Natural Volcanic Tuff for Sustainable Concrete Industry

Kamel K. Al-Zboon[1)*] and Jehad Zou'by [2)]

[1),2)] Environmental Department, Al-Huson University College, Al-Balqa Applied University, Irbid, Jordan.
* Corresponding Author. P.O. Box 50, Al-Huson-Irbid (21510) Jordan.
E-Mail: alzboon@bau.edu.jo; kalzboon@yahoo.com

ABSTRACT

In this study, Jordanian volcanic tuff aggregates were used as a source of construction materials in concrete mixtures. Five concrete mixtures were prepared by replacing normal aggregate with volcanic tuff aggregate of similar size in ratios of 0, 25, 50, 75 and 100%. The impacts of this replacement on concrete density, slump, bleeding, compressive strength, flexural strength, modulus of rupture, modulus of elasticity and stress-strain behavior were investigated. The results revealed an improvement in compressive strength and flexural strength at a replacement ratio of 25%, with concomitant reduction at higher replacement ratios. Modulus of elasticity, workability and unit weight decreased for all mixtures containing volcanic tuff. The impact of replacement on compressive strength was much higher than on flexural strength. Based on these results, it can be asserted that the addition of Jordanian volcanic tuff at a ratio of 25% will improve some characteristics with adverse impacts on the modulus of elasticity and workability.

KEYWORDS: Concrete, Compression strength, Flexural strength, Modulus of rupture, Modulus of elasticity, Volcanic tuff.

INTRODUCTION

High consumption of raw materials by the construction sector has resulted in chronic shortage of building materials, which triggered the search for new uncommon sources of these materials. Volcanic tuff is considered an attractive option for this purpose. The unique structure of zeolitic tuff gives rise to remarkable physical and chemical properties, allowing it to play a vital role in many engineering applications.

Tuff is a term used to describe a relatively soft, porous rock that is usually formed by the compaction and cementation of volcanic ash or dust. Volcanic tuff is characterized by its highly porous structure, high surface area and low density. It is found in different forms, sizes and colors and can reduce concrete dead weight. It is an inexpensive raw material, the utilization of which in concrete production leads to a considerable cost saving per unit of concrete (Turkmenoglu and Tankut, 2002). It was reported that substitution of aggregate with zeolite could improve the strength of concrete *via* pozzolanic reaction with $Ca(OH)_2$ (Negis, 1999). It can prevent bleeding, segregation and delamination of fresh concrete, facilitate pumping processes, decrease permeability of hardened concrete, enhance durability (especially resistance to alkali-aggregate reactions), increase concrete strength and minimize cracking in concrete caused by self-shrinkage (Kılınçarslan, 2011).

Many recent studies have examined the feasibility of using volcanic tuff as a light-weight aggregate in cement and concrete (USBR, 1963; Kan and Gul, 1996; Kılıc et al., 2009; Oboo, 2009; Augenti and Parisi, 2010; Faell et al., 1992, Smadi and Migdady, 1991; Kavasat and

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Evcin, 2005; Abali et al., 2006; Turkmenoglu and Tankut, 2002). Al-Zou'by and Al-Zboon (2014) utilized volcanic tuff in cement mortar and found that a replacement ratio of 50% enhanced compressive strength and flexural strength. Abalia et al. (2006) investigated the possibility of using blends of tincal waste (TW), fly ash (FA), bentonite (BE) and volcanic tuff (VT) as cement admixtures. The results showed that the inclusion of 15% zeolite in concrete mixes has resulted in an increase in compressive strength at early ages, but decreased compressive strength when used in combination with fly ash. The setting time was also decreased when zeolite was substituted. Yasin et al. (2012) used Jordanian tuff for concrete production. The results showed that the replacement of fine aggregate by 20% of volcanic tuff has improved the concrete compressive strength for brown, grey and yellow tuff. Awwad et al. (2012) found that the same percentage of replacement (20%) would improve flexural and shear capacities of reinforced concrete beams by 6%-16% for brown tuff, 3%-8% for grey tuff and 10%-26% for yellow tuff. In the USA, results have buttressed the feasibility of volcanic tuff aggregates (scoria and pumice) which are to be used for the production of light-weight concrete (USBR, 1963). Smadi and Migdadi (1991) studied the potential use of tuff aggregates to produce high strength light-weight concrete and affirmed that it is possible to produce light-weight concrete for reinforced and pre-stressed concrete structures, with a compressive strength as high as 60 MPa at 90 days. Kavas and Evcin (2005) studied the addition of 9, 14 and 15% wt. of Afyon Volcanic Tuff (AVT) to a standard wall tile body and found that alkaline properties, viscosity, water absorption and compressive strength of the specimens were slightly affected by the addition of AVT.

Jordan has huge reserves of volcanic tuff, especially in the northeastern area where phillipsite deposits were first discovered in 1987 at Jabal Artin. According to Natural Resources Authority (NRA) estimates, volcanic tuff reserves in Jordan exceed two billion tons (NRA, 2006).

From the point of view of engineers and environmentalists, such material should be considered on the basis of its performance in concrete mixes, cost-effectiveness and availability. Therefore, the aim of this study is to evaluate how raw volcanic tuff affects the characteristics of concrete using different ratios of normal to volcanic tuff aggregates. In each replacement ratio, the normal aggregate with different particle size distribution (coarse, medium, fine) was substituted by volcanic aggregate of similar particle size, whereas previous studies have used limited particle size fractions of volcanic tuff. High ratio of volcanic tuff (up to 100%) was also utilized in this work, whereas lower ratios were used previously and this has buttressed the novelty of this work.

