

Ultra-Lightweight EPS Concrete: Mixing Procedure and Predictive Models for Compressive Strength

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Received July 23, 2020; Revised August 31, 2020; Accepted September 29, 2020

Cite This Paper in the following Citation Styles

(a): [1] Fayez Moutassem, "Ultra-Lightweight EPS Concrete: Mixing Procedure and Predictive Models for Compressive Strength," *Civil Engineering and Architecture*, Vol. 8, No. 5, pp. 963 - 972, 2020. DOI: 10.13189/cea.2020.080523.

(b): Fayez Moutassem (2020). *Ultra-Lightweight EPS Concrete: Mixing Procedure and Predictive Models for Compressive Strength*. *Civil Engineering and Architecture*, 8(5), 963 - 972. DOI: 10.13189/cea.2020.080523.

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Abstract Expanded polystyrene (EPS) lightweight concrete is increasingly used in various applications due to its lightweight, excellent heat preservation, sound insulation and energy absorbing characteristics. However, due to the hydrophobic nature and very low density of EPS beads, EPS concretes are prone to segregation, poor bonding, and homogeneity issues. The properties of EPS concrete are highly dependent on the mixture proportions and mixing procedure. This study involves the development of a quality mixing procedure for Ultra-lightweight EPS concrete and the development of two predictive compressive strength models function of concrete mixture and density, respectively. An experimental program is developed to implement the mixing procedure and to calibrate and evaluate the accuracy of the models. The proposed models were found to accurately predict the strength of concrete mixtures. The corresponding standard error for the models is less than 0.3 MPa and the corresponding correlation coefficient is greater than 0.93. To ensure quality control before concrete is cast, a link between the plastic density of fresh concrete and the compressive strength was established. Furthermore, to accommodate tight construction schedules, the effects of concrete age on the compressive strength development were studied and the 28-day strength was related to strengths at early ages.

Keywords EPS Concrete, Lightweight Concrete, Foamed Concrete, Expanded Polystyrene, Compressive Strength, Density, Mixture Proportioning, Mixing Procedure

1. Introduction

There is a growing interest in using alternative sustainable and economical materials. Expanded polystyrene (EPS) is normally used as a packaging material due to its low density, hydrophobic properties, good thermal insulation, low absorption, and low cost. The yearly global production of polystyrene is over fourteen million tons and a very significant quantity of EPS ends up as waste materials that are sent to landfills, which are of limited space [1,2]. EPS concrete is increasingly being used in various applications in the construction industry and other industries mainly due to its lightweight, excellent heat preservation and sound insulation [1,3]. It can be used as base coarse materials for pavements, construction materials for cladding panels, lightweight partition walls, floating marine structures, sea beds, an energy-absorbing material for protection of buried military structures, and fenders for offshore oil platforms [4, 5, 6, 7, 8]. Ultra-lightweight EPS concrete is produced by fully replacing the normal aggregates (fine and coarse) with EPS beads and using other materials/admixtures to ensure proper bonding, high flowability, good stability and good surface finish.

The hydrophobic nature and very low-density of EPS beads can be a disadvantage when used in concrete because EPS concrete will be prone to segregation and poor bonding in comparison with normal weight concretes [9]. The significantly lower stiffness of the EPS aggregates in comparison with the cement paste will cause varying stress distributions inside the concrete. In addition, there is a difference between the failure pattern and the interfacial

transition zone (ITZ) for EPS concrete in comparison with normal weight concrete. Unlike EPS concrete, failure of normal weight concretes occurs around the aggregate particles because the tensile strength of aggregates is higher than that of the surrounding cement paste [2]. Because of the low bond between the EPS and the cement paste, and hydrophobic nature and low mechanical strength of EPS beads, there is a significant decrease in the compressive strength of EPS concretes [7,10,11]. The properties of EPS concrete are highly dependent on the mixture proportions and mixing procedure. Therefore, understanding the behavior of fresh EPS concrete and following a proper mixing process can significantly improve its quality, homogeneity, stability, and avoid segregation. Furthermore, adding silica fume as a cement replacement provides mixtures that are more cohesive and less prone to segregation [12].

Research studies have shown that the density of EPS concrete significantly affects its compressive strength and that compressive strength is more sensitive to the density compared to tensile strength and modulus of elasticity [13]. Multiple previous studies have shown that the density of lightweight concrete is the most significant property influencing its compressive strength where an increase in density results in a higher compressive strength [7,14,15,16]. Research has shown that the compressive strength of EPS concrete increases with a decrease in EPS bead size, for the same concrete density. However, for lower EPS concrete densities, it was observed that EPS bead size's influence on the lightweight concrete compressive strength becomes negligible [17].

