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Experimental Determination of Optimum Mixture Design of Lightweight Concrete

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1. Introduction

Over the past few decades the increased use of lightweight concrete (LWC) for the structural elements has become a more and more important aspect of the modern construction industry (Rumsys et al. 2018). Despite many undoubted advantages like good thermal properties and low density (Liu et al. 2019), concrete fully made with the lightweight aggregate exhibits significant reduction in mechanical properties (Han & Xiang 2017). For instance, during pull-out test LWC is characterized by about 70% smaller bond strength between rebar and matrix than normal-weight concrete (NWC) (Alexandre et al. 2014). Compressive strength of concrete decreases with increase of lightweight aggregate content. The compressive strength of structural LWC is about 60% smaller than NWC at 28 days of curing when coarse aggregate is fully replaced with expanded clay aggregate (Aarthi et al. 2019). Considering the applications of LWC and NWC in structures and differences in material properties between them, the interfacial performance needs further study (Huang et al. 2019). All above facts inspired authors to conduct research programme dedicated to determine optimum mixture design of lightweight concrete.

2. Materials, experimental methods and specimens preparation

During the research programme following materials were used for the LWC preparation: aggregate consisted of expanded clay granules, Portland cement CEM I 42.5R which was used as a binder, tap water and superplasticizer (in case of selected mixes). Crushed (in industrial grinder - see Fig. 1) expanded clay granules were used as fine aggregate 0-4 mm. Expanded clay granules 4-16 mm were used as coarse aggregate. Superplasticizer reduced the amount of water by about 20% (in case of selected mixes). The research tests procedures were based on European and Japanese standards (see Table 1). The research programme was divided into two stages. During the first stage four different lightweight aggregate compositions (mix-1 to mix-4) were prepared. Based on these aggregates four LWCs (LWC-1 to LWC-4) were cast. Consistency, density, compressive strength and splitting tensile strength were tested for all four LWC. After an analysis of the achieved characteristics one LWC was qualified for the second stage of the research programme. During this part of the research programme more sophisticated properties of LWC in question were tested such as dynamic modulus of elasticity, flexural strength, shear strength and abrasion resistance.

Fig. 1. Industrial grinder used for crushing lightweight aggregate granules

Table 1. The research test procedures

Type of test	Standard number	Stage
Consistency	EN 12350-3:2001*	I
Density	EN 12390-7:2011*	
Compressive strength	EN 12390-3:2011*	
Splitting tensile test	EN 12390-6:2011*	
Dynamic modulus of elasticity	EN 12504-4:2005*	II
Flexural strength	EN 14651:2007*	
Shear strength	JCI-SF6:1984**	
Abrasion resistance	EN 13892-3:2005*	

* – European standard, ** – Japanese standard

The adopted design of experiment is summarized in Table 2 where number of specimens utilized for each test, their shape and dimensions are listed. The apparatus used for compressive strength and splitting tensile strength together with cubic specimens are shown in Fig. 2. Flexural and shear strength tests results are presented in Fig. 3.

Table. 2. Number of specimens, their shapes and dimensions used in the research tests

Type of test	Specimen shape [cm]	Number of specimens	
		in one test	overall
Density	–	6	24
Compression strength	cube 15x15x15	8	32
Splitting tensile test	cube 15x15x15	8	32
Dynamic modulus of elasticity	cylinder ⌀15x30	10	10
Flexural strength	beam 70x15x15	6	6
Shear strength	cuboid 30x15x15	12	12
Abrasion resistance	cube 7.1x7.1x7.1	3	3

Fig. 2. The strength apparatus (left) and specimens (right) used for compressive strength and splitting tensile strength tests

Fig. 3. Apparatus and specimen during flexural strength test (left) and shear strength test (right)

3. Research test results

Four different lightweight compositions prepared for the research programme are presented in Table 3. All aggregate compositions didn't exceed the diameter of 16 mm. Mix 1 and 2 were characterised by maximum volume of the voids and minimum tightness. The dust content, sand content and water absorption was highest for the mix 3. Fine aggregate grading significantly affects the concrete properties in the hardened state (Katzer & Kobaka 2009b). The large surface area of the fine aggregate increases the amount of water necessary to wet all the solids (Katzer & Kobaka 2009a). Three of four aggregate mixes (except mix 3) were characterised by fineness modulus by Kuczynski within the recommended range 5-7.5. Fineness modulus by Hummle varied from 110.8 for mix 3 to 136.9 for mix 2.