MATERIALS AND METHODS

Materials

Twelve cubic meters of raw volcanic aggregate (red tuff) were obtained from Jabal Artin, south-east of Jordan. The material obtained was crushed, sieved and tested according to the specifications of ASTM D 75, ASTM C 136, ASTM C 29, ASTM C 127, ASTM C 128 and ASTM C 131 for sampling, grading, unit weight, relative density, specific gravity, absorption and hardness tests, respectively. The chemical composition of tuff sand was determined using X-ray diffraction (XRD) and X-ray fluorescence (XRF). The cement used in this study was ordinary type 1 Portland cement which complies with ASTM C 150 requirements.

Concrete Mixture Composition

Five different concrete mixtures were prepared using successive replacements of normal (crushed limestone, silica and sand) aggregates by natural tuff aggregates with similar particle size distribution.

A control mixture was designed based on the characteristics of normal aggregates; with maximum particle size of 25 mm that resulted in a compressive strength of 25 MPa at 28 days and an average slump value of 60 mm. Table 1 illustrates the constituents of the control mixture.

Table 1. Composition of control mix, kg/m^3

Material	Weight of material (kg/m^3)	Ratio to total constituents (%)
Course aggregate (10-25mm)	830	32.1
Medium aggregate (4.75-10mm)	436	16.9
Fine aggregate (850μm-4.75mm)	390	15.1
Fine aggregate (silica)	390	15.1
Water	207	8.0
Cement	332	12.8
Total	2585	100

According to the ratios used, as shown in Table 1, the required quantities of materials were batched using an electrical tilting drum concrete mixer of 200-liter capacity. Five concrete batches, designated as T1, T2, T3, T4 and T5, were prepared. Experiments included gradual replacements of the required normal quantity of aggregates by tuff aggregates (weight basis). Those replacements were (0, 25, 50, 75 and 100%) as illustrated in Table 2. Both normal aggregates and tuff aggregates were in a saturated surface dry condition. Fixed water/cement ratio was used for all batches. Batching was started by placing coarse aggregate in a mixer followed by gradual placing of course, medium and fine aggregates as well as cement into the mixer. After homogenization, the required amount of water was added for workability and reaction purposes. Mixing was continued for about 3-5 min. and precautionary measures were taken in order to ensure that all materials have formed a homogeneous mixture.

Table 2. Composition of different concrete batches

Mix. Code	**T1**		**T2**		**T3$^+$**		**T4**		**T5**	
Aggregate Type Materials	NA*	TA**	NA	TA	NA	TA	NA	TA	NA	TA
Coarse (10mm-25mm) (kg)	100	0	75	25	50	50	25	75	0	100
Med. (4.75mm-10mm) kg)	52.5	0	39.36	13.124	26.25	26.25	13.124	39.36	0	52.5
Fine (850μm-4.75mm) (kg)	47	0	35.25	11.75	23.5	23.5	11.75	35.25	0	47
Fine (silica) (kg)	47	0	35.25	11.75	23.5	23.5	11.75	35.25	0	47
Water (kg)	25		25		25		25		25	
Cement (kg)	40		40		40		40		40	
Total (kg)	311.5		311.5		311.5		311.5		311.5	

* NA: Normal Aggregate, **TA: Tuff Aggregate, +: Not considered for stress-strain test due to error in the curing period.

Molding and Curing

Molding of specimens for slump, bleeding, compressive strength, flexural strength and stress-strain tests was started after completion of batching, in accordance with ASTM C 143 (Standard Test Method for Slump of Hydraulic-Cement Concrete), ASTM C 232 (Standard Test Method for Bleeding of Concrete), BS1881; part 111 (Testing Concrete Method of Normal Curing of Test Specimens), ASTMC 293 (Standard Test Method for Flexural Strength of Concrete (Center-Point Loading)) and ASTM C469 (Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression). Dimensions and numbers of specimens for each test are given in Table 3. All molding requirements (preparation of mold, layers of concrete, tampering and finishing) were considered. Immediately after completion of molding, compressive strength, flexural strength and stress-strain specimens were placed in a moist room with their upper surfaces exposed to moisture. After 24 h, these specimens were cured in a water bath tank made of a non-corroding material at 20°C until the test day (Al-Zboon and Al-Zou'by, 2015).

Table 3. Dimensions and numbers of specimens

Test	Specimen dimensions	Number of specimens
Compressive strength	15 cm cubes	60
Flexural strength	10x10x30 cm	60
Stress-strain	10cm diameter with 20cm length cylinders	12
Slump	Standard cone	10
Bleeding	Standard bowel	10

Testing

Slump test was carried out after mixing using a standard slump cone 30 cm in height, with a bottom diameter of 20 cm and an upper diameter of 10 cm. Bleeding test was undertaken within 10 min. of completion of mixing using a standard steel cylinder with an inside diameter of 254 mm and an inside height of 280 mm in two layers. Each layer was vibrated using a vibrating table to compact the concrete. The mold was tilted, placed at an angle of 11° and then covered and left to stand for the test duration. Tilting the concrete mold can ease the collection of bleed water from concrete. A pipette was used to draw off the bleed water at intervals of 30 min. for 3 h. Bleeding capacity was measured in milliliters of bleed water per each mold.

For hard concrete samples, at the end of the curing period (7, 28 days), the specimens were removed from the baths, wiped to attain a surface-dry condition and any loose sand grains or incrustations were wiped off from the faces.