Therefore, based on previous studies, there is a further need to minimize the lack of homogeneity and stability issues encountered through proper mixture proportioning and mixing design process. Since the EPS concrete behavior and failure pattern are different from normal concretes, the models developed to predict the compressive strength of normal concretes should not be used and specific models should be developed for EPS concrete. Accurate prediction of the compressive strength of EPS concrete before concrete is cast is needed for appropriate design of EPS concrete mixtures and for quality control purposes. This study involves the development of a quality mixing procedure for EPS concrete and the development of two predictive compressive strength models function of concrete mixture and density, respectively. An experimental program is developed to implement the mixing procedure and to calibrate and evaluate the accuracy of the strength models. Furthermore, to ensure quality control before concrete is cast, a link between the plastic density of fresh concrete and the compressive strength of hardened concrete needs to be established.

2. Experimental Program

2.1. Materials

This section presents the details for all materials used in concrete mixtures including their technical properties. A total 30 mixtures were fabricated. ASTM Type I ordinary Portland cement (OPC) was used for all concrete mixtures. The chemical and physical properties of the cement are summarized in Table 1. Condensed silica fume (ELKEM 920D) with a 28-day compressive strength of 56 MPa and meeting the ASTM requirements was used as cement replacement for 11 mixtures. Commercially available Grey colored spherical EPS beads (NEOPOR F 5300- BASF) as shown in Figure 1 were used for all mixtures. EPS beads size was 2.5-3.5 mm and bulk density was 15-20 kg/m³. Polycarboxylate-based High-Range Water Reducers (HRWR) were used to produce highly flowable concrete mixtures. A foaming admixture (FA) was used for 24 mixtures and an air-entraining admixture (AA) was used for 6 mixtures. A latex-based bonding agent (Planicrete SP- MAPEI) was used for all mixtures to improve the bonding between EPS beads and the paste.

Table 1. Chemical and Physical Properties of OPC

Properties	% of Weight
SiO ₂ (%)	19.5
Al ₂ O ₃ (%)	4.69
Fe ₂ O ₃ (%)	3.70
CaO (%)	63.3
MgO (%)	1.46
SO ₃ (%)	2.58
Loss on Ignition (%)	3.59
Equivalent Alkalies (%)	0.54
Specific Surface Area (Blaine) (m ² /kg)	345
Soundness, Expansion (mm)	1.10
Time of Setting-Initial (min)	160
Compressive Strength – 28 Days (MPa)	47.6



Figure 1. EPS Beads (NEOPOR F 5300) – Grey Color

Table 2. Concrete Mixture Design Composition

Mix #	w/c	EPS (kg/m ³)	OPC (kg/m ³)	SF (kg/m ³)	High-Range Water Reducer (kg/m ³)	Air Agent (kg/m ³)	Type
1	0.24	13.8	744	0	4.10	0.0	-
2	0.25	14.0	550	0	9.60	3.0	AA
3	0.30	14.0	500	0	5.80	3.1	FA
4	0.30	14.0	500	0	4.15	2.1	FA
5	0.30	14.0	500	0	6.00	2.0	FA
6	0.30	14.0	500	0	5.80	3.1	FA
7	0.30	14.0	450	0	3.05	3.0	FA
8	0.33	15.2	400	0	1.52	3.5	FA
9	0.30	14.8	450	0	2.65	3.5	FA
10	0.30	14.8	450	0	3.20	3.0	FA
11	0.30	14.8	450	0	2.70	3.0	FA
12	0.30	14.8	450	0	1.80	3.0	FA
13	0.30	14.8	450	0	2.50	3.5	FA
14	0.30	13.9	430	0	2.50	3.3	FA
15	0.30	13.9	430	0	1.50	3.3	FA
16	0.30	13.9	430	0	1.25	3.3	FA
17	0.30	13.9	430	0	1.25	3.3	FA
18	0.30	13.9	430	0	3.15	8.8	AA
19	0.30	13.7	407	23	5.90	7.0	AA
20	0.30	13.8	407	23	1.75	7.0	AA
21	0.30	13.7	407	23	5.00	3.0	FA
22	0.30	13.8	407	23	2.18	3.5	FA
23	0.28	14.0	407	23	2.00	7.0	AA
24	0.30	13.8	407	23	1.98	7.0	AA
25	0.30	13.8	407	23	2.18	3.0	FA
26	0.30	13.8	407	23	2.18	3.5	FA
27	0.30	13.8	407	23	2.15	2.5	FA
28	0.30	13.8	407	23	2.13	2.0	FA
29	0.32	14.9	350	0	2.20	1.5	FA
30	0.32	13.5	325	30	2.20	1.5	FA

