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INVESTIGATION OF MECHANICAL PROPERTIES OF HIGH-PERFORMANCE LIGHTWEIGHT CONCRETE WITH PUMICE AGGREGATE

ABSTRACT

Traditional concretes, which have a lot of usage in practice, have huge unit weights. Lightweight concretes have less weight than traditional concretes. By using lightweight concrete in the reinforced concrete structures, the total amount of concrete to be used in the buildings can be reduced, the buildings can be lightened, and the total weight of the building can be reduced. High-performance concrete is needed to build permanent and long-lasting structures. The aim of this study is to assess comprehensively the previous studies on high-strength lightweight concrete and to present a different perspective for this subject. In the present study, the mechanical properties of high-performance lightweight concretes with different mixing ratios were examined. Compressive strengths of traditional concretes and lightweight concretes were compared. In addition, the compressive strengths of the concrete specimens produced in the building materials laboratory were tried to be estimated by the statistical analysis. A good fitting was obtained between the experimental and the predicted results.

Keywords: High-Performance Lightweight Concrete, Mechanical Properties, Compressive Strength, Statistical Analysis

1. INTRODUCTION

Lightweight concrete is a type of concrete obtained by using lightweight aggregate derived from nature. ASTM, ACI, TSE and other similar standards define lightweight concrete as concretes with a dry unit value weight less than $2.0 g/cm^3$ produced using lightweight aggregates such as perlite, pumice, clay, shale, and schist. Lightweight concretes with a compressive strength of up to 6.89MPa is defined as low density concretes, those having a compressive strength of 6.89-17.24MPa are defined as moderate strength concretes (fill concretes) and those with a compressive strength of 17.24-41.36MPa and higher are defined as structural lightweight concrete [1].

The first use of lightweight concretes dates back to the Roman period B.C. The lightweight concretes made with lightweight aggregates in those periods continued to exist until today. The Sumerians and the Romans used the lightweight concretes in building construction in the 3rd century B.C. Hagia Sophia in Istanbul, St. Sofia Cathedral, the

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Temple of Pantheon, and the Coliseum can be shown as the examples of the oldest buildings ever made with the lightweight concrete [2 and 3].

Considering the structural applications, lightweight aggregate concretes have the advantages of being extremely light, providing heat and sound insulation, and being resistant to fire [4, 5]. The potential of these concretes in structural applications is of critical importance, especially if it provides sufficient strength performance comparable to traditional normal concretes. The lightness of lightweight aggregate concretes gives engineers flexibility in their designs. Important features such as thin section and reduced size structural elements, less foundation cost, increased performance against seismic effects, and heat and acoustic insulation performance are obtained by reducing the self-weights of the structures. However, because the mechanical and physical properties of the concretes are directly related to the properties of the aggregates they contain, the lightweight aggregate concretes may be in a more negative condition in terms of their elastic properties, even if they reach a sufficient strength level [6]. For concretes to be light and high performance, their compositions should be determined. Pumice is most common lightweight aggregate material in Turkey due to its abundant reserves. The use of pumice as building material becomes increasingly common in Turkey. However, it is not possible to produce high-performance lightweight concrete with the use of pumice alone. As with other high-performance concretes, it is necessary to use chemical and mineral additives [7].

Carrier lightweight concrete is a special type of concrete that has been used for structural purposes especially in recent years. Today, carrier lightweight concretes are used especially for reducing the self-weight of a building and the weights of reinforced concrete structural elements to be used. Accordingly, especially the effective use areas and spaces of high structures can be increased [8]. In addition, carrier lightweight concretes are mostly used in the construction of wall panels and blocks and in attic floors, bridge gaps, and precast concrete units. For these purposes, the carrier lightweight concrete is preferred to construct structures especially in earthquake zones [9]. The investment costs will be reduced as the light and delicate structures are built to replace heavy and bulky structures. In addition, since there will be a low pressure in the concrete mold because of the reduction of the total material weight per unit volume, the production and installation process will be easier [10]. It was determined that the self-weight of the structure and the reinforcement area to be used would decrease by using the lightweight aggregate in concrete. Since the effect of the earthquake on a building is proportional to the weight of that building, the risk of collapse will be reduced too. Today, the increase in the risk of earthquake has increased the interest in the carrier light concrete [11 and 12]. The total amount of concrete to be used will be reduced and the buildings will be lightened with the use of high-performance lightweight concrete (HPLC) instead of normal concrete and the use of higher-class concretes in buildings. The use of HPLCs as a carrier element is extremely important. The carrier properties should be known for this. For this reason, it is necessary to determine the bearing capacities of the carrier systems such as beams, columns, curtains to be constructed by the HPLC and their behaviors of the carrier frameworks under lateral loads [13 and 14]

