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Characterization of Jordanian Volcanic Tuff and its Potential Use as Lightweight Aggregate

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Abstract

In the current study, Jordanian volcanic tuff (JVT) as a lightweight aggregate is experimentally evaluated. Two types of JVT are investigated, namely zeolitic volcanic tuff (ZT) and the black volcanic tuff (BT), from two volcanic eruptions at Al Hala area in southern Jordan. They are investigated in terms of specific gravity, bulk density, porosity, water absorption, and slake durability using the Los Angeles method. Ten mixtures were prepared using the typical crushed limestone aggregate at first, then volcanic tuff aggregate was used as a replacement for the limestone aggregate at the various ratios of 25, 50, 75 %, followed by a total replacement of 100 % volcanic tuff aggregate. Compressive strength, abrasion, indirect tensile strength, flexural strength, ultra-sonic velocity, thermal conductivity, permeability, specific gravity, shear strength and modulus of rupture tests are conducted on the prepared concrete samples.

The results of aggregate characterization indicate that specific gravity ranges from 1.8 to 1.92 for BT and from 1.98 to 1.98 for ZT. Bulk density (kg/m3) ranges from 1189 to 2012 for BT and from 2010 to 2110 for ZT. The two samples possess good porosity with a value of 0.605 (60.5 %), while water absorption for the two samples ZT and BT is 8.7 and 10.2 %, respectively. The above results showed good specifications for JVT to be used as lightweight aggregate. An experimental program based on testing several standard cubes containing different percentages of volcanic tuff as coarse aggregate was prepared.

The results indicated that the best compressive strength obtained is for the mixture of BTC4 as 41 Mpa and with a corresponding density of 1.85g/cm3.

Black volcanic tuff and zeolitic tuff concrete are considered to be light weight concrete compared to the normal weight concrete. The main distinguished characteristic of lightweight concrete is its low density and its higher compressive strength as well.

Keywords: Jordanian Volcanic Tuff, Zeolitic Tuff, Compressive Strength, Flexure Strength.

1. Introduction

Concrete has been one of the most important construction materials over the last century worldwide. Its consumption is increasing in spite of its environmental consequences. The main components of concrete are cement, aggregate and water. The commonly used aggregates are crushed stones or natural gravels that are characterized by high density and low insulation characteristics that make them not environmentally friendly. This has always urged researchers to investigate other options of aggregates such as light weight aggregates in order to produce lightweight concrete (LWC). This issue has become an important interest and research material due to the several resulting advantages, such as savings on reinforcement and foundation costs, in addition to a better fire resistance, heat insulation, sound absorption, frost resistance, superior anti-condensation properties and increased damping (CEB/FIP, 1977).

The main component of LWC is the light weight aggregate (LWA). Volcanic tuff is an excellent light weight aggregate that has been used for many years (Polat et al., 2010), however, they vary in physical and geotechnical characteristics.

Aggregates are commonly defined as natural or artificial incoherent materials possessing different grain sizes that are used in the production of concrete. Lightweight aggregates are formed from materials lighter than water and distinctly more porous than sand, gravel and crushedrock, that are commonly referred to as "dense" aggregates (Klinefelter, 1960; Loughbrough, 1991).

Many materials were used as LWA to produce LWC. Natural materials that are mostly used for the production of lightweight aggregates are sedimentary or very low-grade metamorphic rocks -clay shales (Purbrick, 1991). In addition to the natural or artificial lightweight aggregates, such as Bamboo reinforced, oil palm shells, bottom ash, starch based aggregate, etc. (Ghavami, 1995; Jamal et al., 1997), volcanoclastite and zeolitized rocks can also be used to obtain lightweight aggregates (Colella et al., 2001).

Volcano tuff (clastic) (VT) varies from one location to another based on the weathering rate and zeolitization processes which reflect the mineral content and the quantity of secondary minerals associated with volcanic tuff with zeolites being the most important (Al Dwairi, 2014).