2.2. Mixture Proportions

The design variables used in proportioning the concrete mixtures include the water-to-cementing materials ratio, cementing materials content, which includes OPC and Silica Fume, amount of EPS beads, amount of air entrainment, and amount of HRWR. The range selected for w/c was from 0.24 to 0.33. The water content values ranged from 112 to 179 kg/m³. The cementing materials content ranged from 350 to 744 kg/m³. Amount of EPS beads

ranged from 13.5 to 15.3 kg/m³ (56 to 63% by volume). The amount of bonding agent was 4 kg/m³ for all mixes. Amounts of air entrainment and superplasticizers were varied to produce highly flowable low-density mixtures. Corresponding proportions for the 30 mixtures are given in Table 2.

2.3. Proposed Mixing Procedure

Mixing was performed in a horizontal pan mixer in the

laboratory. It is well known that EPS concrete is prone to segregation mainly because of the EPS beads, which are very low in density and high in volume fraction. Accordingly, in this study, the ideal mixing process and sequence was investigated and varied in order to produce high quality homogeneous mixtures and avoid segregation.

The proposed mixing procedure is as follows:

1. Add the EPS beads to the mixer
2. Add the bonding agent to 1/3 of the water and mix them together.
3. Pour it into the mixer and mix for 3 minutes. Note that wetting of the EPS beads with part of the mixing water and bonding agent is essential to ensure proper bonding with the rest of the materials and because the interfacial zone between cement paste and the EPS beads play a critical role in determining mechanical properties of concrete.
4. Pour the cementing materials and mix for 4 minutes
5. Add the foaming agent or air entrainer to the remaining water and mix them thoroughly for 1 minute.
6. Slowly pour it into to the mixer and mix for 2 minutes.
7. Add water reducer as needed to produce high workability and mix for 1.5 minutes.
8. Check the Slump. If the slump is as needed then proceed to concrete casting

2.4. Casting, Curing and Testing

Concrete casting, curing and testing was consistent for all of the concrete mixtures. The fresh concrete densities and slump values were measured immediately after mixing for all the concretes ASTM C138 and ASTM C143 respectively [18,19]. The concrete specimens were cast in steel molds, followed immediately by curing at room temperature for 24 h before being demolded. After demolding, the specimens were cured in lime-saturated water up to the date of testing. The density of hardened EPS concrete test was conducted in accordance with

ASTM C567 [20] at the age of 28 days. The compressive strength of hardened EPS concrete was measured on cube specimens (150 mm x 150 mm x 150 mm) at the age of 1, 7 and 28 days.

2.5. Calibration and Validation Procedure

The proposed models require determining of the calibration constants. Model Calibration was carried out by minimizing the standard error (σ) between the model predictions and the measured experimental data. The standard error, which provides a global assessment of the model predictions, is defined in Equation 1 [21]:

$$\sigma = \{\Sigma[f^c_{c_m}(i) - f^c_{c_{exp}}(i)]^2 / (n - p)\}^{1/2} \quad (1)$$

Where parameters $f^c_{c_m}(i)$ and $f^c_{c_{exp}}(i)$ refer to the model and experimental compressive strength values that correspond to mix i , respectively. Parameters n and p refer to the number of tested points and the number of model constants, respectively. This application provides an assessment of the goodness of fit and the soundness of the proposed model. In addition, the correlation coefficient (R^2), which provides a measure of the proportion of model variability, was also calculated. Such measures permit assessment of the capabilities of the proposed model in predicting the trends reported in the literature.

3. Results, Discussion, and Proposed Models

3.1. Experimental Testing Results

Table 3 presents the experimental results for each mix, which includes values for the slump, air content, fresh density, hardened density, and compressive strength at 1, 7 and 28 days. The following sections will discuss the relevancy of the results obtained, and present and discuss the calibration and accuracy of the proposed compressive strength models.

