JOURNAL OF CURRENT RESEARCH IN SCIENCE
ISSN 2322-5009
CODEN (USA): JCRSDJ
Available at www.jcrs010.com

JCRS
4 (3), 2016: 181-185

Optimization of Lightweight Concrete Mix Design Methods

Negin Haghighat[1], Arman Montazerian[2], Behzad Saeedi Razavi[3]

1.Department of Civil Engineering, Bu-Ali Sina University, Iran
2.Department of Civil Engineering, Bu-Ali Sina University, Iran, Research and Development manager of Pars Laneh Company
3.Constraction and Mining Department, Standard Research Institute (SRI), Iran
Corresponding Author email: haghighat.negin@yahoo.com

K E Y W O R D S: lightweight concrete, strength, water-cement ratio, fineness modulus, LECA

ABSTRACT: Due to the development construction technologies numerous efforts have been made to replace old materials with new material types. An effective step towards this end is optimization of lightweight concrete mix design methods to provide for analysis of the effects of all parameters on achievement of the desired design mix strength and efficiency. In this research, using results of mix design of 100 concrete samples with $10 \times 10 \times 10$ cm^3 dimensions it was tried to express the effects of variables such as fineness modulus, lightweight aggregate to total aggregate ratio, and water content of lightweight concrete mix design. Hence, the aforementioned factors were considered the parameters optimizing lightweight concrete mix design. Similar to normal concrete, in lightweight concrete the concrete mix water content is proportional to strength. Results suggest that to obtain a homogenous lightweight concrete mix design it is necessary to consider the level and gradation of lightweight aggregates and sand fineness modulus.

Introduction

Today, lightweight construction captures considerable attention due to its effects on reduction in earthquake damage and economic optimization, timing, human force, and energy saving. As the most popular construction material, concrete plays a major role in the amount of dead loads acting on structures. Hence, reducing concrete weight while maintaining its quality is among the most important engineering challenges, and producing structural lightweight concrete is significantly important. Use of lightweight concrete dates back to the ancient Rome, when cylindrical furnaces were used to heat clay and shale to obtain the aggregates known as LECA (light expanded clay aggregate), nowadays. In the 1950s and 1960s, numerous buildings and bridges were built with lightweight concrete worldwide. As a continuation of studies on lightweight concrete, Zhang and Gjorv examined the effect of lightweight concrete density on mechanical strength and failure mechanism of highly-resistive lightweight concrete. Yang and Huang determined the significance of volume percentage of aggregate content for compressive strength and elasticity modulus of lightweight concrete. Karl and Wogler tried to determine the effects of aggregate strength on mechanical properties of lightweight concrete by comparing the development of strength in lightweight concrete and its mortar phase. They proposed a theory based one existence of a strength limit and a point of yield strength.

Extensive research has been conducted in Iran on production of structural lightweight concrete with lightweight materials. Research results mainly reflect difficulty of obtaining structural strength, necessity of using low water-cement ratios, and use of additives and admixtures (such as silica fume and fly ash) in lightweight concrete. The first step in producing structural lightweight concrete is developing a suitable mix design. The three common methods for designing lightweight concrete design mix are the ACI weight method, two-phase mix method, and the resistive-capacity-based mix design method. Each of these advantages has its advantages and pitfalls, and thus following the initial estimation of the mix design it is necessary to correct pilot designs to achieve a satisfactory final mix design.

In this research, to optimize a design mix a design method based on lightweight LECA and sand aggregate was employed. By comparing 100 lightweight concrete cubes factors influencing the lightweight concrete mix design were studied in two parts. In the first part, the most important factor, i.e. existence of water in the concrete mix, was studied. In the second part, the LECA and sand aggregates ratio were examined. The effects of LECA gradation and use of grains larger than 4.75 mm (coarse-grained LECA) and grains smaller than 4.75 mm (fine-grained LECA) on efficiency and strength were investigated. Reinforcement of the plastic phase of lightweight concrete, which is meant to improve efficiency and prevent detachment, leads to formation of fresh plastic and highly-resistant concrete. The homogenous form of the resulting concrete covers large differences between materials bulk density.

Materials

Type I Portland cement, silica fume, sand with standard gradation, and sand filler were used in this research to control fineness modulus. The lightweight material used in this research included LECA aggregates, which based on the ASTM C127 standard had a spatial bulk density of 529 kg/m^2 and 595 kg/m^2 in the non-compact and compact corroded rod states, respectively.