Volcanic tuff in Jordan (VT and ZT) is available in the Northeastern, Central and Southern parts of Jordan (Al

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Dwairi, 2007; Khoury et al., 2015). Volcanic tuffs in Jordan are studied with regard to their mineralogy, petrology and their environmental, industrial and agricultural applications (Dwairi 1987; Ibrahim 1993, Al Dwairi et al. 2009; Al Dwairi 2010, Yasin et al. 2012; Awwad et al., 2012; Al Dwairi et al., 2014; and Al Dwairi et al 2015). Also, Sarireh (2015) had studied the volcanic tuff (black minerals) of Jabal Al-Hala and its physical, chemical, and mechanical properties. The research had presented the properties of Volcanic Concrete (VC) by employing the Volcanic Aggregate (VA) in a concrete mixture in the proportions of 10, 20, 30, 40, and 50 %. The physical tests, such as sieve analysis and specific gravity, density and absorption for both VA and normal weight aggregates (all specific gravities of VA less than those of the normal weight aggregate) were conducted. Also, the density and compressive strength of concrete on the seventh day and twenty-eighth day, flexural strength, and permeability.

The use of volcanic tuff in the concrete industry has been known worldwide. One of the most challenging issues facing the construction sector in Jordan is the increasing cost of the building materials which lead to the increasing cost of construction especially when using traditional building materials.

The present study is aimed at investigating the suitability of the south Jordanian volcanic tuff to be used as light weight aggregate, and attempts to produce a new lightweight concrete mixture by shedding light on volcanic tuff as a promising material used as aggregate.

2. Materials and Methods

2.1. Material

Two locations in Tafila Governorate in southern Jordan were selected to sample volcanic tuff, namely Jabal Al Hala1 (Ataita) and Al Hala 2 volcanic tuff as the map in Figure (1) shows. The two volcanoes are located about 200 km south of Amman City. Al Hala1 is about one km to the southeast of the Rashadiya Cement Plant at an elevation ranging from 1573 – 1643 m above the mean sea level (AMSL), while, Al Hala 2 is about 3km from Al Ees Area at an elevation ranging between 1500- 1524m AMSL.

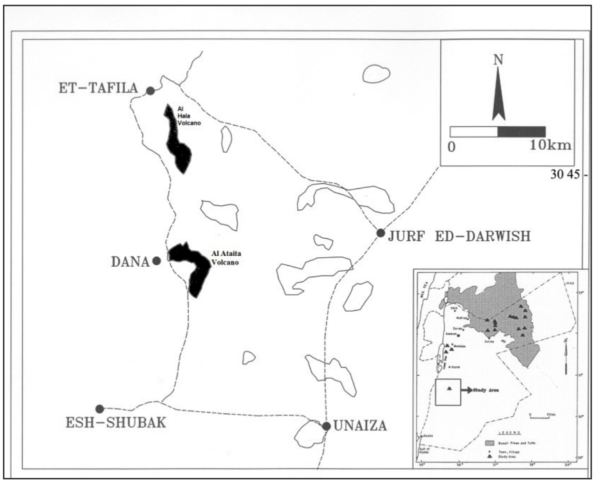

Figure 1. Volcanic tuff location map (Modified after Al Dwairi, 2007).

2.2. Material's Characterization and Preparation

Volcanic tuff from Al Hala1is highly altered to zeolite (ZT), brown and gray colored with a thickness of more than 50 m. Volcanic tuff from Al Hala2 is black fresh scoria (BT) with a thickness of 20 m. The tuff in both locations is of Paleocene and Neogene

age (Gradstien, 2012). Limestone is obtained from a local quarry in Tafila. The chemical composition and physical properties of ZT and BT were determined and characterized by Al Dwairi (2007) and (2014).

Coarse aggregates of BVT, ZVT and LS that are shown in Fig. (2-a) were used in five designed mixtures as shown in distribution in Fig. (2-b).

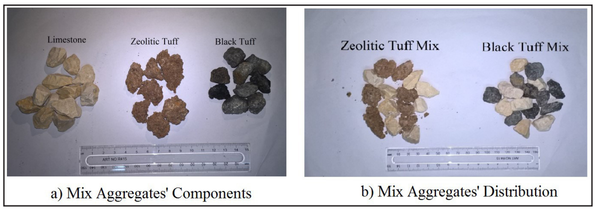

Figure 2. BVT, ZVT, and LS Aggregates Components and Distribution in Mix.