2. RESEARCH SIGNIFICANCE

The high-performance lightweight concrete is a new and current issue in the structural engineering. Today, because of the increasing need for high-performance lightweight concrete, the gap about this subject in the literature will be tried to be filled with the present study. The aim of the present study is to make a detailed literature review about the high-strength lightweight concrete and to analyze the subject with the statistical analysis by using the previous experimental study data. It is aimed to determine the compressive strength of pumice aggregated high strength lightweight concrete with high accuracy with the equation developed. Thus, the compressive strength of the samples with a certain mixture content will be determined and the labor and time savings will be ensured.

3. HIGH STRENGTH LIGHTWEIGHT CONCRETES

The properties of high strength concrete depend on the aggregate type, the cavity structure of the cement paste, and the aggregate-cement paste transition zone. Since the transition zone from these parameters is weaker compared to others, this zone needs to be improved in order to produce high strength concrete. For this, the *w/c* ratio must be reduced by using a super plasticizer and the maximum grain diameter of the aggregate must be lowered. In addition, it is necessary to prevent the formation of $Ca(OH)_2$ crystals found in the concrete structure, which show easy fragility. Using active pozzolans such as fly ash or silica fume to prevent the formation of $Ca(OH)_2$ crystals will be sufficient to obtain the high strength concrete [15].

Although the concepts of high strength concrete and high-performance concrete seem close to each other, they actually define different situations. The performance criterion aimed for the high strength concrete is the compressive strength. However, the targeted performance criteria aimed for the high-performance concrete are much beyond the compressive strength. The high-performance concrete is designed according to many performance criteria such as elasticity module, creep, shrinkage, fire resistance, freeze-thaw resistance, volumetric stability, high early strength, toughness, abrasion resistance and so on.

Bridges that need to be resistant to external influences and open sea platforms are the primary structures that require high performance concrete. The expanded clay aggregate was used to increase the buoyancy of water in the construction of the Heidron floating offshore platform (Figure 1a) built in 1996. Here, the water/binder ratio was 0.37, the unit volume weight was 1940kg/m^3, and the compressive strength was 79 MPa. An example of the structures where the high-performance lightweight concrete was used is the New Benica-Martinez Bridge built in 2007 in California, where there is a high earthquake effect (Figure 1b). The beam segments of this bridge were constructed with the artificial lightweight aggregate concrete. Thus, the most economical method was chosen, and the bridge was lightened against the weak ground conditions and the earthquake effect. Thus, it was also become possible to reduce the number and size of the bridge pillars. For this bridge, 1965kg/m^3 unit volume weight, 26.2GPa elasticity modulus, and 75MPa compressive strength were obtained. In New Zealand, which is highly risky in terms of earthquakes, an expanded schist aggregate (water absorption ratio 7-8%) was used for the Wellington Stadium (Figure 1c) built in 2000. A concrete strength of 35MPa and an elasticity module of 19.1GPa were targeted for this stadium. In addition, the Bank of America Corporate Center (Figure 1d), built in 1992 with high-strength lightweight concrete, was constructed on the principle of green building. In this building, a unit volume weight of 1890kg/m^3 and a fire resistance of 3 hours were taken as basis, and average compressive strength was obtained as 47MPa [16].

(a) (b) (c) (d)

Figure 1. Some high-performance concrete applications in the world:
(a) Heidrun Offshore Oil Platform,
(b) New Benicia Martinez Bridge,
(c) Wellington (Westpac Trust) Stadium,
(d) Bank of America Corporate Center [16]

4. PUMICE AGGREGATE

Pumice is mostly used in construction sector in Turkey and the world. Eighty percent of the pumice produced in Turkey is used as the lightweight concrete aggregate in the construction sector in the domestic market. The use of pumice in the construction sector has been increasing rapidly in recent years, as it does not require energy and investment to expand. The main reason for the preference of pumice is that it has a density of 33-66% of normal sand and gravel. Because the concrete produced with pumice is lighter than normal concrete, it saves time and labor. In addition, in terms of soil mechanics, 17% of the reinforcing bars is saved considering the loads are transferred to the foundation. Considering the thermal conductivity coefficient of pumice, it is seen that it has 6 times more isolation than the normal concrete [17].