To increase efficiency and reduce the w/c, a third generation modified poly-carboxylate-based super-plasticizer was used. This additive was added to the mix design based on the cement weight, and for designs with low water/cement rations super-plasticizers with a maximum cement weight percentage of 1 were used.

Mix Design

The primary mix design was divided into three ten-member groups, and each group was designed using a different lightweight concrete design method. After comparing results of samples with the primary designs, the smallest standard deviation from the design was delivered by the resistance capacity mix design method. It is worth mentioning that results of all of the three methods differed from the desired results, and the secondary designs were formed based on experience and modifications to the primary designs. Similar to normal concrete, lightweight concrete consists of three parts: aggregate, cement, and water. The important point in this regard is the skeletal structure of lightweight concrete. Hence, the aggregate part was divided into the coarse-grained aggregate, fine-grained aggregate, sand, and filler parts. This classification considerably contributes to examination of the micro-structure of concrete skeleton and more precise observation of factors influencing the primary concrete mix design.

Mix Design Optimization

Similar to the weight and two-phase methods, in the resistance capacity method the concrete is divided into the cement mortar and lightweight coarse-grained aggregate parts. However, instead of theoretically calculating concrete strength, the resistance capacity diagram (which shows the relationship between concrete strength and mortar strength) is used. The next steps of design (i.e. determining water/cement ratio, determining water content, calculation water plasticity, determining water content, and adjusting volume of coarse-grained aggregates) lead to the initial lightweight weight concrete mix design. In this method, density, strength, and plasticity of concrete are simultaneously included in the design, and thus its result differs from the final design less than the other methods. The role of factors influencing efficiency and strength of concrete is neglected in design steps, and this flaw considerably influences precise design of the mix design.

The first part of this research discusses the role of the water/cement ration and water content of lightweight concrete. Due to its porous structure, LECA is not a saturated light aggregate with dry surface and it is extremely difficult to provide this condition for light aggregates. Since the water content of the mix design substantially influences efficiency and strength, it should be noted that a large part of water is used for saturation of lightweight aggregates, and the other part is consumed during hydration. On the other hand, due to the high water absorption capacity of lightweight aggregates, addition of water to the mix at the wrong time leads to a loss of concrete water and dehydration of the concrete mix. Therefore, with an increase in water for the ease of molding a decrease in strength, which is known as concrete cavitation, is observed.

Based on previous studies, to control water consumption, it is better to allocate the water supplied for water absorption in lightweight aggregates to lightweight aggregates before mixing. Some researchers believe that water absorption by lightweight LECA is approximately 70 or 80% of the 24-hour water absorption of LECA within the first 30 minutes. Some researchers such as Gjorv and Punkki consider a one-hour water absorption period in the concrete mix design. By comparing properties of the LECA used in this research and the LECA used in these studies, it is recommended to determine a 10 to 30-min LECA water absorption before mixing by subtracting from the water/cement ratio.

This period depends on plasticity, environmental conditions, and type of light aggregates, and thus in a normal environmental and a slump of 1 to 7 cm, water absorption is estimated to be 10 minutes. Another factor influencing selection of concrete water is the fineness modulus. Control of fineness modulus in fine-grained sand gradation is important for the control of mortar strength. The importance of this process is revealed by examining the following group of mix designs. In this group, contents of coarse-grained light aggregates and cement are invariant. To change the fineness modulus sand filler was used. The same amount of additive is added to all designs. Table (1) shows a number of mix design used in this research.

Table 1: Analysis of the effect of fineness modulus on strength and water/cement ratio

Strengh 7days	W/C	Cement	FM	Filler	Sand	Sand LECA	Coarse LECA	name
Mpa				Kg/m3	Kg/m3	Kg/m3	Kg/m3	
15.7	0.4	400	5	0	1300	63	137.5	T21
16.4	0.4	400	4.9	105	1073	75.6	137.5	T22
17.5	0.4	400	4.81	105	975	94.5	137.5	T23
25.2	0.4	400	4.68	175	900	126	137.5	T29
26.2	0.4	400	4.3	390	683	126	137.5	T34
31.7	0.4	400	4.3	390	683	126	137.5	T33

As seen in Figure (1), strength escalates with a decrease in sand fineness modulus. To provide workshop conditions and allow for mass production, sand filler was added to the sand to control its fineness modulus. Hence, the sand fineness modulus can be controlled by changing the filler amount. An increase in the strength of the group of mix designs results in a decrease in the water/cement ratio.

