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Research Article

Sustainable Structural Lightweight Concrete Design and The Investigation of The Mechanical Properties

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Abstract

This paper reports an experimental investigation and statistical analysis carried out to evaluate sustainable structural lightweight concrete (SSLWC) design and the mechanical properties of SSLWC. CEM I 42,5 N cement was partially replaced with silica fume (SF) 10% and fly ash (FA) 30% by weight, respectively. The tests of compressive, split tensile strength and ultrasonic pulse velocity were performed on the specimens prepared with admixtures at ages of 3, 28 and 90 days. From the results it was seen that specimens prepared with SF showed better strength properties than others. While control concrete specimens showed similar strength properties to concrete specimens with SF admixture at early age, those of concrete specimens with FA admixture did not increase at the same age. Furthermore, FA concrete series gave very close results to control concrete at advanced age. In this study, analysis of variance (ANOVA) and F-test were performed to see the effects of the experimental parameters on results.

Key words: Sustainable Structural lightweight concrete, Pumice, Admixtures.

1. Introduction

The gaining acceleration of the sustainable developments including also construction industry has constrained the improvement and acceptance of the suitable methods for environment protection in all industry branches. Approximately 20-25% of whole world energy has been spent to produce construction materials such as cement, steel and plastics. Moreover, concrete manufacturing plants have brought along the high rate power consumption which increases the CO_2 emission and the spending of the raw materials. Accordingly, every year, 1 billion ton of water, 1.5 billion tons of cement and 10 billion tons of aggregate have been consumed as raw materials in all over the world (Becchio et al. 2009).

The structural lightweight concrete is a versatile material because it provides some technical, economical and environmental advantages (Haque et al. 2004). Nowadays, structural lightweight concrete has been used to decrease the death-load of the building and to reduce cross sectional area of the structural members. In this way, the effective usage areas and spaces of high and heavy buildings can be increased (Kok and Min-Hong 2002). Moreover, structural lightweight concrete has been preferred to produce and design wall panel and block, etc. For all these reasons, the designing of the structural lightweight concrete is especially preferable in the areas under earthquake risk (Sari and Pasamehmetoglu 2005).

The most common method to produce structural lightweight concrete is to use lightweight aggregate, since the aggregates constitute approximately 70-80% of the concrete. Because of the high rate usage of the aggregate in the concrete mix, it has important effect on the mechanical and some other properties of the concrete (Mindess 1981). The effect of the aggregate properties on concrete characteristics has been investigated by the most researchers (Giaccio et al. 1992; Baalbaki et al. 1991; Nilsen et al. 1995). Yang and Huang (1996) reported that the compressive strength of the concrete was affected by the aggregate volume and properties. Lydon (1982) indicated that the compressive strength of the concretes dependent on the aggregate type for some lightweight aggregates and it increases by increasing of density of the concrete. Topçu (1997), Al-Khaiat and Haque (1998) reported that thanks to the porosity of the lightweight aggregate, the produced concretes with this material have the higher strength/weight rate, the better capacity of the splitting tensile strength, the lower thermal permeability coefficient, effective heat and sound insulation properties. Moreover, Topçu (1997), Yaşar and et al. (2003) reported that the usage of lightweight aggregate in concrete mix provides to decrease the death load of the building and the cross sectional area of the steel was used in concrete. The concern which is on structural lightweight concrete has increased day by day since the earthquake risk has increased nowadays.

The aim of this study is to design the more economic and environment friendly a sustainable structural lightweight concrete with volcanic pumice of Elazig area using admixtures and to identify statistically the effects of the experimental parameters on the test results.

2. Experimental Study

2.1. Materials

In this study, CEM I 42.5 Class N, Normal Portland cement 42.5, which was provided by Elazig in Turkey was used. Specific gravity of the cement is 3.10 gr/cm^3. Silica fume and fly ash were used as mineral admixtures.

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They were obtained from Antalya Electro Metallurgy Enterprise and Sivas Kangal Power Plant in Turkey, respectively. The chemical composition and some physical properties of Portland cement, silica fume and fly ash are given in Table 1.
Crushed volcanic pumice obtained from natural deposits in Elazig city and its apparent reserve was about 20 million m^3 was used as the coarse aggregate while the fine aggregate was river sand which had 2.72 of specific gravity and 1.15% of water absorption rate, respectively. In the study, two different sizes of coarse aggregate, 5-10mm and 10-20mm, were used while fine aggregate was 0-5mm. Bulk dry unit weight and Water absorption of coarse aggregate were 1.29 gr/cm^3, 22.36% respectively. Los Angeles test (500 revolution) result of coarse aggregates were 42%. As a cubic stone, mean compressive strength of volcanic pumice aggregate was 11.30 N/mm^2.