The experimental program depends on the replacement of the LS with BVT Mix and ZVT Mix in ratios from 0 to 100 % at an increments of 25 % as shown in Table (1), in addition to the normal proportion of sand stone as the fine part that is used in concrete mix. All Samples of VT were crushed using a jaw crusher with 5cm and 3cm aperture, and were sieved into aggregate size (1-4 and 4-16 mm). They were then sorted and labeled to be tested for properties.

2.3. Lightweight Aggregate (LWA) Tests

To investigate the ability of using the VT as LWA, the two bulk samples (BT and ZT) were subjected to the following laboratory tests: Specific gravity and absorption (ASTM C127-84 and ASTM C330-82a), bulk density (ASTM C 127-88 and ASTM C 128-88), porosity of LWA that was conducted according to ASTM C29 / C29M - 17a., and abrasion in the Los Angeles Machine by applying (ASTM C131 / C131M - 14). Analyses were carried out at the laboratories of the Department of Civil Engineering at Tafila Technical University in southern Jordan.

2.4. Lightweight Aggregate Concrete (LWAC) Tests

The following techniques were used to determine the most appropriate mix of VT and LS aggregate to be used as a lightweight concrete in civil engineering constructions; compressive strength, Splitting strength, Thermal conductivity, Permeability, Modulus of rupture, Shear failure and Flexural strength. Compressive strength on Concrete Cubes is determined by testing 28-days old (15x15) cm at specified rate of loading (BS 1881: Part 107: 1983 and BS 1881: Part 108: 1983). Comprehensive experimental investigations were conducted to assess the effect of volcanic tuff on concretes compressive strength. All previous techniques were conducted at the Natural Resources Authority Geotechnical Labs/ Jordan and Civil Engineering Laboratories in Tafila Technical University/ Jordan.

Table 1. Bulk samples collected from different sites in the two locations.

Concrete Type	BTC1	BTC2	BTC3	BTC4	ZTC1	ZTC2	ZTC3	ZTC4	LSC
Mixing Ratio VT:LS	100:00	75:25	50:50	25:75	100:00	75:25	50:50	25:75	00:100

3. Results

3.1. LWA Results

The obtained results of the different engineering properties for BT and ZT to be used as LWA are listed in Table (2).

Table 2. Physical properties of limestone and VT aggregates used in the experiments mixes

Type	Specific gravity	Bulk density (kg/m^3)	Porosity (%)	Water absorption (%)	Abrasion (%)
Coarse BT	1.80	1189	60	10.2	20.1
Fine BT	1.92	1812	60	11.7	19.2
Coarse ZT	1.98	2110	50	8.7	25.1
Fine ZT	2.00	2010	50	9.2	26.7
Coarse LS	2.56	2560	15	3.12	31
Fine LS	2.47	1800	15	2.51	29

Specific gravity results showed that the coarse BT has a specific gravity of 1.89 and 2.00 for the coarse ZT which conforms to the theoretical value stipulating that volcanic tuff has a specific gravity of 1.64-2. Ordinary limestone aggregate from the laboratory tests had a specific gravity of 2.51 which also conforms to the theoretical values.

Comparing specific gravities of ordinary limestone with volcanic tuff indicates that ordinary limestone is much heavier than volcanic tuff; it is, therefore, proper to categorize volcanic tuff as a light weight aggregate. Results are shown in Fig. (3).