The created four LWC mixes are thoroughly described in Table 4. The w/c ratio varied from 0.45 to 0.54. The consistency of fresh LWC was tested using ordinary VeBe method. The results of the VeBe test are shown in Table 5. Fresh LWC no. 1 was too liquid to be established by VeBe method (the fresh mix cone collapsed during tests preparation). LWC no. 2 was characterised by V2 consistency class, fresh LWC no. 3 and 4 were characterised by V3 consistency class according to EN 206:2016 standard.

Table 3. Properties of the aggregate mixes used for LWC creation

No	Property	Units	Mix 1	Mix 2	Mix 3	Mix 4
1	Voids volume	%	40	44	32	36
2	Water absorption (by weight)	%	18	21	26	22
3	Tightness	–	60	56	68	64
4	Median diameter (Katzer 2012)	mm	1.65	2.9	0.88	1.34
5	Dust content (d ≤ 0.125 mm)	%	10.46	9.73	19.7	12.3
6	Fine grains content (d ≤ 0.5 mm)	%	25.3	16.7	37.4	27.78
7	Sand content (d ≤ 2 mm)	%	41.1	27.17	56.6	48.8
8	Fineness modulus by Kuczynski	–	5.25	5.63	4.76	5.14
9	Fineness modulus by Hummle	–	125.5	136.9	110.8	122.2

Table 4. Composition of the LWC

LWC	Aggregate		Cement	Water	w/c	Admixture
	Fine	Coarse				
	[kg/m^3]				–	[kg/m^3]
1	560	560	370	200	0.54	–
2	480	620	410	220	0.54	–
3	790	320	460	220	0.48	10.1
4	730	420	510	230	0.45	11.3

Table 5. Consistency tests results based on VeBe method

Mix no.	Test result [s]	Consistency class
1	0	–
2	3.5	V2
3	9.6	V3
4	6.1	V3

Particle size distribution test results are shown in a chart form in Fig. 4. The characteristics of all aggregate mixes in question were not compliant with the concrete aggregate recommendations yet in the case of mix 3 and 4 the differences were not significant.

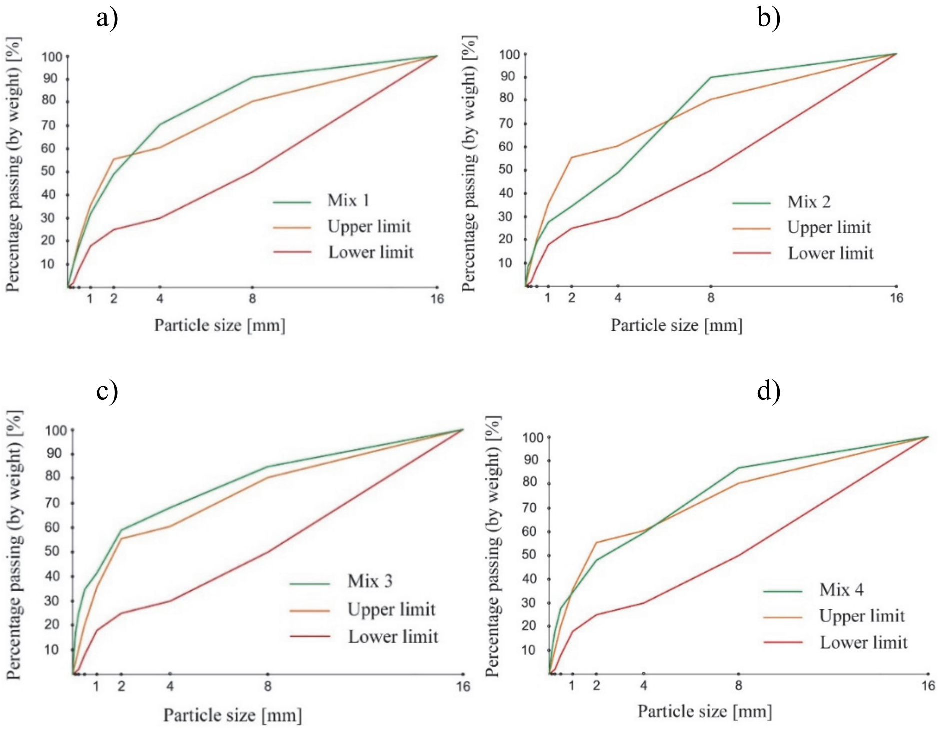

Fig. 4. Particle size distribution curves of customized aggregate compositions used: a) mix 1, b) mix 2, c) mix 3 and d) mix 4

4. Analysis of the test results

LWC-1 and LWC-2 were characterised by the lowest density (see Fig. 5) but also the lowest compressive and splitting tensile strength (see Figs. 6 and 7). LWC-3 was characterised by the highest density, compressive and splitting tensile strength. LWC-4 was characterised by lower density (by 22%), compressive strength (by 39%) and splitting tensile strength (by 21%) than LWC-4.