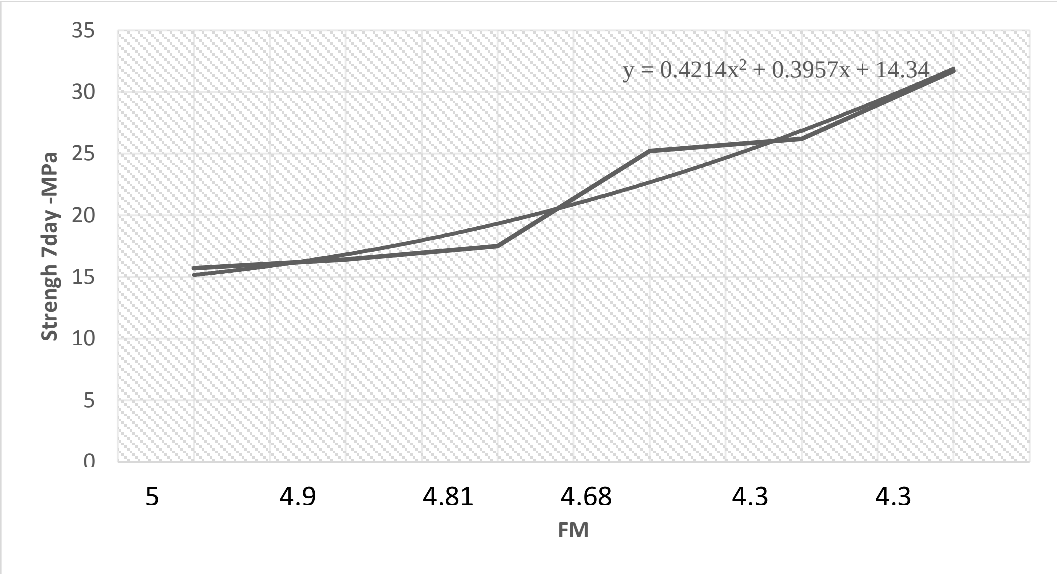

Figure 1. Changes of 7-day strength as a result of changes of fineness modulus

In the resistance capacity design method, mortar strength is usually attributed to the water/cement ratio. In this method, plasticity of fresh concrete is a function of the mix water content, and to adjust k-slump, the mixture water content depends on the maximum grain size and concrete air content. The water/cement ratio is calculated regardless of the direct effect of gradation of fine-grained aggregates and fineness modulus on water. In the ACI weight method, the proposed water content is determined based on slump and maximum nominal size of light aggregates, and the water/cement ratio is only based on compressive strength of concrete samples. Therefore, in this method gradation and fineness modulus do not influence the water content of the mixture.

LECA grains are divided into the fine-grained and coarse-grained groups to facilitate achievement of efficiency, and this procedure directly influences the water/cement ratio. However, considering the results of this research, the water/cement ration is proportional to the fine-grained gradation and the expected concrete efficiency. Hence, after analyzing results of lightweight concrete mix designs, Table (2) is presented for calculating the approximate initial water/cement ratio to apply the most suitable water content of concrete to the design.

Table 2. proposed water/cement ratio

20-25	17-19	16-17	14-16	Strengh 7days MPa
4.8-4.5	4.9-4.6	5-4.6	5.2-4.8	fineness modulus FM
water/cement ratio				Slump- cm
0.51	0.5	0.44	0.45	1.5-3
0.53	0.56	0.48	0.49	7-4

It is worth noting that with the ratios presented in Table (2), the amount of water required for 10-minute absorption of water by lightweight LECA materials before mixing is provided and there is no need to add water to control absorption of water by lightweight aggregates. As seen in Table (2), the effect of gradation is directly applied to the water/cement ratio, and with a decrease in fineness modulus and variations of filler content, water consumption decreases and strength escalates.

In lightweight concrete, due to the large difference between bulk densities of mixed aggregates detachment is intensified. In lightweight concrete with a slump larger than 5 mm, light aggregates show a strong tendency to detach from mortar and move toward the fresh concrete free surface. To compensate for the detachment, the concrete should be in a satisfactory plastic phase. In other words, the rule regarding the use of rollers for compensating for plastic slump decline should be followed. Hence, another group of lightweight concrete mix designs was used to study the effect of fine-grained LECA on efficiency. According to the previous procedure, the amounts of cement, coarse-grained LECA, and additives are invariants, whereas the amount of fine-grained LECA changes. Since fine-grained LECA is round-shaped, it plays the role of fine rollers unlike fine-grained sand, which has sharp rounds, and this effect increases plasticity of concrete. In this group, the $W_{leca/fine}$ parameter, which denotes the ratio of fine-grained LECA weight to total fine-grained aggregates weight is calculated as follows.