Table 3. Results of Experimental Testing

Mix #	Slump (mm)	Air (%)	Fresh Density (kg/m ³)	Hardened Density (kg/m ³)	f'_{c1d} (MPa)	f'_{c7d} (MPa)	f'_{c28d} (MPa)
1	70	-	978	996	4.32	7.05	7.79
2	40	6	788	794	2.69	3.46	5.16
3	150	11	764	759	1.93	3.58	3.99
4	220	15	622	629	1.17	2.78	3.16
5	240	11	669	646	1.64	2.35	3.45
6	260	16	634	634	1.09	1.84	2.57
7	230	13	679	691	1.52	3.05	3.78
8	240	21	490	458	0.64	1.22	1.45
9	245	16	541	533	0.96	1.72	2.20
10	275	14	604	576	0.79	1.45	2.63
11	265	25	503	478	0.88	1.71	1.65
12	240	20	527	554	1.24	2.21	2.83
13	240	20	560	480	0.94	1.88	2.26
14	255	19	547	585	1.25	2.20	2.72
15	260	17	551	521	1.12	1.98	2.08
16	235	14	644	561	0.97	2.08	2.72
17	245	15	664	555	1.03	1.87	2.52
18	220	17	588	605	1.22	2.22	2.86
19	230	13	669	595	1.40	2.78	2.82
20	220	15	625	538	1.27	2.13	2.40
21	220	11	661	706	1.46	2.77	3.51
22	225	18	574	568	1.08	2.02	2.55
23	230	10	706	691	1.77	2.76	3.31
24	230	9	697	680	1.67	2.73	3.28
25	225	17	580	608	1.00	2.54	2.57
26	230	15	587	533	0.87	2.50	2.35
27	245	20	509	509	1.07	1.62	2.21
28	240	20	578	500	0.66	1.96	1.87
29	240	18	528	478	0.52	1.32	1.75
30	240	22	544	473	0.53	1.53	1.91

3.2. Workability and Surface Finish

The workability of fresh concrete was evaluated in terms of the slump test. High workability was achieved for 28 mixtures to ensure ease of casting and placing. Mixtures 4 to 30 shown in Table 3 exhibited high flow characteristics with the slump values exceeding 220 mm. Figure 2 demonstrates the slump test performed for a typical mix and shows the high workability, consistency and stability

of the mixture. Good surface finish is very important for EPS concrete to ensure proper bonding with other materials especially if used as a core filling material such as for partition walls or other purposes. Figure 3 demonstrates the good surface finish of cast cubes for a typical mix. Good consistency, uniformity, stability and surface finish confirm the successful mix design and implementation of the proposed mixing procedure.



Figure 2. Consistency of a Typical EPS Concrete Mix

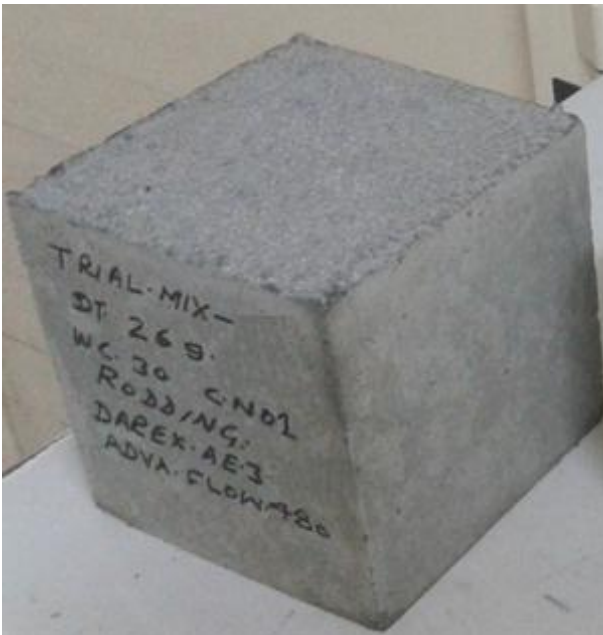


Figure 3. Surface Finish for EPS Concrete Cubes

3.3. Concrete Density

Density is one of the important parameters which can control many physical properties in EPS concrete [7,14,15]. The density and compressive strength of EPS concrete are dominated by the porosity of specimen, which is mainly controlled by the volume fraction of air (entrapped and entrained), capillary porosity which depends on the water to cementing materials ratio, and the volume fraction of the EPS beads which are of negligible density and strength. Accordingly, density (ρ) and compressive strength (f'_c) are