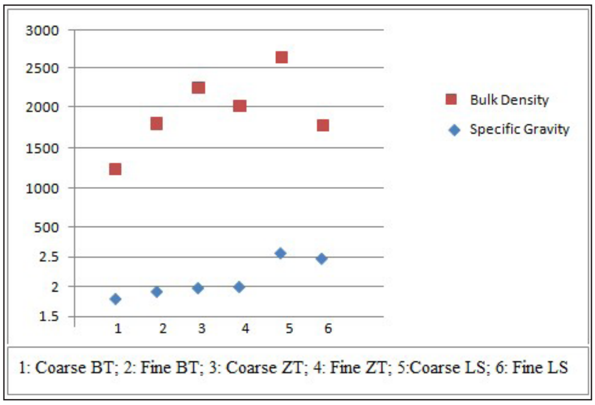

Figure 3. Specific Gravity and Bulk Density for BT, ZT, and LS

Results of bulk density (Kg/m^3) shows that coarse LS is heavier than coarse BT and ZT. Similar results are obtained regarding fine BT, ZT, and LS. The results of specific gravity and bulk density are also presented in Fig. (3). It is clear through the bulk density that fine BT is heavier than coarse BT, while the coarse ZT is heavier than the fine ZT, and coarse LS is heavier than fine LS. Also, the results of the specific gravity show that coarse and fine LS are heavier than coarse and fine ZT and BT. As for porosity, the values of BT and ZT are higher than those of LS. So, they can be used as light aggregates in the production of light concrete. The idea of using lightweight aggregates is that it acts as a water reservoir which can provide water to replenish the hydration-consumed water. The results show that porosity was about 50 % for ZT and 60 % for BT, whilst for LS it was less than 15 %. Such results indicate that a large amount of water can be stored in the pores of light weight aggregates better than ordinary limestone aggregates, providing it with more humidity which maintains the hydration of the cement and gain of strength. These results can be correlated with the water absorption results which increase more in LWA than in ordinary limestone aggregates due to the relatively high porosity. This assumption supports the use of LWA as a green and safe construction material.

As a result of porosity, absorption for BT and ZT is higher than for LS, that is, BT possesses a water absorption range of 10.2-11.7 % compared to a rate of 8.7-9.2 % for ZT. These results show that volcanic tuff can absorb 7 % more water than ordinary limestone which aborbs at a rate of 3.1 %. This rate of absorption definitely affects the workability of the mixture while producing concrete. This value is however acceptable since water absorption depends not only on the void content of volcanic tuff, but also, on the nature of volcanicity and the distance from the volcanic mountain.

As for abrasion, the values for BT and ZT were encouraging while being less for LS. The abrasion resistance of concrete is strongly influenced by the compressive strength, surface finishing techniques, curing types, aggregate properties and testing conditions, i.e. dry or wet (Topcu et al, 2009). The values of abrasion resistance for BT are ~ 20.6 %, ZT ~ 25.9 % and ~ 30 % for LS. This means that the abrasion resistance of ZT and BT as lightweight aggregate is better than the ordinary Limestone with all types of LWA. This is based upon the fact that lightweight aggregates are not as strong as the crushed stones.

3.2. BT, ZT, and LWC Results

The results of engineering properties of the lightweight aggregate concrete using different mixes are listed in Table (3).

3.2.1. Slump Test

This test is used to determine the slump of concrete. This method is applicable to plastic concrete having a coarse aggregate up to 1.5 inch in size. This method is not considered applicable to non-plastic and non-cohesive concrete. Slump test was conducted according to ASTM C143 / C143M - 15a.

3.2.2.

Modulus of rupture as determined by concentrated load. Three beams (15x15x75) cm were prepared according to (BS 1881: Part 109: 1983) and tested according to the (ASTM C78 / C78M – 18).

3.2.3.

Shear failure conducted by applying load at the midpoint of the specimen. Three beams (20x25x110) cm were tested by the (ASTM D6916 - 06c,2011)**.**

3.2.4.

Flexural strength was conducted under a concentrated load at the midpoint of the span (D 790 – 03). Three beams (20x25x310) cm were tested. Five mixes were prepared, namely 0 % basalt (as areference mix), 25 % basalt, 50 % basalt, 75 % basalt, and100 % basalt. The composition of each mix was 40 % fine aggregate passing sieve # 4 and 35 % passing ½" retained on sieve #4 and 25 % course aggregates passing 1" and retained on ½" sieve. In order to enhance the workability of the mix, the portion passing sieve # 4 consisted of 20 % limestone sand and 20 % basalt sand for all mixes.

3.2.5.

Splitting strength determined by the indirect tensile strength test. Three cylinders of 10 cm diameter by 20 cm height were tested. Splitting strength is determined according to the (ASTM C1006 - 07(2013).