All samples were tested within one hour after the curing period. For compression strength test, a constant loading of the specimen within the range of 0.2-1.0 MPa/s was applied. Flexural strength (center point load) was performed according to ASTM C293 at the end of the 28-day curing period. The beam was cleaned, turned on its side with respect to its position as molded and placed in the breaking machine. Forces applied to the beam will be perpendicular to the face of the specimen and the applied force without eccentricity. In order to avoid shock or interruption, load was uniformly applied with an increasing rate of 3700 N/min. This process was continued until the beam got broken and the maximum load, in Newton, was recorded. Stress-strain behavior was determined using 1200 kN compression machine, based on cylindrical concrete specimens, 10 cm in diameter and 20 cm in length, according to ASTM C469.

The validity of the ACI equation (Equation 1) to predict modulus of rupture was evaluted based on the compressive strength results (ACI, 1999):

$$fr = 0.62\ (fc)^{0.5} \qquad (1)$$

where:
fr = modulus of rupture, MPa.
c = compressive strength, MPa.

RESULTS AND DISCUSSION

Physical and Chemical Characteristics

In comparison with normal limestone aggregate, volcanic tuff has lower bulk density (25.2% and 28.8% for coarse and fine materials, respectively), as shown in Table 4. In contrast, it has higher water absorption capacity (10.1%-11.5%) compared with normal aggregates (less than 2%) and may adversely affect concrete properties. Higher water absorption could be attributed to the high surface area and high porosity. Yasin et al. (2012) found that water absorption of Jordanian tuff ranged from 11.1% to 25.1% depending on its type. Topçua and Uygunogˇlub (2010) found that water absorption capacity for volcanic tuff in Turkey was 23.82%.

Regarding chemical composition, Table 5 illustrates the constituents of volcanic tuff in comparison with normal aggregates and silica sand. It was found that volcanic tuff consists mainly of silica (41.7%), lime (12.8%), aluminum oxide (10.6%), ferric oxide (8.87%) and other oxides, while 97% of normal aggregates is calcium carbonates and 99.5% of silica sand is silicates. Other researchers (Yasin et al., 2012; Zou'by and Al-Zboon, 2014) have obtained similar results. Higher silica ratio (65%) was found in zeolitic volcanic tuff samples collected from Tioc (Cluj County, Romania) (Bedelean et al., 2010). Physical and mechanical properties of tuff vary widely according to quarry locations and rock types (Evangelista and Pellegrino, 1990).

Table 4. Physical properties of normal aggregates, tuff aggregates and silica sand

Parameter	NA course	NA fine	TA course	TA fine	Silica sand
Oven dry specific gravity	2.60	2.55	1.962	1.82	2.7
Saturated surface dry specific gravity	2.63	2.60	2.02	2.00	2.7
Bulk density (kg/m^3)	2650.0	2630	1982	1872	2710.0
Water absorption ratio by weight	1.2%	1.70	10.1%	11.5%	2%
NA: Normal aggregates, TA: Tuff aggregates.					

Fresh Concrete Properties

Fresh concrete was tested for its slump and bleeding according to ASTM C143 and ASTM C232, respectively. Results showed a reduction in slump values from 60 to 40, 30, < 10, <10 mm for T1, T2, T3, T4 and T5, respectively. This reduction was expected, since tuff aggregates act as absorbents when coming in contact with water in order to fill the capillary pores before forming a film of water that is used by the binder in concrete (Oboo, 2009).

Table 5. Chemical composition of normal aggregates, tuff aggregates and silica sand

Parameter	Volcanic sample (%)**	Normal aggregates (%)**	Silica sand (%)
SiO_2	41.699	0.90	99.5
CaO	12.831	53.0*	0.03
Al_2O_3	10.604	0.40	0.22
Fe_2O_3	8.87	0.40	0.09
MgO	6.249	0.50	0.005
TiO_2	2.300	BDL	0.02
K_2O	1.416	BDL	BDL
Na_2O	1.057	BDL	BDL
P_2O_5	0.360	BDL	BDL
MnO	0.126	BDL	BDL

BDL: Below detectable limit, * All in the form of $CaCO_3$, ** (Al-Zou'by and Al-Zboon, 2014).

Volcanic tuff has high water absorption; therefore, pores absorb some of the added water and this makes it unavailable for workability purpose. Also, high ratio of surface area to volume will lower workability of the mixture (Ravindrarajah and Tam, 1989). Awwad et al. (2012) and Yasin et al. (2012) found that the use of volcanic tuff materials decreases the workability of concrete and the use of super plasticizers is necessary with such concrete mixtures. Topçua and Uygunogˇlub (2010) found that slump of self-consolidating light-weight concrete (SCLC) made of tuff aggregates is lower in comparison with pumice and diatom aggregates.

The results shown in Figure 1 indicate that the bleeding values increased noticeably from 4 to 28 ml with an increase in tuff ratio from 0 to 100%. For all concrete mixtures, the rate of bleeding decreased as time elapsed and the cement begins to stiffen. After 1.5-2 h, the bleeding process was found to be insignificant for the chosen mixture composition. Increasing bleeding rate is attributed to an increase in the number of flow channels of highly porous tuff aggregates combined with the high initial water content of these aggregates compared with normal aggregates.