Table 1. The chemical and physical properties of the cement and mineral admixtures

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss of Ign.	Blaine (cm^2/gr)	Specif. Gravity
Cement	21.12	5.62	3.24	62.94	2.73	1.79	1.78	3382	3.10
Silica Fume	91	0.58	0.24	0.71	0.33	1.06	1.84	-	2.20
Fly Ash	38.34	16.69	5.11	27.62	1.60	4.44	0.79	1343	2.50

2.2. Mix Proportions and Sample Preparation Process

A control lightweight concrete mixture made with lightweight volcanic pumice containing only portland cement (KB), and lightweight concrete mixture containing 30% fly ash (UKB) and 10% silica fume (SDB) as a replacement of the cement by weight were prepared in three different concrete types for each age. The same aggregate gradation was used and cement content was chosen as 310 kg/m^3 for all concrete series. The concrete mixes with mineral admixtures were prepared adding 10% silica fume and 30% fly ash as a replacement of the cement by weight, respectively. In this study, moreover, slump test results were kept constant between 6 and 9 cm for all fresh concrete mixes. The mix proportions prepared trough this way was given in Table 2.

Table 2. The proportions of the concrete mix

Concrete Type/Constituents	Control Concrete (Kg/m3)	Fly Ash Concrete (Kg/m3)	Silica Fume Concrete (Kg/m3)
Portland cement CEM-1	310	217	279
Fly Ash	-	93	-
Silica Fume	-	-	31
Fine Aggregate (natural aggr.)	780	780	780
Coarse aggregate (5-10 mm)	360	360	360
Coarse aggregate (10-20 mm)	490	490	490
Water/Binder	0.65	0.63	0.67
Coarse aggregate /Total aggregate	0,52	0,52	0,52
Fine aggregate/ Total aggregate	0,48	0,48	0,48
Average Relative Density (kg/m3)	1900	1865	1890

Cube concrete specimens, 150mmx150mmx150mm, were prepared to determine compressive strength and ultrasonic pulse velocity, and cylindrical concrete specimens, 150 mm in diameter and 300 mm high, were prepared for splitting tensile strength tests. A different way was followed from the preparation process of the normal concrete mixes by considering earlier studies. First, fine aggregate, cement and ½ of water were added to the revolving pan type mixer for 2-3 min. Then, the concrete constituents remained were mixed in the mixer for approximately 10 to 12 minutes to obtain uniform consistency, because porosity ratio of volcanic pumice is higher than other coarse aggregate types (Sari and Pasamehmetoglu 2005). After mixing, concrete mixtures prepared were filled in cubic and cylindrical moulds in three layers by tamping. Later, all the test specimens were stored at temperature of 22±3ºC (about 23ºC) in the laboratory. On the day following casting, the specimens were de-moulded and placed in water to cure for periods of 3, 28 and 90 days.

2.3. Applied Tests

Using UPV test apparatus provides to measure passing time of P and S waves from one side to the opposite other side of the concrete tested and to calculate wave passing time in concrete. Then, UPV is calculated formulation following,

$$V = (S / t)\, 10^6 \qquad (1)$$

As a result of this, the approximately relation on compressive strength of concrete and some other properties can be estimated (Erdoğan 2003). Where V is the velocity of the P wave (m/sec.), S is the distance between the surfaces of the concrete sent and received the waves (m) and t is the passing time (μsec.) of the P wave from one surface to the opposite surface of concrete tested (Erdoğan 2003; ASTM C 597 1994). This test was performed on cubic concrete specimens at three different ages (3, 28, 90 days).

Compressive Strength tests were applied on cubic concrete specimens, 150 mm x 150 mm x 150 mm, based on TS EN 12390-3 (2003). An automatic controlled press which had 3000 kN load capacity was used for this test. As for the splitting tensile strength tests, these tests were conducted on cylindrical concrete samples had sizes 150 mm diameter and 300 mm high at same ages with compressive strength and UPV tests. Splitting tensile strength tests were performed based on TS EN 12390-6 (2002).

2.4 Statistical Analysis

In the study, ANOVA and F-test were applied to be able to identify the importance levels of the experimental parameters on results obtained from the tests. Bigger F value indicates that the variations of the parameters cause the great changes on performance characteristics (Tosun and Cogun 2003; Tosun and Ozler 2004; Ross 1996).