related to the mixture proportions using the following relationship proposed in this study (Equation 2):

$$\rho, f'_c \propto (w + a + eps) / cm \quad (2)$$

Where w , a , eps and cm are the volume fractions of water, air, EPS, and cementing materials in the concrete mix. The experimental values for densities (fresh and hardened) ranging from 458 to 996 kg/m³ are provided in Table 3 for each concrete mixture. Figure 4 shows the relationship between $(w+a+eps)/cm$ and the density of hardened concrete. As shown, an increase in the porosity results in a decrease in the density. An R^2 value of 0.86 confirms the high significance of this relationship on the density of concrete. Table 3 also shows that the fresh density exceeded the hardened density for 17 mixtures. Unlike the traditional concrete consisting of heavy aggregate, ultra-lightweight concrete consists of EPS aggregates with densities lower than the density of water. Any water not consumed during the hydration process would eventually evaporate leaving voids behind. The weight of the water lost may have a significant effect on the overall density of hardened ultra-lightweight concrete.

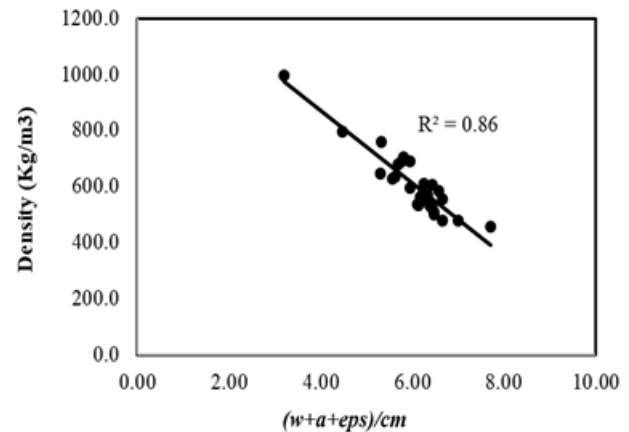


Figure 4. Relationship between Concrete Mixture and Density of Hardened Concrete

3.4. Compressive Strength

The 28-day compressive strength values (f'_{c28}) for the 30 concrete mixtures are given in Table 3. For the 30 mixtures, the maximum and minimum compressive strength values are 7.79 MPa and 1.45 MPa. Utilizing the dimensionless relationship presented in Equation 2 and applying statistical regression, it yields the following proposed fundamental model for predicting the compressive strength of lightweight EPS concrete as function of the mixture (Equation 3):

$$f'_c = A (B)^{(w + a + eps) / cm} \quad (3)$$

Where A and B are calibration constants. Calibration constant A depends on the type and strength of cement and its unit is in MPa (or psi). Calibration constant B is a dimensionless term, which depends on the specimen shape

and the test conditions. The values of these calibration constants are given in Table 4. These constants were determined by minimizing the model standard error between the model predictions and measured experimental values. Figure 5 shows the goodness of fit of the proposed model (function of mixture) in comparison to the measured experimental data. The corresponding standard error and correlation coefficient were 0.30 MPa and 0.93, respectively. The high degree of correlation and low standard error are evidence of the model's ability to predict the compressive strength of EPS concrete as a function of concrete mixture.

Multiple previous studies have shown that the density of light-weight concrete is the most significant property influencing its compressive strength [7,14,15,16]. Accordingly, the relationship between the density and compressive strength was investigated in this study. Using statistical regression, the following is the proposed fundamental model for predicting the compressive strength of lightweight EPS concrete as function of its hardened density (Equation 4):

$$f'_c = A (B) \rho^{1000} \tag{4}$$

Similarly, the calibration constant *A* depends on the type and strength of cement and its unit is in MPa (or psi), and the calibration constant *B*, a dimensionless term, depends on the specimen shape and the test conditions. The values of these calibration constants are given in Table 4. Figure 6 shows the goodness of fit of the proposed model (function of density) in comparison to the measured experimental data. The corresponding standard error and correlation coefficient were 0.25 MPa and 0.96, respectively. The high degree of correlation and low standard error are evidence of the model's ability to predict the compressive strength of EPS concrete as a function of its hardened density.

In addition to the proposed predictive models, this study establishes a link between the plastic density of fresh concrete and the compressive strength of hardened concrete. This is important to ensure quality control before concrete is cast. Figure 7 presents this relationship and shows the goodness of fit. The corresponding correlation coefficient is 0.86.