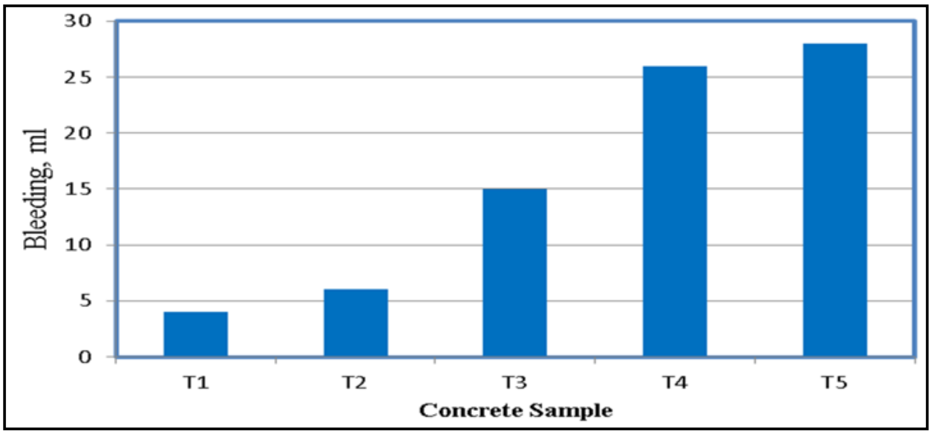

Figure (1): Bleeding test results

Density of Concrete

The conducted tests showed that T1 (100% normal aggregates) had the highest density (2322 kg/m^3), while T5 (100% volcanic tuff) had the lowest density (1994 kg/m^3) with a reduction of 14.1% (Figure 2). This result is attributed to the lower specific gravity of volcanic tuff in comparison with normal aggregates. Table 2 shows that aggregates constitute only 79% of the mixture volume, while cement and water contribute by 21%. Water and cement contents were kept constant in all batches and a slight impact of light tuff aggregate on concrete density was noticed. Al-Zou'by and Al-Zboon (2014) found that the utilization of volcanic tuff in cement mortar caused a density reduction by 7%. Abu-Baker (2009) found that the density of concrete made of volcanic tuff materials was 2059 kg/m^3 against 2398 kg/m^3 for normal concrete. Incorporating volcanic ash (VA) in concrete mixture with 30% VA decreased the density by 4.4% in comparison with control samples (0% VA) (Olawuyi and Olusola, 2010).

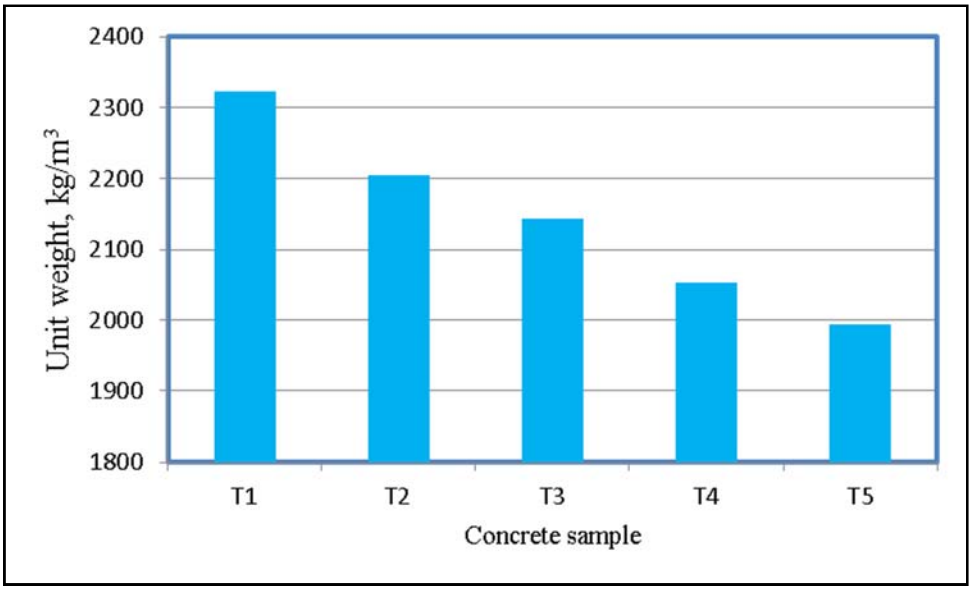

Figure (2): Average unit weight of concrete

Compressive Strength

After curing periods of 7 and 28 days, concrete compressive strength of 150 mm cubes was tested according to BS1881-part 111. The average compressive strength ranged from 31.4 MPa (T2) to 10.55 MPa (T5) for 7 days and from 38.65 MPa (T2) to 13.19 MPa (T5) for 28 days. Figure 3 shows that T2 batch (25% volcanic Tuff) had higher strength than the other batches. Based on the average strengths for all tests and ages, the batches were ranked in the order of T2>T1>T3>T4>T5. It can be concluded that replacing normal aggregate with 25% volcanic tuff improved the compressive strength by 17.57% and 13.57% at 7 and 28 days, respectively. Conversely, a significant reduction in compressive strength for T3, T4 and T5 was observed as shown in Figure 3.

Such behavior was expected, since volcanic tuff aggregates have more angularity and rough surface texture, which enhances the mechanical bond between the aggregates' surface and cement paste by virtue of interlocking, resulting in higher concrete strength (Polat et al., 2013). Neville and Brookes stated that low to moderate strength aggregate will increase concrete strength by preserving its integrity if added in small percentages, which is the case for T2 mixture (Neville and Brookes, 1987). Conversely, the large specific surface area of volcanic tuff, compared to that of normal aggregates, would require more cement paste for coating, which explains why T3, T4 and T5 had lower compressive strength values than T2. At higher ratios, volcanic tuff materials have higher water absorption, leading to decrease available water for chemical reaction, which affects the progress of strength.