It is emphasized that, with the lightweight concrete produced by pumice aggregate, besides the opportunity of making constructions in low carrying capacity floors, high, economical, low cost, high thermal insulated and durable buildings can be erected. It was also stated that the light concrete produced with pumice aggregate could be developed for protection against radiation by the addition of colemanite [18]. Pumice is most common lightweight aggregate material in Turkey because of its abundant reserves in our country. The appearance of the pumice aggregate in the quarry is presented in Figure 2.

Figure 2. Images of the pumice quarry in Elazığ organized industrial zone

5. DATA FROM THE LITERATURE AND THE STATISTICAL ANALYSIS

When the studies in the literature are reviewed, it is seen that Normal Portland PC 42.5 is the cement that is mostly used in constructions. However, many researchers preferred pumice as aggregate in high strength lightweight concrete production in their studies. This is because the visible reserve of pumice aggregates in Turkey is high and the unit volume weight is low. One of the high-strength lightweight concrete components is fly ash. Fly ash, which provides the reduction of water demand, provides high strength, low hydration temperature and high final strength values. Silica fume, which is used as a mineral additive, also provides high strength in the concrete. In addition, a high strength is achieved in the concrete by using a high water-reducing super plasticizing chemical additive.

The experimental data of high strength lightweight concretes obtained in the literature by using pumice aggregate were used in the present study. In this section, the materials used for the production of concrete and the mixture designs in these studies are presented in Table 1.

A non-linear equation has been developed for the compressive strength by using data of relevant studies in the literature. In the present study, the compressive strengths (f_c) of high strength lightweight concrete obtained by using pumice aggregate, silica fume and fly ash in the literature were analyzed with the Statistica 8.0 program and the Equation (1) was developed. In the method developed by using the related software program, the experimental data of the f_c and the values of the parameters which it is affiliated to were entered into the program. For the numerical estimation of the f_c, the coefficients of the relevant parameters in the equations entered in the program were determined by the program. The equation which gave the best correlation coefficient (R^2) was taken into account.

$f_c = (C\times0.069)+(FA\times0.086)+(SF\times0.172)+(W\times0.017)+(PA\times(-0.008))+(SA\times0.212)$ (1)

where

f_c=compressive strength (MPa),

C=cement content (kg/m^3),

FA=fly ash content (kg/m^3),

SF=silica fume content (kg/m^3),

W=water content (kg/m^3),

PA=pumice aggregate content (kg/m^3) and

SA=super plasticizer content (kg/m^3).

Table 1 shows the predicted f_c values obtained from the Equation (1) developed by the Statistical method in the present study.

Table 1. Mixture designs of the mentioned studies, and measured f_c and calculated f_c values

	C (kg/m^3)	FA (kg/m^3)	SF (kg/m^3)	W (kg/m^3)	PA (kg/m^3)	SA (kg/m^3)	f_c (measured) (MPa)	f_c (calculated) (MPa)
[19]	519	0	74	276	1245	0	45.60	43.27
	498	0	71	226	1181	0	42.40	40.97
	474	0	68	246	1036	0	39.40	40.30
	446	0	64	257	1165	0	36.50	36.83
	406	0	58	263	1138	0	33.80	33.36
[20]	500	0	0	275	1250	0	28.00	29.18
	400	100	0	275	1250	0	29.20	30.88
	450	0	50	275	1250	0	38.90	34.33
	350	100	50	275	1250	0	36.80	36.03
[12]	500	0	0	275	1250	0	28.00	29.18
	400	100	0	275	1250	0	29.00	30.88
[21]	500	0	0	275	1250	0	28.00	29.18
	350	100	50	275	1250	0	37.00	36.03
[22]	440	0	0	281	881	0	26.10	28.09
	375	0	0	293	938	0	21.60	23.35
	320	0	0	291	960	0	19.20	19.35
	280	0	0	300	980	0	16.60	16.58
	245	0	0	301	980	0	14.60	14.18
[23]	350	0	0	0	1235	3.5	16.50	15.01
	332.5	0	17.5	0	1230	3.5	17.20	16.85
	315	0	35	0	1227	3.5	19.10	18.68
	297.5	0	52.5	0	1221	3.5	20.20	20.53
	280	0	70	0	1218	3.5	18.70	22.36
[24]	450	0	50	175	1253	4.5	31.00	33.55
[25]	500	0	0	210	1444	7.5	29.50	28.11
	450	0	50	189	1429	7.5	32.60	33.02
	425	0	75	178.5	1419	7.5	33.90	35.50
	450	50	0	175.5	1470	7.5	31.00	28.16
	425	75	0	165.8	1461	7.5	29.70	28.50
	400	100	0	156	1454	7.5	28.70	28.81
	400	50	50	156	1453	7.5	31.20	33.12