Table 4. Calibration of Proposed Compressive Strength

Models	<i>A</i>	<i>B</i>	σ	R^2
Compressive Strength (Function of Mixture)	25.8	0.69	0.30	0.93
Compressive Strength (Function of Density)	0.55	14.6	0.25	0.96

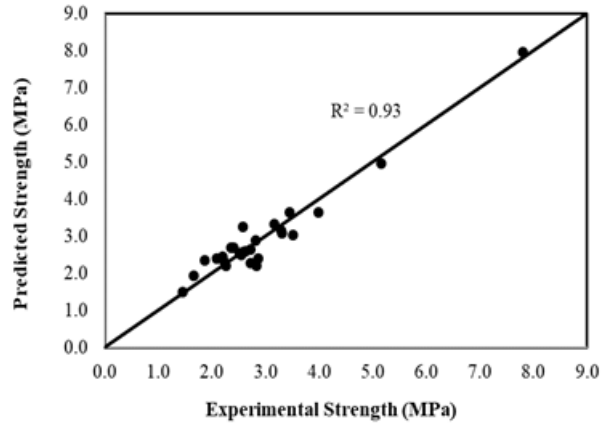


Figure 5. Compressive Strength Model (Function of Mixture) Vs. Experimental Values

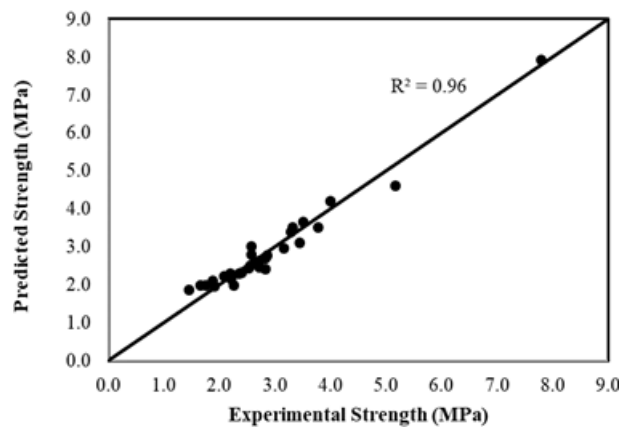


Figure 6. Compressive Strength Model (Function of Density) Vs. Experimental Values

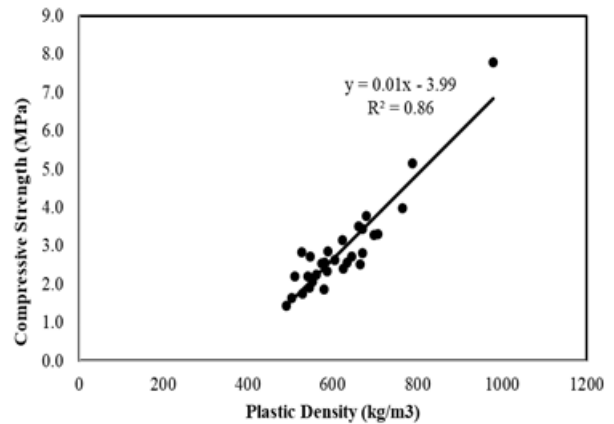


Figure 7. Relationship between Plastic Density and Compressive Strength

3.5. Rate of Strength Development and Concrete Age

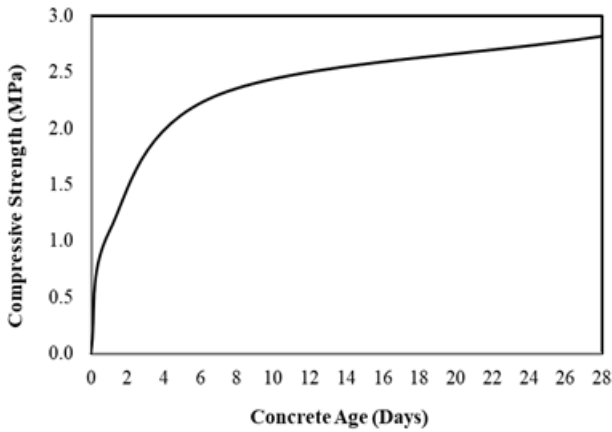
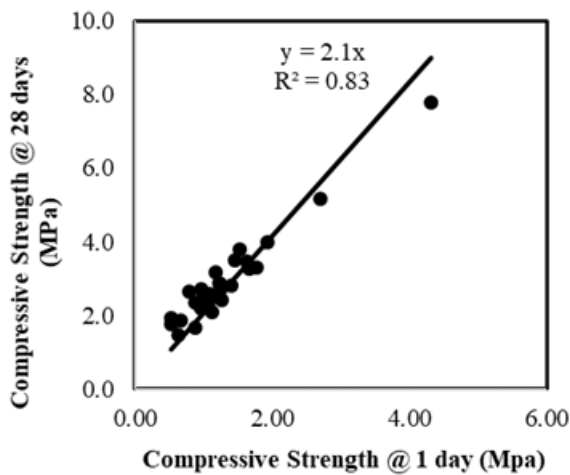