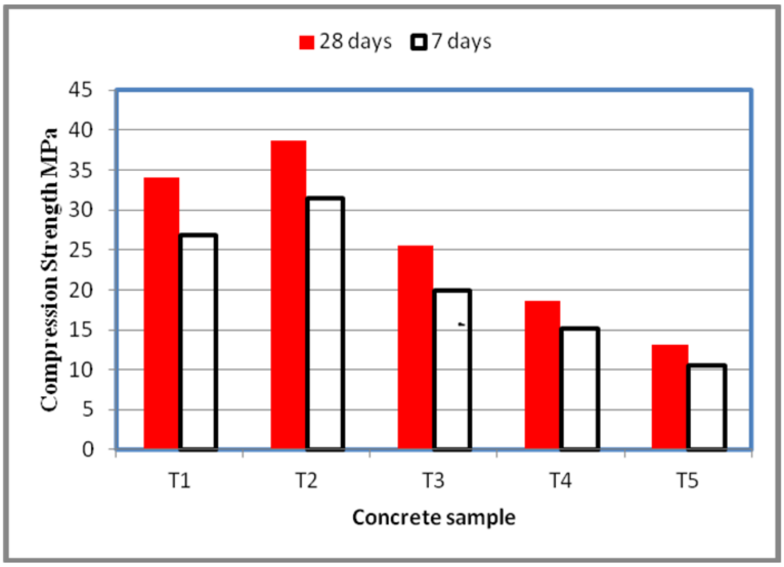

Figure (3): Average compressive strength of concrete batches

Al-Zou'by and Al-Zboon (2014) reported that utilization of volcanic tuff in cement mortar mixtures with a ratio of 50% increased compressive strength by 0.7% at 28 days, while a significant decrease was noticed at higher ratios.

Yasin et al. (2012) found that the addition of volcanic tuff to concrete mixture by a ratio of 20% would increase its compressive strength by 3.8%-19.9%. Abu Baker (2009) found no significant difference in compressive strength of light-weight concrete-based volcanic tuff and normal concrete. Basyigit (2010) used zeolite in concrete with ratios of 5%, 10% and 15% and found that compressive strength increases with increasing zeolite ratio. Olawuyi and Olusola (2010) found that 30% of volcanic tuff in concrete has resulted in the reduction of compressive strength by 28%. Piyachon (2004) reported that compressive strength of normal concrete made with limestone after 28 days was greater than that made with volcanic rock by approximately 2%-10%, depending on aggregate size.

Flexural Strength

Flexural strength test results showed a similar behavior to that of compressive strength, where T2 mixture had the highest value (Figure 4). At 7 days, T2 showed a slight increase in flexural strength (6.3% higher), while T3, T4 and T5 showed significant decrease (24.7%, 30.3% and 47.0% lower, respectively). At 28 days, T2, T3, T4 and T5 showed differences of +0.8%,-18.2%, -30.7% and -35.37%, respectively. In the case of compressive strength, the differences were +13.57%, -24.88%, -45.27% and -61.22% for the same batches, respectively. This result indicated that volcanic aggregates have higher impact on compressive strength compared with that on flexural strength of concrete.

Al-Zou'by and Al-Zboon (2014) found that utilization of volcanic tuff in cement mortar mixtures increased flexural strength at 28 days and 56 days for all tested ratios (25, 50, 75 and 100%). Awwad et al. (2012) reported that the replacement of fine aggregates by 20% volcanic tuff improved flexural strength and shear strength of reinforced concrete beams by 6% to 16% for brown tuff aggregates, 3% to 8% for gray tuff aggregates and 10% to 26% for yellow tuff aggregates.

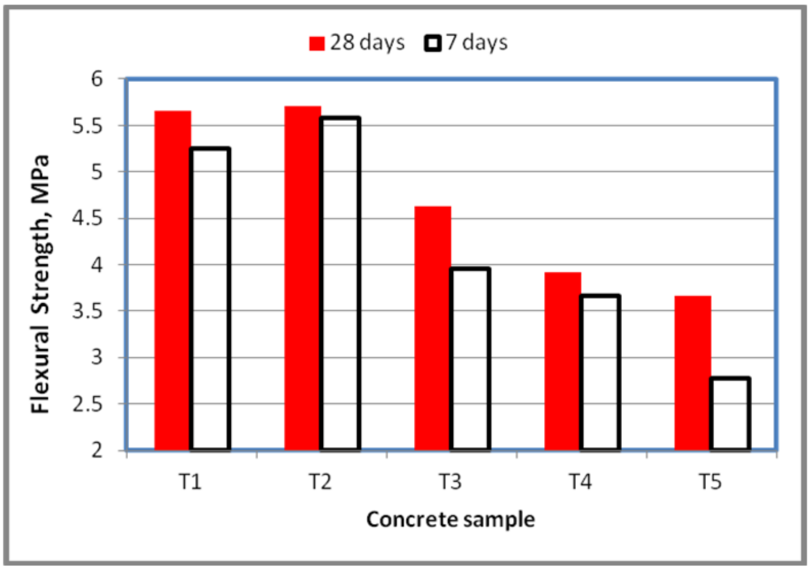

Figure (4): Average flexural strength of concrete batches

Piyachon (2004) reported that normal concrete made with limestone at 28 days had a lower flexural strength than concrete made with volcanic rock by approximately 6%, 4% and 2% for a maximum aggregate size of 10 mm, 20 mm and 40 mm, respectively.