W_{leca}= Weight of LECA per kg/m^3 of concrete

W_{fine}= Total weight of fine-grained aggregates per kg/m^3 of concrete

$W_{leca/fine}$= Ratio of fine-grained LECA weight to total fine-grained aggregates weight per meter

According to Table (3), analysis of the effect of fine-grained LECA to total fine-grained aggregates ratio on strength and efficiency of concrete indicates that fine-grained LECA plays the role of fine rollers that contribute to the increase in concrete plasticity. Hence, it is important to adjust the ratio to control concrete plasticity.

Table 3. Effect of fine-grained LECA to total fine-grained aggregates ratio on strength

weight	Strengh 7days	%Wlika/fine	Filler	Sand	Sand LECA	Coarse LECA	name
Kg/m3	Mpa		Kg/m3	Kg/m3	Kg/m3	Kg/m3	
1678	13.4	9.5	105	975	113.4	137.5	T17
1818	15.7	4.6	0	1300	63	137.5	T21
1720	16.4	6	105	1073	75.6	137.5	T22
1765	17.5	8	105	975	94.5	137.5	T23
1746	18.8	9.5	105	975	113.4	137.5	T24
1758	25.2	10.2	200	900	126	137.5	T29
1724	25.7	10.2	400	700	126	137.5	T30
1840	26	4.20	75	1170	56	137.5	T32
1802	31.5	10.5	390	682.5	126	137.5	T33
1700	13	7.4	0	1170	94.5	137.5	T36
1736	15	11.5	500	550	138.6	137.5	T44
1710	17	12.7	400	760	170.1	137.5	T45
1736	16	12.7	500	660	170.1	137.5	T46

In this group, the water required for LECA absorption is added before mixing. Figure (2) indicates that by controlling the $W_{leca/fine}$ ratio it is possible to reduce concrete porosity and obtain a plastic consistent mixture. It should be noted that an increase in lightweight concrete slump is not solely achieved by increasing the plasticizer content or the water/cement content, because simultaneous control of the $W_{leca/fine}$ ratio substantially contributes to control of detachment of light aggregates from the mortar.

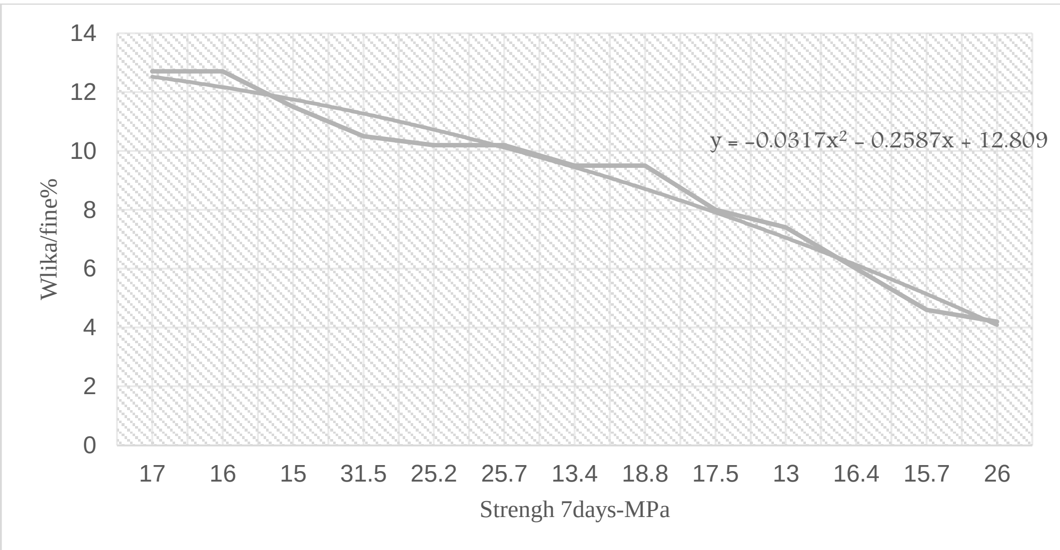

Figure 2. The relationship between LECA to fine-grained aggregate ratio and compressive strength

In the resistance capacity design method, after calculating the volume of paste and subtracting the cement and air volumes from the past volume, the volume of aggregates is calculated, and the weights of sand and light aggregates are calculated using the desired density based on primary design data. In this method, light coarse-grained aggregates should make up about 25% to 35% of the total concrete volume. It should be noted that in the resistance capacity method, volumes of sand and light aggregates are calculated based on the primary hypothesis regardless of the effect of aggregate gradation in the plastic phase. According to Table (2), based on aggregate gradation there is a relationship between efficiency and concrete strength and weight, and the aggregates mix ratio cannot be calculated only by calculating the initial density. Table (4) presents ratios proposed for calculation of aggregates content.