6. EVALUATION OF THE STATISTICAL ANALYSIS

This section discusses the accuracy of the equation developed with the statistical method. In Figure 3, the data of the said experimental studies and empirical formula obtained from the present study were compared with the f_c values calculated by Equation (1). Accordingly, when the results obtained for the compressive strength (f_c) were compared, it was seen that there was a deviation of approximately 4.7% on the average. As a result, it is seen that the values determined by the equation are consistent with the values obtained from the experimental studies in the literature.

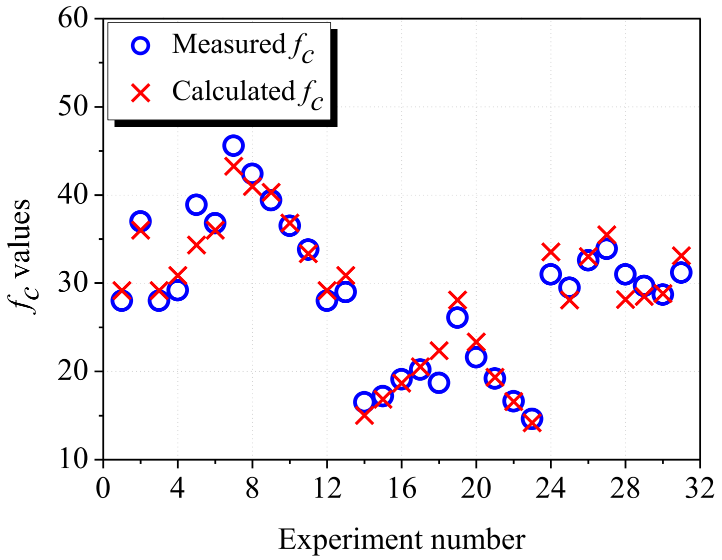

Figure 3. Variation of f_c with experiment number for the present study and related studies

The correlation coefficient was determined as R^2=0.96. It is seen that the data mostly coincides with a perfect line. Therefore, the measured and calculated f_c values were consistent as demonstrated in Figure 4. Thus, the equation (1) was considered safe to use.

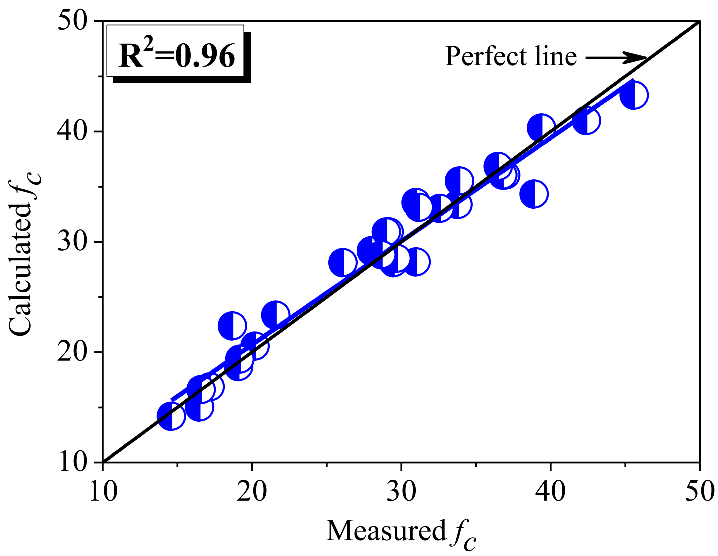

Figure 4. Comparison of measured and calculated f_c values for the present study and related studies

Figure 5 presents the frequency distribution of the differences between the values measured in the experiments and the values calculated by Equation (1). Accordingly, it is seen that the deviation values mostly vary between -2.0 and +2.0. For the remaining values, the expected normal curve appears to be very close to the horizontal axis. This indicates that Equation (1) has very high accuracy.