Modulus of Rupture and Compressive Strength Relationship

Compressive strength and modulus of rupture are closely related; as compressive strength increases, modulus of rupture also increases (Salem et al., 2001).

Results of modulus of rupture for concrete samples are shown in Figure 5 along with the ACI equation. It was found that the experimental modulus rupture at 28 days ranged from 14.7% to 27.7% of the compression strength for T5 and T1, respectively. The validity of the ACI equation to predict modulus of rupture was evaluated. Experimental flexural strength was 46.5% to 62.5% higher than the value predicted by the ACI relationship given in Eq. 1.

Regression analysis was carried out to determine the empirical relationship between compressive strength and modulus of rupture using the following regression model:

$$fr = a(fc)^n \quad (2)$$

where a and n are coeffiients determined from regression. The following predicted relationship was obtained with the coefficient of determination R^2= 0.965, as shown in Figure 6:

$$fr = 0.94\ (f'c)^{0.5} \text{ MPa.} \quad (3)$$

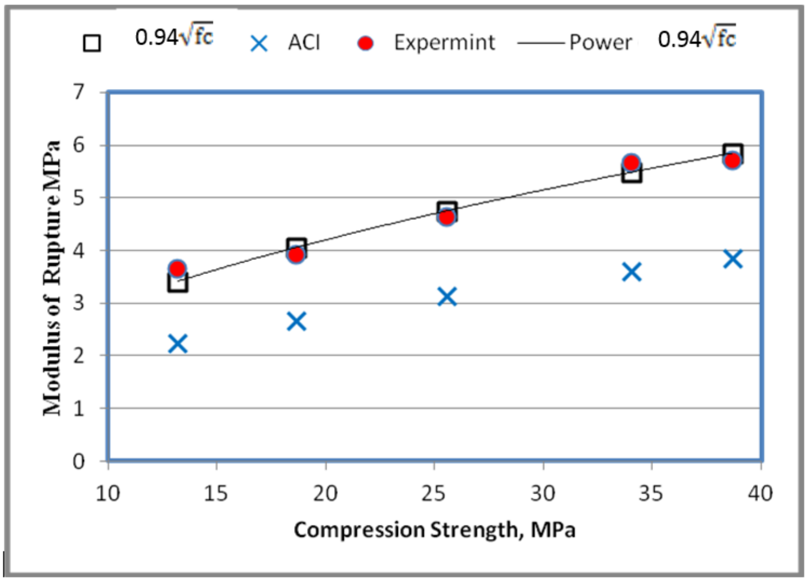

Figure (5): Average experimental, predicted and ACI modulus of rupture

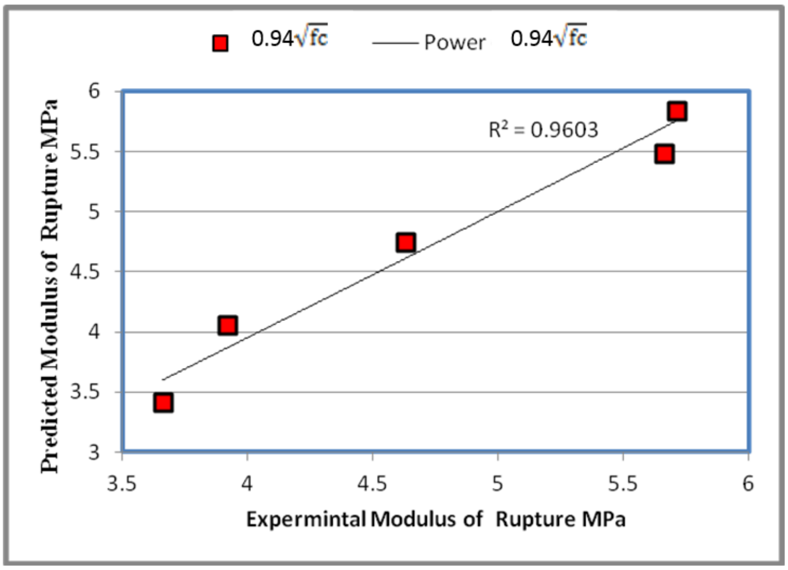

Figure (6): Correlation between experimental and predicted modulus of rupture

This result is close to that obtained by Salem et al. (2001), where they used recycled aggragates produced by crushing the original (old) concrete to determine the relationship between fr and fc and found that: fr = 0.93 $(f'c)^{0.5}$ MPa. They reported that the ACI equation resulted in a significant underestimation (sometimes as much as 40%) of the modulus of rupture, thus generating conservative results.

Stress-Strain Behavior

Stress and modulus of elasticity of concrete are fundamental parameters necessary in structural analysis for determination of displacement and strain distribution, especially when design is based on elasticity considerations (Topçua et al., 2010).

Effect of volcanic tuff aggregates on strain ability of concrete under compressive force was evaluated using four batches (T1, T2, T4 and T5) with volcanic tuff ratios of 0, 25%, 75% and 100%, respectively. In comparison with normal concrete, volcanic tuff concrete has higher strain corresponding to maximum stress. Figure 7 shows clearly that strain of the concrete specimen increases as the percentage of volcanic tuff increases. Normal concrete (T1) reached a strain value of 0.0047 at maximum stress of 24.5 MPa, while T5 (100% volcanic tuff) concrete reached a strain of 0.0071 at maximum stress of 10.1 MPa. There is a slight difference in concrete stress and strain between T1 and T2, which proves the benefit of replacing normal aggregate with 25% of volcanic tuff.