In the ANOVA method, a loss function is used to be able to calculate the deviation between desired values and experimental results. In the other step, this loss function is transformed into a signal/noise (S/N) ratio to define the deviation of performance characteristic from the desired value. There are different generated S/N ratios based on characteristic type (Ross 1996). Having a high performance characteristic of concrete is determined by means of having some high characteristic properties like compressive, splitting tensile strengths and UPV value. For this reason, "Larger is Better: LB" is used as a loss function in the study. Formulations related this loss function and S/N ratio are given below.

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ijk}^{2}} \quad (2)$$

$$S/Nij=-10\log(Lij) \quad (3)$$

Where Lij is the loss function of performance characteristic i in the experiment j and n is the number of tests. As for the y, it expresses the experimental value of the performance characteristic i in the experiment j at the test k. Control parameters and their levels used for calculation of the S/N ratios are given Table 3.

Table 3. Control parameters and levels

	Level 1	Level 2	Level 3
Concrete type	KB	UKB	SDB
Curing age	3	28	90

3. Test Results and Discussion

3.1. UPV Test

Figure 1a gives the UPV test results for KB, UKB and SDB concrete series, respectively, at 3, 28 and 90 days. From the figure, it is clearly recognised that the velocity of the P waves which belong to concretes produced with different mineral admixtures shows different characteristic based on characteristic of the admixtures used in the concrete mix. The highest UPV values were obtained from the SDB followed by KB and UKB concrete series at 90 days, which indicates the effect of the filling and packing capacity of silica fume particles on UPV values. Since SF particles were much finer than Portland cement and FA, they filled the micro-pores in cement paste and the mechanical properties and durability of concrete were improved, by reducing permeability and porosity (Tasdemir 2003). Because of the weakness of FA activation and having rougher particle size than cement and SF, UKB concrete series did not show expected influence at early ages. On the other hand, FA has a reaction with free lime particles existed by hydration showed pozzolanic activity and filler effect at 90 days (http://www.fhwa.dot.gov/pavement/recycling/fach03.cfm). Therefore, UKB concrete series displays a sharper inclination between 28-90 days on the Figure 1a.

There is no any direct relation between concrete strength characteristic and the velocity of the P wave passing in the concrete. But there is an evident relation between concrete density and the velocity of the P wave. In a concrete has a low level of density, passing time of the P wave in the concrete is longer. In another words, the larger porosity percentage in the concrete means the smaller P wave velocity (Erdoğan TY (2003). Consequently, it can be sad that SDB concrete series has smaller porosity than the others. This circumstance may be clarified by SF particles has a big filler effect.

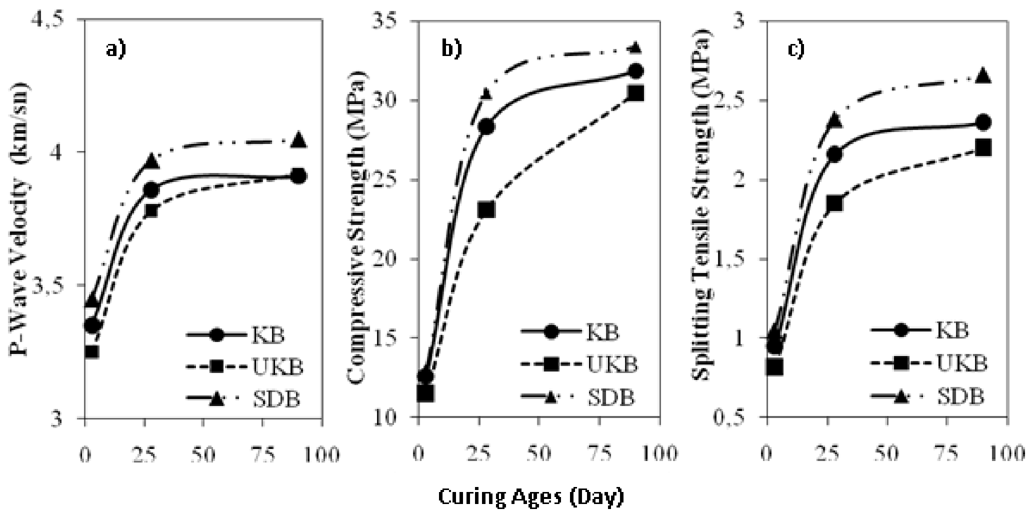

Figure 1. Curing Age-P wave velocity, compressive and splitting tensile strength graphs of concrete series

3.2. Compressive Strength Test

The concrete specimens which were sustainably designed with volcanic pumice and mineral admixtures were tested at the ages of 3, 28 and 90 days. In the results obtained from the tested specimen, ±2 N/mm^2 deviations occurred. The compressive strengths of the concrete series prepared and tested were given in the Figure 1b. In the Figure 1b, it can be seen that every single concrete series show normally increasing in their strength at each age. Although the concrete series show similar strength properties until 3 days age, especially after 28 curing days, the highest compressive strength was obtained from the SDB specimens and then KB concrete specimens while the lowest compressive strength properties was obtained from the UKB concrete samples. It is well known that silica fume contributes effectively to strength properties of the concretes in terms of pozzolanic activation even early ages. That result can be clarified by reaction of silica fume and free calcium-hydroxide in cement during cement hydration (Almussalam et al. 2004; Khatri and Sirivivathnanon 1995).