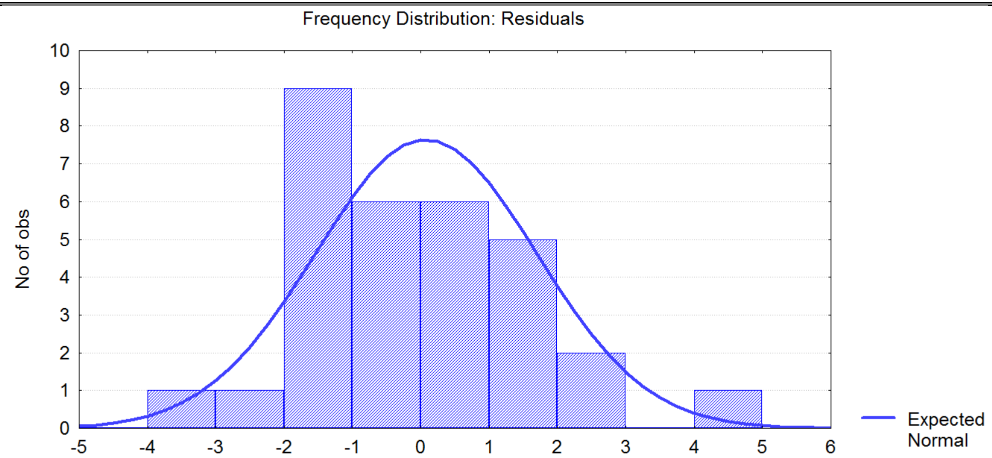

Figure 5. Frequency distribution for compressive strength (f_c) for the present study and related studies

Similarly, Figure 6 shows that Equation (1) gives very close results to the experimental results. It is seen that the deviation values are mostly concentrated around the zero line and very little deviations are observed. It is also seen that the observed deviation values are mostly close to the zero axis.

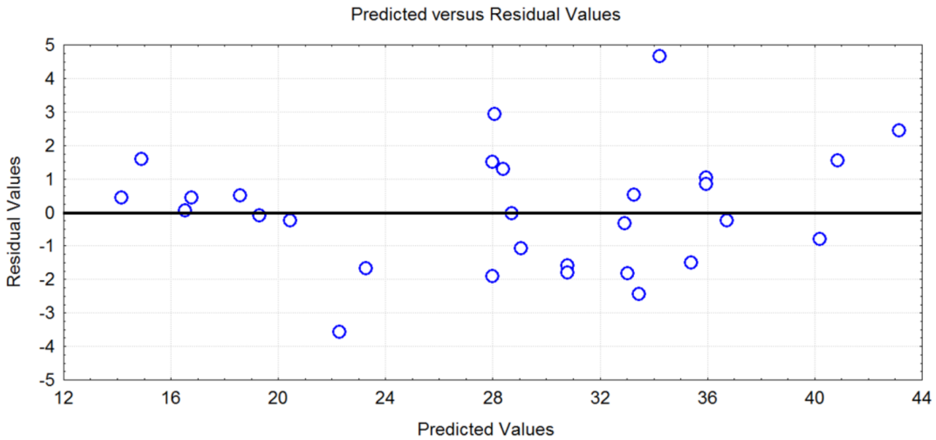

Figure 6. Comparison of predicted and residual f_c values for the present study and related studies

7. CONCLUSIONS

The conclusions of the present study are summarized below:

- The compressive strengths of the high strength lightweight concrete samples produced were tried to be predicted by the statistical analysis. A good fit was obtained between the experimental results and the predicted results.
- As a result of this study, there was a difference of approximately 4.7% on the average between the predicted results obtained by using the equation developed in this study and the experimental results. This result shows that the method developed can be used safely for high strength lightweight concretes produced with pumice aggregates.
- It is seen that the deviations between the results obtained from the developed equation and the results of these experimental studies are mostly between -2.0 and +2.0.

- By using the method developed, the compressive strengths of high strength lightweight concretes with pumice aggregates can be determined with a high accuracy.
- Thus, the labor and time savings will be ensured.

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