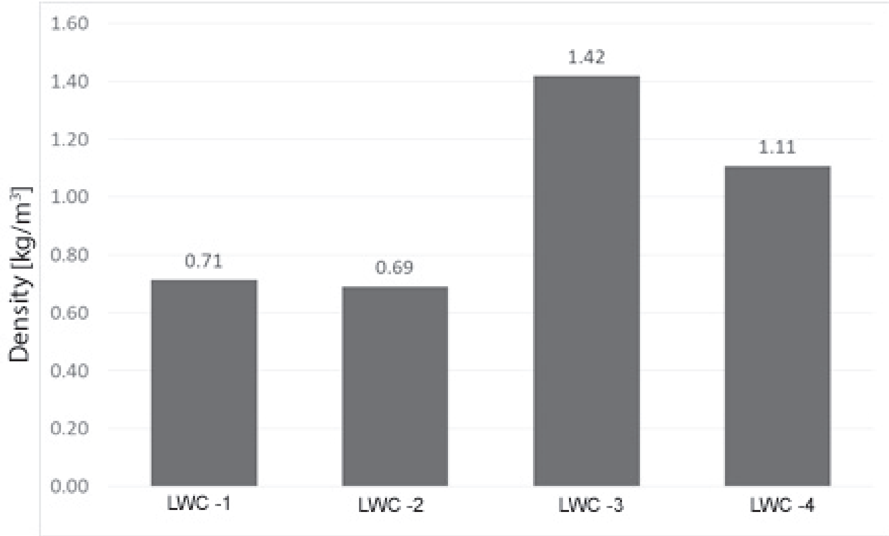

Fig. 5. Density of LWC

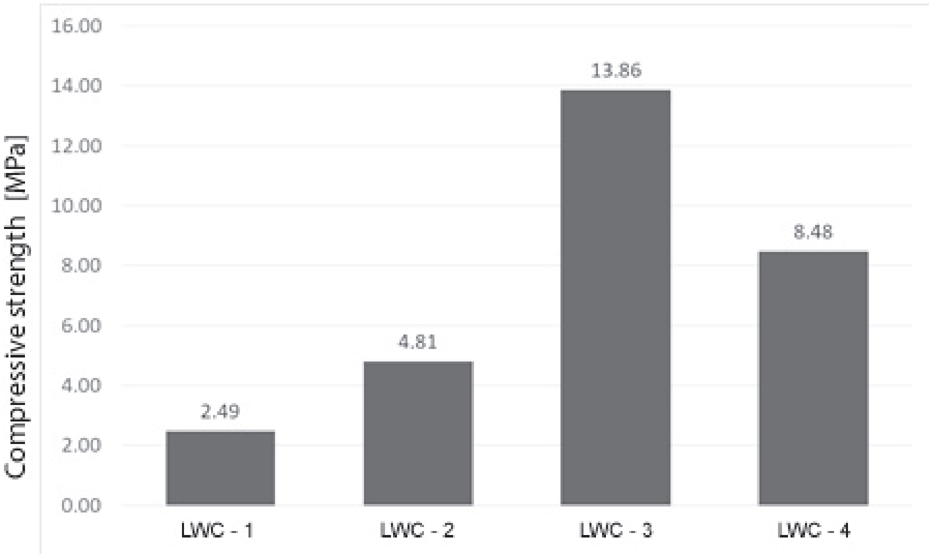

Fig. 6. Compressive strength of LWC

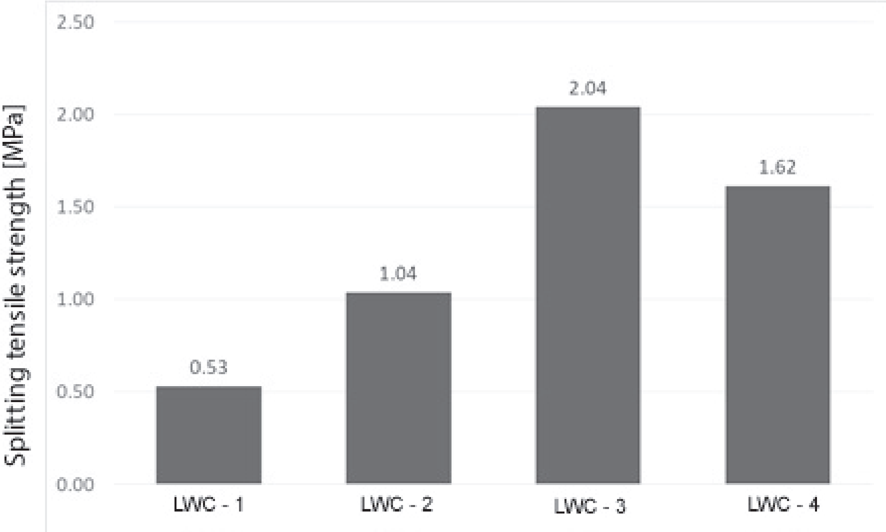

Fig. 7. Splitting tensile strength of LWC

Due to relatively high compressive and splitting tensile strength, low density of hardened concrete (equal 1.11 kg/m^3) LWC-4 was chosen for the second stage of the research programme. During the second stage such properties as dynamic modulus of elasticity, flexural strength, shear strength and abrasion resistance were of interest. The achieved results are presented in Table 6. Abrasion resistance measured in [cm^3/cm^2] was equal to 9.07 so according to EN 13813:2002 standard A12 abrasion resistance class can be assigned to this LWC-4.

Table 6. Selected properties of LWC-4

Property	Value
Dynamic modulus of elasticity [GPa]	6.21
Flexural strength [MPa]	8.48
Shear strength [MPa]	1.35
Abrasion resistance *A* [cm^3/cm^2]	9.07

5. Summary

The density and compressive strength are the key parameters in case of LWC. Low density is often accompanied by poor strength which can be observed in the test results of LWC-1 and LWC-2. LWC-3 was characterised by relatively high compressive and splitting tensile strength but also high density. LWC-4 was characterised by lower strength than LWC-3 but also over 20% lower density which was the reason for choosing this mix for the second stage of research. Additional tests of multiple properties such as dynamic modulus of elasticity test, flexural strength test, shear strength test and abrasion resistance have proven usefulness in providing experimental determination of LWC optimum mixture design.

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Abstract