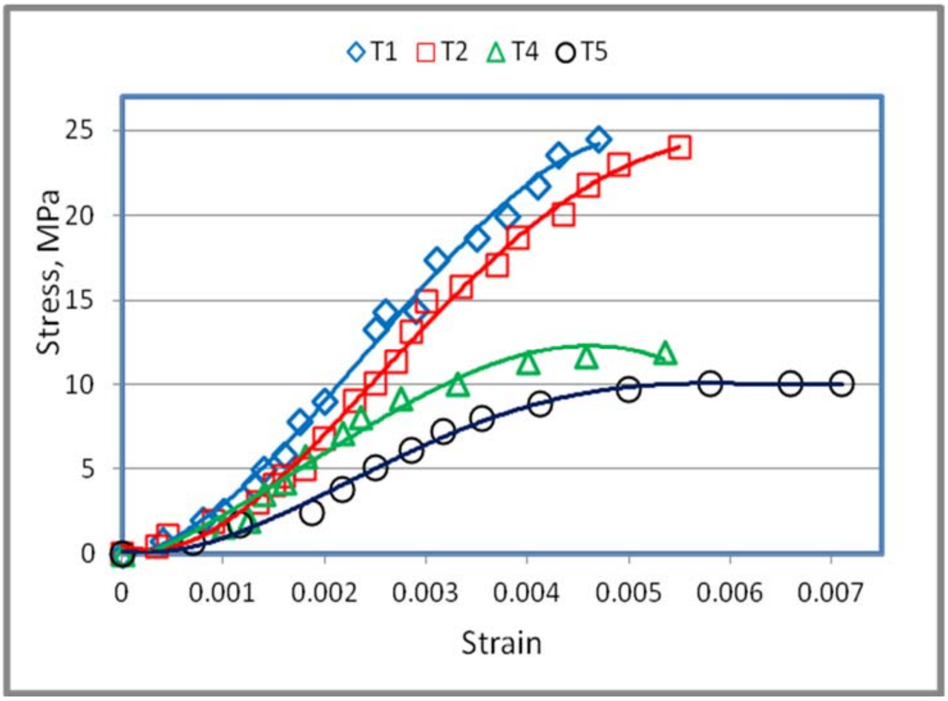

Figure (7): Stress-strain behavior for all batches

Modulus of Elasticity

The static modulus of elasticity is defined as the slope of the concrete compressive stress-strain curve either as a tangential slope at the origin or as the secant slope between the origin and a point on the stress-strain curve at approximately 30%-40% of the peak stress (Knaack et al., 2009).

Secant modulus is the more practical measure of the modulus of elasticity and is mostly taken as the static modulus of elasticity.

The static chord modulus was calculated from the stress-strain diagram according to the following equation (Salem et al., 2001):

$$Ec = (S_2 - S_1) / (\sum 2 - 0.00005) \quad (4)$$

where:

Ec = chord modulus of elasticity.

S_2 = stress corresponding to 40% of the ultimate load.

S_1 = stress corresponding to a strain of 0.00005.

$\sum 2$ = longitudinal strain produced by stress S_2.

The calculated modulus of elasticity according to Equation 4 was found to be 16.98 GPa, 19.94 GPa, 12.69 GPa and 7.62 GPa for T1, T2, T4 and T5, respectively. It can be concluded that replacement of volcanic tuff with natural aggregate causes a significant reduction in modulus of elasticity up to 55% for T5 (100% volcanic tuff). This reduction is attributed to the difference in compression strength for different batches, where the higher compression strength corresponds to the higher modulus of elasticity.

Usually, modulus of elasticity increases with the increase in compressive strength, but there is no agreement on the precise form of this relationship. The actual values ranged between 500 and 1600 times the compressive strength (Reynolds et al., 1988). Various research studies concluded that concrete with the same compressive strength might have different modulus of elasticity values if different types of aggregate are used (Iravani, 1996; Mokhtar-Zadeh and French, 2000). Rashid et al. (2002) determined the modulus of elasticity of concrete made of many types of gravel. They found that sandstone gives the smallest elastic modulus, followed by gravel, whereas dolomite provides the largest value. Limestone, granite, quartzite, trap rock and diabase were found to give comparable elastic modulus values. Usually, light-weight concrete has lower modulus of elasticity which is about 25%-50% lower than for normal-weight concrete (Brown, 1973). Haranki obtained similar results, where the elastic modulus of mixtures containing light-weight aggregates was lower than that for mixtures containing limestone or granite.

Piyachon (2004) found that the modulus of elasticity of normal strength concrete made with limestone was more than that for concrete made with volcanic rock by approximately 1%, 4% and 5% for 10 mm, 20 mm and 40 mm maximum aggregate sizes, respectively. Kılınçarslan found that the elasticity modulus decreased with increasing zeolite amount in concrete up to 50% at a zeolite ratio of 50%.

Relationship between Compressive Strength and Modulus of Elasticity

According to the ACI Code, the empirical relationship between compressive strength and modulus of elasticity of normal concrete is as follows (Salem, 2001):

$$Ec = 0.043\ \rho^{1.5}\,(fc)^{0.5} \tag{5}$$

ρ = unit weight of concrete in kg/m^3 and fc is the compressive strength in MPa.

The results of the modulus of elasticity for the concrete samples are shown in Figure 8 along with the ACI equation. For all batches, experimental modulus of elasticity is less than the value predicted by the ACI relationship given in Eq. 5, ranging from 44.6% to 68.2% of the ACI value. This result indicates that ACI equation provides an overestimated value of the modulus of elasticity of light-weight concrete.