The compressive strength improvement of SDB series at 28 days is 7.5% higher than KB series. Even though Fly Ash used in the UKB series is sulpho-calcic and has high proportion of lime, SiO_2 dosage is markedly low in content. It is well known class C fly ash (having high level of lime; CaO>10%) has both pozzolanic activity and self-binding effect (Tokyay and Erdoğdu 1998). Though fly ash used in the study is not provide the provision "S+A+F>70%" indicated in Turkish Standard (TS 639), it is Class C fly ash based on ASTM C-618 (1994). It was also reported in an earlier research that fly ash used had a weak pozzolanic activity (Tokyay and Erdoğdu 1998). Besides, that fly ash was used at a high percentage (30%). For all these reasons, UKB series did not show sufficient compressive strength performance at early ages.

In Figure 1b, the highest compressive strength was obtained from the SDB series at the curing age of 90 days. KB and UKB series gave a very close compressive strength result to each other at the same age. The compressive strength improvement percentages of KB and UKB series are 12.4% and 31.7% at the end of 90 days, respectively. It is noticed that UKB series reflects the sharper strength improvement than others at 90 days because pozzolanic activity of fly ash is starting ultimate ages(http://www.fhwa.dot.gov/pavement/recycling/fach03.cfm).

It is seen from the Figure 1b that the compressive strength test results of all concrete series at 28 days are above 20 MPa. If it is considered that the limit for structural lightweight concrete is 17 MPa, the importance of these results is understood (Yasar 2003). In Turkey which is continuously under an earthquake risk, class C20 concrete is necessary in constructions at least. In this respect, the lowest compressive test result is in class LC20/22 while the highest compressive test result is in class LC25/28 based on TS EN 206-1. The weight of the normal strength concrete is approximately 2300 kg/m^3 for C20 concrete. On the other hand, the producing of sustainable lightweight concrete provides 20% lightness in weight (Yasar 2003). All these results are important not only for the earthquake and its destructive effect but also for the economy.

3.3. Splitting Tensile Strength Test

The splitting tensile strength test results of all the concrete series were given in Figure 1c. The figure shows that the splitting tensile strengths of all the concrete series increase as well as the compressive strength at the each curing age. From the result, it is determined that ±0.15 N/mm^2 of deviation is occurred. It is observed that the failure on samples during the tests occur on the surfaces of the samples at early ages while it occurs on the middle of the samples as a splitting after 28 days. Consequently, the failures in the samples formed between the aggregate and binder interface at early age although they occurred on the coarse aggregates in concretes during tests at advanced concrete ages. While the highest splitting tensile strength result was obtained from the SDB concrete series, the lowest was obtained from the UKB concrete series at 28 days. However, UKB series showed better splitting tensile strength improvement than KB series after 90 days.

3.4. Statistical Analysis Results

S/N ratios calculated for control parameters defined in chapter 2 were given in the Table 4. Furthermore, Figures 2-4 show the effect of control parameters on performance characteristics, the velocity of P wave, splitting tensile and compressive strength. Tables 5-7 show the ANOVA results of performance characteristics responded. As a general result, it is sad that experimental study findings are confirmed by statistically proving that characteristic properties of concrete are affected from the curing time and the admixture type used in the study. It is well known that the curing time and method has an important effect on characteristic properties of concrete. In this study, the relative importance percentages of the experimental parameters on the velocity of P wave, splitting tensile and compressive strength were calculated. As seen clearly from the ANOVA tables (Tables 5-7), different admixtures used in the study have an importance at the level of 3-6%. On the other hand, curing time has the utmost importance (94-96%) on performance characteristics.