The cube strength development curve shown in Table (3) indicates that the strength of concrete increases steadily from a minimum value of 32.5 MPa at the control point to reach its maximum strength of 29.56 KN/m^2 at an 80 % replacement and then the strength decreases again steadily to a value of 27.25 KN/m^2 at 100 %. The above value for control cubes conforms to the theoretical value of 25KN/m^2 for class 25 concrete at a twenty-eight day strength. Volcanic tuff has shown an incredible increase in strength above what was expected at twenty-eight days with all the values falling above 25 KN/m^2. The reasons behind the high strength in volcanic tuff are the process of high strength concrete first involves a balancing water demand and a paste aggregate bond potential. This was greatly achieved at an 80 % replacement due to its parking density and its corresponding particle size distribution of the combined aggregate used. In theory, this generates savings due to the reduction in the paste volume that can be used to coat the aggregates. In this study, since cement content was a constant parameter, much of the cement was used in achieving strength beyond what was anticipated in the mix design leading to the increasing strength development curve.

The optimum gradation of the fine aggregate for high strength concrete is determined more by its effect on water demand than on particle packing. High strength concrete typically contains high volumes of cementation sized materials (as in the case of volcanic tuff, it has some pozzolanic properties due to fly ash). As a result, fine sands that would be considered acceptable for use in conventional concretes may be less suited for high strength concrete due to their sticky consistency; conversely, coarse sands that may not comply with the standard specifications for concrete aggregates may be highly desirable for high strength concrete.

In regard to their impact on workability, physical grading of fine aggregates is less critical in high strength concrete mixtures compared to conventional concrete.

Water also played a very important role in achieving the strength shown above. It is important to know that mixing water includes the free water introduced during mixing and after batching and the free moisture on aggregates.

The hardened cement paste has two fundamental types of pores capillary and gel pores. Capillary pores are the spaces between the masses of cement gel grains; they make up what is called the "capillary system". Depending on the degree of hydration and the initial separation of the cement grains, capillary pores may be interconnected (percolated). The gel pores are spaces between the solid products of hydration within the cement gel.

Gel pores are normally filled with water that is strongly held to the solids. Capillary and gel pores will be filled with water if the paste is saturated. When the paste is exposed to drying conditions, these pores become empty, as the evaporable water is lost. Due to the sticky consistency of conventional concrete, the fine aggregates fill most of the pores leading to complete disconnection between the capillary and gel pores hence making internal hydration quite difficult.

Table 3. Fresh and Hardened Concrete Properties for BT, ZT, and LS Concrete.

Concrete Type	Slump (mm)	Density g/cm^3	Water Absorption %	Flexural Strength (MPa)	Splitting Strength (KN)	Compressive Strength (MPa)	Modulus of Rupture (MPa)	Shear Stress (MPa)
BT C1	27	2.128	5.6	1.2	162	33	2.40	0.82
BTC 2	24	1.931	5.3	1.31	166	35.3	2.60	0.91
BTC3	28	1.900	4.2	1.50	171	38.1	3.20	0.95
BTC 4	26	1.850	4.5	1.60	178	41.0	3.50	1.10
ZTC1	28	2.210	4.6	1.1	164	31	1.9	0.71
ZTC 2	26	2.140	4.5	1.20	169	32.3	2.20	0.73
ZTC 3	30	1.988	4.6	1.32	174	33	2.40	0.81
ZTC 4	27	1.899	4.8	1.50	178	35.50	2.70	083
LSC	42	2.400		1.10	181	30	1.50	0.72

Compressive strength was found to decrease with the increase of VPP content, and more than 25 % reduction in strength is observed at the 25 % replacement compared to 0 % VPP. This is reasonable due to the reduction of the cement content in the mix with the increase of VPP content. The finely divided silica (61%) in VPP can combine with calcium hydroxide (liberated by the hydrating Portland cement) in the presence of water (Hossain, 1999) to form stable compounds like calcium silicates, which have cementation properties. Such pozzolanic action of VPP contributes to the enhancement of strength and long-term durability (Hossain, 1999); however, the reduction of strength in the blended cement due to the cement replacement by VPP is not compensated in the current study.

