxial and flexural strength. Therefore they are more stronger and more durable and have longer life under weathering. The strongest being Antique Brown and the weakest is Desert Yellow.

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