Figure 8. Rate of Strength Development

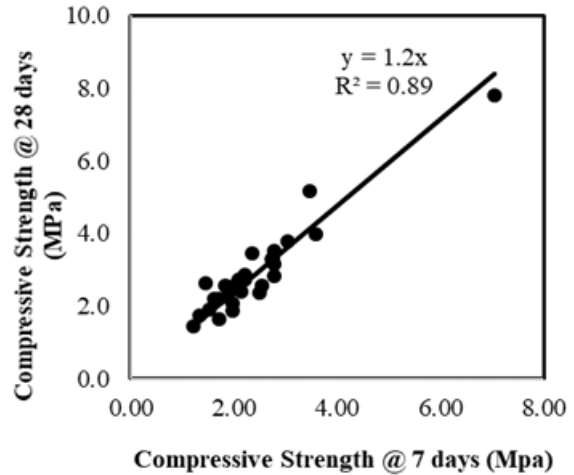
The effects of concrete age on the compressive strength development are illustrated in Figure 8. The rate of strength development was greater initially and decreased with time which is similar to traditional concretes. Based on the

experimental results from this study, concrete develops around 48% of its 28-day strength within 1-day, and 83% of its 28-day strength within 7 days. These results show that the rate of strength development for EPS concrete is higher than the traditional normal density concretes. It should be noted that 3 out of 30 mixtures (11, 26 and 28) resulted in 7-day strength slightly exceeding the 28-day strength. While this should not be the case, it may occur due to the high rate of strength development, low compressive strength values, and the sensitivity of ultra-lightweight concrete to casting and testing in comparison to normal concretes.

The proposed strength models (Eq. 2 and 3) were developed and calibrated for 28-day strength only because it is the main mix design requirement. However, the 28-day compressive strength can be related to strengths at early ages. This is important to accommodate tight construction schedules. Figure 9 shows the relationships between the 28-day compressive strength versus compressive strengths at 1-day and 7 days. The corresponding coefficients of correlation are 0.83 and 0.89 for the 1-day strength and 7-day strength, respectively.



(a)



(b)

Figure 9. Relationships between Compressive Strengths at different Ages (a) 1-day vs. 28 days, (b) 7 days vs. 28 days

4. Conclusions

In this study, a mixing procedure for Ultra-lightweight EPS concrete was developed and predictive compressive strength models function of concrete mixture and density were formulated. An experimental program was developed to implement the mixing procedure and to calibrate and evaluate the accuracy of the strength models. This study revealed the following main conclusions:

- The proposed mixing procedure was successfully implemented and all 30 mixtures has shown homogeneity, stability, and no segregation.
- The proposed compressive strength models provide a good fit to the experimental data. The standard error for both models is less than 0.3 MPa and the corresponding correlation coefficient is greater than 0.93. These models can be utilized in the design of concrete mixtures to meet specific strength requirements as a priority and ensure quality control before concrete is cast.
- In order to ensure quality control before concrete is cast, a link between the plastic density of fresh concrete and the compressive strength of hardened concrete was established. The corresponding correlation coefficient was 0.86.
- The effects of concrete age on strength development were studied and the 28-day compressive strength was related to strengths at early ages. Results reveal that EPS concrete develops around 48% of its 28-day strength in 1-day, and 83% in 7 days. The corresponding correlation coefficients were 0.83 and 0.89 for the 1-day strength and 7-day strength, respectively. This is important to accommodate tight construction schedules.

Acknowledgements

This work was supported by the American University of Ras Al Khaimah and Concrete Technology LLC. The author would like to thank Concrete Technology LLC for providing the resources to successfully conduct the experimental part of the paper. The author would like to thank the American University of Ras Al Khaimah for providing additional resources and time that helped shape up the development of the analysis and writing of the paper

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