This paper describes the mixture design of lightweight concrete. The authors proposed lightweight concrete based solely on expanded clay aggregate. Commercially available expanded clay granules (used as coarse aggregate) were supplemented with crushed expanded clay granules (which played the role of fine aggregate). The created mixes were differentiated by particle size distribution of lightweight aggregate and the amount of used cement. Properties of both fresh concrete mixes and hardened composites were of interest. The tested properties were as follows: consistency, density, compression strength, splitting tensile strength, dynamic modulus of elasticity, flexural strength, shear strength and abrasion resistance. Experimental results have shown some satisfactory mechanical characteristics of concretes in question.

Keywords:
lightweight aggregate, expanded clay granules, lightweight concrete, properties, research testing

Eksperymentalne określanie optymalnego projektu betonu lekkiego

Streszczenie

Artykuł opisuje projektowanie betonu lekkiego. Autorzy zaproponowali projekt betonu lekkiego wykonanego wyłącznie na bazie kruszywa keramzytowego. Dostępne na rynku kruszywo keramzytowe (użyte jako kruszywo grube) uzupełniono pokruszonym kruszywem tego samego rodzaju (pełniącego rolę kruszywa drobnego). Utworzone mieszanki kruszyw różniły się uziarnieniem kruszyw i zawartością cementu. Zbadano właściwości zarówno świeżej mieszanki betonowej jak i stwardniałego betonu takie jak: konsystencja, gęstość, wytrzymałość na ściskanie, wytrzymałość na rozciąganie przy rozłupywaniu, dynamiczny moduł sprężystości, wytrzymałość na rozciąganie przy zginaniu, wytrzymałość na ścinanie i odporność na ścieranie. Wyniki badań eksperymentalnych wykazały zadowalającą charakterystykę zbadanych właściwości.

Słowa kluczowe:
kruszywo lekkie, keramzyt, beton lekki, właściwości, badania