Table 4. S/N ratios of factor levels

	P Wave Velocity			**Compressive Strength**			**Splitting Tensile Strength**		
Levels	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
Concrete Type	11,35	11,25	11,63	27,04	26,05	27,46	4,5606	3,4929	5,4467
Curing Age	10,53	11,75	11,95	21,83	28,66	30,06	-0,6172	6,5159	7,6014

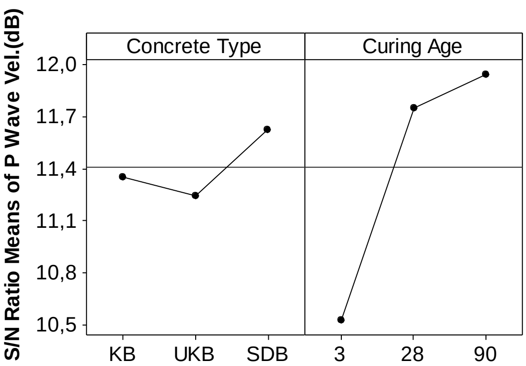

Figure 2. Main effects plot of P wave velocity for S/N ratios

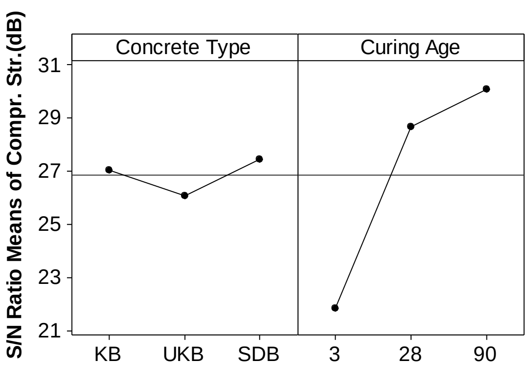

Figure 3. Main effects plot of compressive strength for S/N ratios

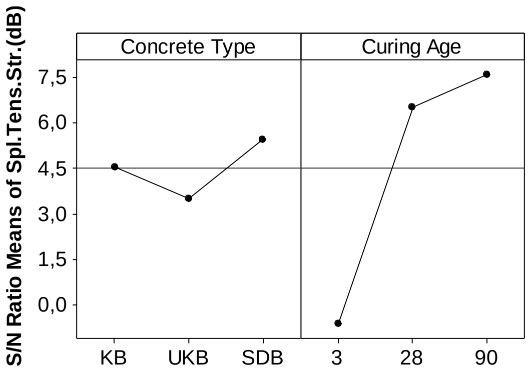

Figure 4. Main effects plot of splitting tensile strength for S/N ratios

As shown from the Figures 2-4, maximum values for performance characteristics can be obtained by using silica fume in the mix and at 90 days of the curing time. Although UKB series gave experimentally good result at 90 days, it gave statistically minimum values. However, UKB series has very close place to the average line in the Figures 2-4. This result indicates that the fly ash causing a big environmental pollution will be able to use in lightweight concrete mix as a sustainable material.

Table 5. The results of ANOVA for P-wave velocity

Control Factors	Degrees of Freedom	Sum of Seq.	Variance	F	Contribution Effect (%)
Concrete Type	2	0,2331	0,1165	49,52	6
Curing Age	2	3,5610	1,7805	756,62	93,7
Error	4	0,0094	0,0023	-	0,3
Total	8	3,8035	-	-	100

Table 6. The results of ANOVA for compressive strength

Control Factors	Degrees of Freedom	Sum of Seq.	Variance	F	Contribution Effect (%)
Concrete Type	2	3,12	1,5602	7,23	3
Curing Age	2	116,536	58,2678	270,14	96
Error	4	0,863	0,2157	-	1
Total	8	120,519	-	-	100

Table 7. The results of ANOVA for splitting tensile strength

Control Factors	Degrees of Freedom	Sum of Seq.	Variance	F	Contribution Effect (%)
Concrete Type	2	5,742	2,8711	67,34	4,6
Curing Age	2	119,604	59,8019	1402,59	95,3
Error	4	0,171	0,0426	-	0,1
Total	8	125,516	-	-	100

4. Conclusion

Based on the all gathering results, it was realised that the volcanic pumice obtained from Elazig in Turkey can be used as a sustainable aggregate material to produce lightweight concrete. Trough this way, not only the death weight of the buildings will be able to be decreased but also designed concrete members having smaller cross sections. As result of this, the consumption rate of the cement and steel used in concrete production will decrease. Usage of silica fume in the production of sustainable structural lightweight concrete has increased the performance characteristic of the concrete, but the production has been a bit expensive. On the other hand, usage of fly ash in production has been more economic and environment friendly. The statistically maximum results were obtained from the maximum curing time and usage of silica fume admixture. Concrete strengths were obtained in the class of LC25/28 by using volcanic pumice and mineral admixtures. The sustainable structural lightweight concrete designed in that class is both in suitable limitation in terms of earthquake damage and beneficial against to its damageable effects in terms of lightness advantage of lightweight concrete.

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