The strength is reduced as a result of increasing the VPP percentage from 0.0% to 25%; 26% (one-day strength), 26.4% (three-days), 22.7% (seven-days) and 24.2% (twenty-eight - days) when VPP content varies from 0% to 25%. The strength reduction is decreased with the increase of age.

Also, The thermal conductivity test was conducted for the samples and the results are shown in Table (4). Three samples (30x30x5) cm were tested according to (ASTM D5334 - 14).

and permeability determined by the water pressure test. Three plate samples (30x30x5) cm were tested according to (CRD-C48-92).

Fig. (4) presents the values of slump (mm), density (g/cm^3), and water absorption %.

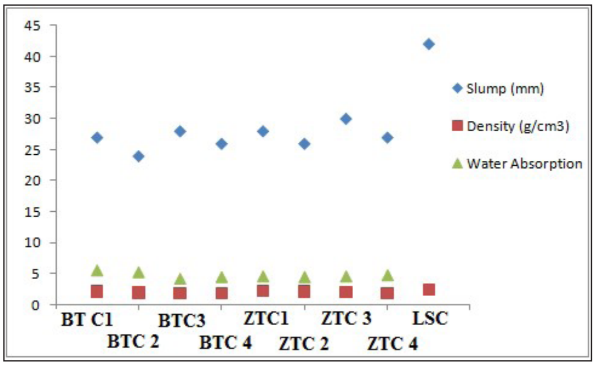

Figure 4. Values for Slump (mm), Density (g/cm3), and Water Absorption %

It is clear that in Fig. (4), the slump values are ranging from 23 to 27 mm for all samples were mixed using BTC and ZTC samples. While the slump value is the highest for LSC which is about 43 mm; it gives more workability in the concrete mix at this value and maintains compressive strength of concrete because of the water/cement ratio that it is constant for all mixes.

Fig. (5) represents values of flexural strength, splitting strength, and compressive strength of the concrete mixes for the samples of BTC 1, BTC 2, BTC 3, BTC 4, ZTC 1, ZTC 2, ZTC 3, ZTC 4, and LSC.

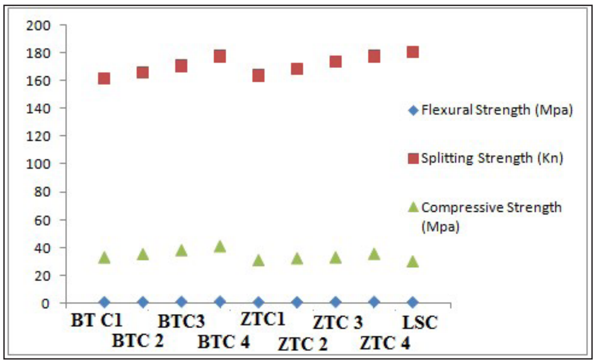

Figure 5. Values for Flexural Strength, Splitting Strength, and Compressive Strength

As is clear from Fig. (5), LSC has higher values regarding splitting strength and flexural strength than the BTZC and ZTC samples. As for compressive strength, BTC has higher values than the ZTC and LSC samples.

Table 4. Thermal Conductivity and Permeability of BT, ZT, and LS Concrete.

Concrete Type	Mixing Ratio VT:LS	Thermal Conductivity	Permeability Pressure
BTC1	100:00	0.35	30
BTC2	75:25	0.48	42
BTC3	50:50	0.67	65
BTC4	25:75	1.14	127
ZTC1	100:00	0.31	36
ZTC2	75:25	0.43	53
ZTC3	50:50	0.62	79
ZTC4	25:75	1.06	136
LSC	0:100	0.94	171

Fig. (6) presents the values of thermal conductivity and permeability pressure for the concrete mixes using BTC 1, BTC 2, BTC 3, BTC 4, ZTC 1, ZTC 2, ZTC 3, ZTC 4, and LSC.