In order to determine an acceptable empirical relationship between compressive strength, concrete density and modulus of elasticity, the following regression model form is proposed:

$$Ec = a\ \rho^{n_1}(fc)^{n_2} \tag{6}$$

where a, n_1 and n_2 are constants determined through regression analysis. Using Excel solver and different values for variables, the following predicted relationship has the lowest error with the coefficient of correlation R^2= 0.92.

$$Ec = 0.033\rho^{1.5}\,(fc)^{0.50} \tag{7}$$

This formula has a lower constant coefficient (0.0331) in comparison with ACI equation (0.043) by about 23%. This difference is attributed to the lower density of concrete made with volcanic tuff compared with normal weight concrete considered in the ACI equation. Salem et al. (2001) used recycled aggregates' concrete and found that the ACI relationship provides a conservative estimate for prediction of the modulus of elasticity by 9%.

Due to the slight difference in the density of concrete for all batches, Eq. 7 is reduced and Ec is expressed in terms of compressive strength only. The following relationship was obtained with the correlation coefficient of 0.87 as shown in Figure 9:

$$Ec = 3549.6(fc)^{0.50} \quad (8)$$

where Ec and Fc are in MPa.

The obtained relationship (Equation 8) also has a lower constant coefficient (3549.6) in comparison with the ACI equation (4700) by about 32.4%.

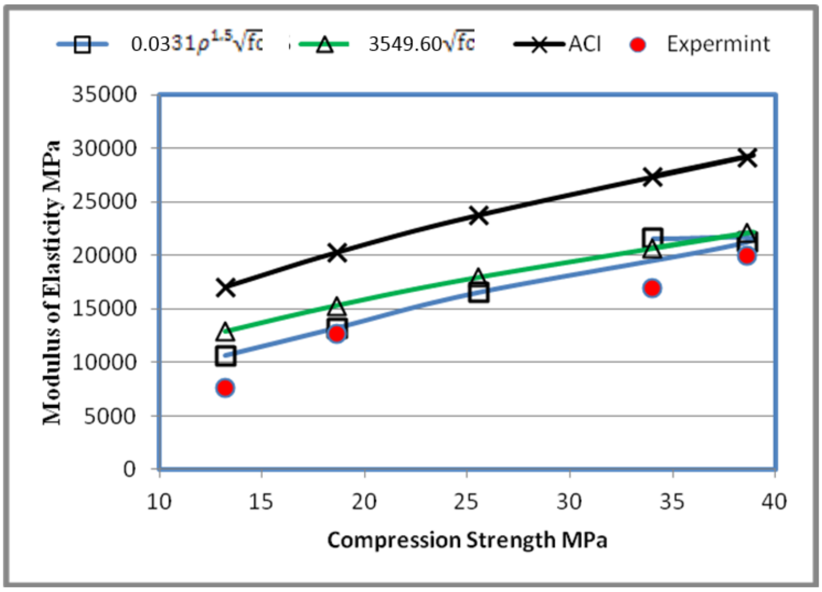

Figure (8): Average experimental, predicted and ACI modulus of elasticity

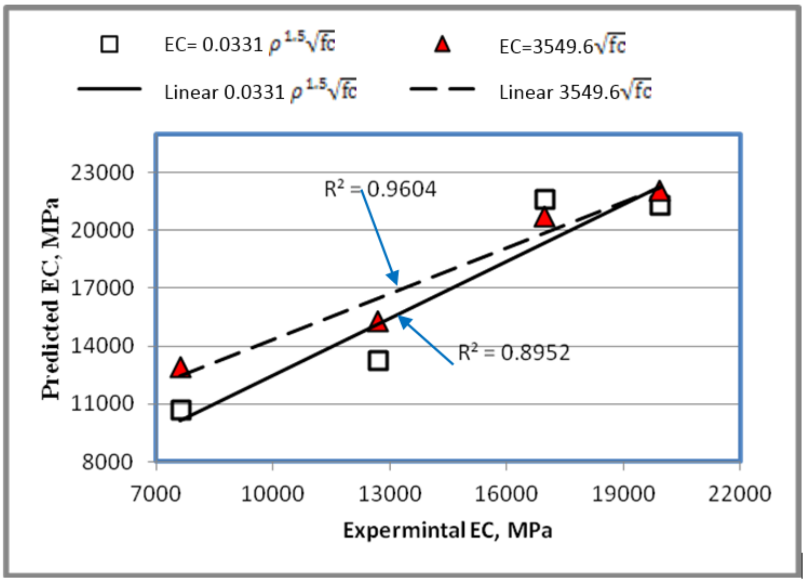

Figure (9): Correlation between experimental and predicted modulus of elasticity

CONCLUSIONS

This paper examined the effect of using volcanic tuff on the characteristics of concrete.

The following are the main conclusions drawn from this research work:

1. The density and workability of concrete decreased with the utilization of volcanic tuff concrete.
2. At 25% replacement ratio, compressive strength and flexural strength increased by 13.57% and 6.3%, respectively and then decreased for all other ratios, while modulus of elasticity decreased for all ratios.
3. ACI equation provided overestimated values of modulus of elasticity and underestimated values of modulus of rupture.
4. Utilization of volcanic tuff with a ratio of 25% can be used in concrete mixtures, which could improve compressive strength and flexural strength while having a slight adverse effect on the modulus of elasticity.

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