Table 4. Proposed fine-grained LECA to total fine-grained content ratios

2-7				Slump- cm
1720-1800	1800-1850	1680-1750	1820-1720	weight Kg/m3
25-30	20-25	16-18	15-17	Strengh 7days MPa
10.2-10.5	4-4.7	9-9.5	4.6-8	%Wlika/fine

The data presented in Table (4) help select the material mix percentage that is more compliant with the initial requirements. This table shows the effect of gradation on strength, efficiency, and weight of concrete. It should be noted that to use this data, the coarse-grained LECA should make up 20% to 25% of the total volume of aggregates, while the best ratio is the 25%. Moreover, to obtain a homogenous mixture without detachment and to increase efficiency the largest size of coarse-grained aggregates is assumed to be 4.75 to 12.5 mm in the mix designs presented in Table (3). In the next design steps, allocation of 5 to 10% of materials volume to fillers to maintain sand fineness modulus in the 4.5-5.2 range seems to be satisfactory.

Conclusion

In this research, after comparing the common lightweight concrete mix design methods and analyzing their pitfalls, a method for mix design optimization was proposed. The proposed data was obtained by considering the relationship of strength and efficiency with mixture water content as well as the relationship between grading and efficiency, strength, and weight of lightweight concrete.

According to the results of this research, it is recommended to allow lightweight LECA to saturate in water for at least 10 and at most 30 minutes before mixing and to overlooked lightweight aggregates water absorption in calculation of concrete water demand.

In the proposed values, as the coarse-grained aggregates volume decreases from the 25-35% range to the 20%-25% the size of the largest grain varies in the 4.75-12.5 mm range.

According to Table (5), in calculating the ratio of fine-grained LECA to total fine-grained content, the optimal ratio for highly-resistant lightweight concrete is approximately 10%.

Unlike normal concrete, for which a sand fineness modulus of 2.3-3.2 is recommended by the codes, in the case of lightweight concrete, it is recommended to add an amount of sand filler equal to 5% to 10% of aggregates to control gradation and maintain fineness modulus in the 4.5-5.2 range.

References

ACI 211.2R, "Standard Practice for Selecting Proportions for Structural Lightweight Concrete",ACI 211.2R

Alexandre Bogas, " A simple mix design method for structural lightweight aggregate concrete ", Materials and Structures Journal, DOI : 10.1617/s11527-013-0029-1, Print ISSN: 1359-5997

Ana M. Bastos, "Methodology for the Design of Lightweight Concrete with Expanded Clay Aggregates", TMS Journal December 2005

ASTM C330, "Standard Specification for Lightweight Aggregates for Structural Concrete",ASTM, 1999.

Chen, H.J., Yen, T., Lia, T.P., Huang, Y.L., "Determination of Dividing Strength and it's Relation to the Concrete Strength in Lightweight Aggregate Concrete", Cement and Concrete Composition,Vol. 21, pp.29-37, 1999.

Day, K.W, " Computer control of concrete proportions", Concrete international, 8(12), 1996

Fib, "Lightweight Aggregate Concrete", Guidance document, Bulletin8, 2000.

Ganju, T.N, " Spread sheeting mix designs", ACI: Concrete international, 18(12), 1996

Grübl P, "Mix design of lightweight aggregate concrete for structural purposes", Int J Cem Compos Lightweight Concrete 1(2), 1997

Hossain KMA, Lachemi M, "Mixture design, strength, durability and fire resistance of lightweight pumice concrete", ACI Mater J 104(5)-M49, 2007

M. ABDULLAHI, "M-FILE FOR MIX DESIGN OF STRUCTURAL LIGHTWEIGHT CONCRETE USING DEVELOPED MODELS", Journal of Engineering Science and Technology Vol. 6, No. 4, 2011

M.H. Zhang, O.E. Gjorv, Characteristics of lightweight aggregates for high-strength concrete, ACI Mater. J., 1991(March-April)150-8

Swamy RN, Lambert GH, "Mix design and properties of concrete made from PFA coarse aggregates and sand", Int J Cem Compos Lightweight Concrete 3(4), 1983