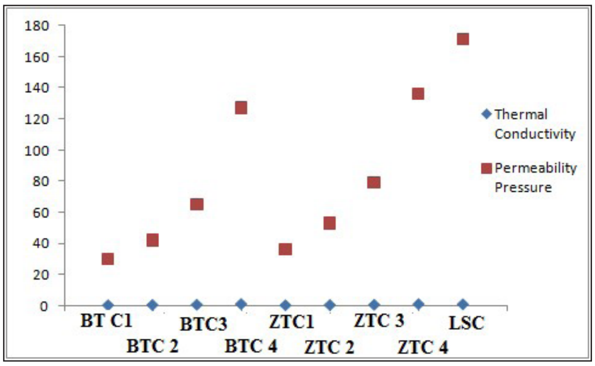

Figure 6. Values of Thermal Conductivity and Permeability Pressure

From Fig. (6), it is obvious that ZTC achieves more in permeability pressure than the BTC samples, but less than LSC samples. As for thermal conductivity, the values are relevant for BTC, ZTC, and LSC.

4. Discussion

The compressive strength is the most commonly used parameter to describe the quality of concrete in practice (Wiegrink et al., 1996). According to ASTM C 330-89, the twenty-eight-day cylinder compressive strength should not be less than 17 MPa (Neville and Brooks, 2008). Okafor (1988) reported that the maximum compressive strength of lightweight concrete produced using this agricultural shell is approximately 25 to 35 MPa. This range is within the typical compressive strength for structural lightweight concrete (20-35 MPa) (Kosmatka et al., 2002). Mannan and Ganapathy (2001) showed that by using 480 kg/m^3 cement, a free water to a cement ratio of 0.41 and mix proportion of 1:1.71:0.77 by weight of cement, sand and OPS aggregate, the twenty-eight-day compressive strength of OPS concrete is between 20 and 24 MPa depending on the curing.

The potential applications of light weight aggregate are more phenomenal in terms of the usage as new construction materials. Cost effective construction practices with alternate construction materials are most desired in terms of huge savings in the construction cost. Fly ash is not a waste and can be effectively used in concrete either as aggregate fillers, replacement for fine aggregates, or as a fly ash brick material. The overall studies conducted by various researches showed that the fly ash aggregate produced by pelletization can be an effective aggregate in the concrete production. Also, the efficiency of pelletization depends on the speed of the pelletizer, angle of the pelletizer, and the type of binder added along with the fly ash. The cost effective and simplified production techniques for manufacturing fly ash aggregate can lead to mass production, and can be an ideal substitute for the utilization in many infrastructural projects. In the near future, the depletion of the nature resources for aggregate can be suitably compensated by the fly ash aggregate.

According to this study, using volcanic tuff as a light weight aggregate concrete material will be most successful. The authors deeply recommend JV and JVT as lightweight aggregates since the results prove that they are less expensive than normal aggregates in terms of transportation, and because the construction will be environment friendly (Green House Building) and because of the chemical characteristics of zeolite itself. Lightweight aggregates are considered to be a promising material which should be replaced by the normal aggregates in the construction projects.

Conclusion

JVT in its two forms including BT and ZT shows suitability and usage in construction as local non-expensive material. Many benefits can be gained through the use of JVT in the concrete mix production:

1. Volcanic tuff lightweight has shown incredible results on issues related to its compressive strength, as well as the tensile strength.
2. It was proven that volcanic tuff and ordinary limestone can be well blended together at different percentages in order to achieve a targeted strength without any significant effects.
3. The correct mix design of volcanic tuff in concrete to be used in modern structural problems was established.
4. Volcanic tuff deposits are well scattered out along the rift valley and in places where there are no major rivers to supply ordinary sand and gravels; hence, volcanic tuff comes out to be the best alternative as an available and cost-effective structural material.
5. Specific gravity of volcanic tuff is 1.89 compared to 2.51 for ordinary limestone/sand. Therefore, modified concrete turns out be lightweight compared to the conventional concrete.
6. The values of abrasion resistance show that the abrasion resistance of ZT and BT as lightweight aggregate is better than the ordinary Limestone with all types of LWA.

Limitations of the Study

During testing and applications in this study, the authors had the following limitations:

1. Volcanic tuff must be tested on a dry-basis for sieve analysis, abrasion, and in taking weight and volume in any season.
2. The samples should be tested for specific gravity periodically at each mixing operation in order to change on volume-basis the mix constituents.
3. A national project on the characterization of volcanic tuff throughout the country.

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