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Compressive strength and mixture proportions of self-compacting light weight concrete

Behnam Vakhshouri* and Shami Nejadi

Faculty of Engineering and Information Technology, School of Civil and Environmental Engineering, University of Technology Sydney, Australia

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Abstract. Recently some efforts have been performed to combine the advantages of light-weight and self-compacting concrete in one package called Light-Weight Self-Compacting Concrete (LWSCC). Accurate prediction of hardened properties from fresh state characteristics is vital in design of concrete structures. Considering the lack of references in mixture design of LWSCC, investigating the proper mixture components and their effects on mechanical properties of LWSCC can lead to a reliable basis for its application in construction industry. This study utilizes wide range of existing data of LWSCC mixtures to study the individual and combined effects of the components on the compressive strength. From sensitivity of compressive strength to the proportions and interaction of the components, two equations are proposed to estimate the LWSCC compressive strength. Predicted values of the equations are in good agreement with the experimental data. Application of lightweight aggregate to reduce the density of LWSCC may bring some mixing problems like segregation. Reaching a higher strength by lowered density is a challenging problem that is investigated as well. The results show that, the compressive strength can be improved by increasing the of mixture density of LWSCC, especially in the range of density under 2000 Kg/m^3.

Keywords: light-weight self-compacting concrete; mixture design; components; compressive strength; density

1. Introduction

Generally, workability, strength and durability are three major characteristics of fresh and hardened concrete. However, hardened properties of concrete are directly relevant to the mixture design and its fresh properties. In other words, mixture design and fresh properties of concrete are the most important factors to control and predict the hardened characteristics of concrete (Domone 2006).

In the recent decades, utilizing the mineral and chemical admixtures in concrete technology has introduced several changes in formulation and mixture design to make the concrete workable, stronger and durable (Güneyisi *et al.* 2012). Light-Weight Concrete (LWC) and Self-Compacting Concrete (SCC) are two commonly used materials in construction industry owing to their particular characteristics and advantages. Combination of LWC and SCC provides the benefits of both. Considering the reduced weight of structure and ease of placement, Light-Weight Self-Compacting Concrete (LWSCC) may be the answer to the increasing construction requirements of slenderer and more heavily-reinforced structural elements. Achievements in modern concrete technology introduce the LWSCC as workable and mass reducing material. However, there are limited studies to prove its suitability in widely application in real construction projects.

Estimation of the hardened properties of LWSCC before hardening is very important. The problem is that after the hardening process, the quality and mechanical properties cannot be changed and improved. Therefore, understanding the effect of mixture proportions on the mechanical properties can facilitate the estimation of hardened concrete characteristics from the fresh concrete.

The fresh concrete behavior from mixing up to compaction depends mainly on the workability of concrete. LWSCC is more sensitive to the change of materials type and proportion; therefore, the modification of the mixture proportions requires reaching the acceptable flowability which may affect the hardened concrete performance, in turn. Therefore, it requires increased quality control to ensure the adequate fresh properties that can have significant consequences for hardened properties, including strength and durability (Koehler and Fowler 2007).

The mixture design of LWSCC doesn't follow exactly the mixture design of LWC or SCC; however the considerations in LWC and SCC still govern the LWSCC mixture design (Vakhshouri and Nejadi 2015). LWC is much better known in construction industry rather than SCC. Existing developed methods for mixture design of SCC in the literature may focus on the fresh properties and mixture proportion to achieve the required flowing ability and self-consolidation capability, rather than the compressive strength. Therefore, the strength requirements in LWSCC mixture need more consideration.

Having broad idea about the effect of each component in the mixture may improve the ability of reducing the unwanted effects. For example, the enhanced flowability of the fresh concrete along with the reduced segregation risk can be balanced by the optimum water to cement ratio in

*Corresponding author, Ph.D.
E-mail: Behnam.vakhshouri@student.uts.edu.au

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Table 1 Data base for mixture design of LWSCC

Reference	Country	CA				Test age	Curing type	LWCA	NWA		Cement	Filler
		SP		AEA								
		Type	Volume Kg/m³	Type	Volume Kg/m³	hr-day			Fine	Coarse		
(Kobayashi 2001)	Japan	PCAE	1.5-1.8%of cement weight			28d	Moist	artificial LWA<15mm	NRS	CLS<15 mm	PC	FA
(Barrios 2010)	USA	PCB Eucon SPJ	3-6 floz/cwt	DARAVAIR 1000, AIR MIX 250 and AIR 30	3.2-4 fl oz/cwt	28,56 d	Humid heat room 32-35℃	crushed granite from Vulcan mine material	NRS		Type III and Class C Boral cement	SF, FA
(Shi and Wu 2005)	China	PCB	3.3	VRB	0.2	1,3,28,90,180d	fog room-23±2℃	ES<9.5 mm	NRS<4.75 mm		CEM I	FA class F
(Hwang and Hung 2005)	Taiwan	NLSB	2-26			3,7,28,56,91 d	N.G.	sintering fine sediment excavated from reservoir <13 mm	Crushed Sand		CEM I -C150	FA class F
(Persson 2006)	Sweden	MB	2.97-7.32	N.G*	0.106-1.203	28 d	N.G.		NRS<2 mm	Gravel<8 , Quartzite sandstone 8-16 mm		SF, LSP
(Hubertova and Hela 2007)	Czech republic	PCB	1.5%	N.G.	0.4%	7,28 d	Moist	EC, Liapore 0-1,4-8 mm	finely ground limestone, NRS<4 mm		CEM I 42.5	FA, SF, metakaolin
(Dymond 2007)	USA	N.G.	11.86	N.G.	0.6	7, 14,28 d	Moist	Aggregate of Carolina Stalite Company	NRS<2 mm		PC	FA
(Ward 2010)	USA	N.G.	7.5 floz/cwt	N.G.	0.3 fl oz/cwt	11,16 hr 7,28,90 d	Moist	EC<20 mm	NRS		PC	N.G.
(Yoğurtcu and Ramyar 2009)	Turkey	PCB	4.9-11.1	Not given	2.88-6.09	7, 28 d	N.G	Pumice 4-8, 8-16 mm	Crushed sand (SSD) <5 mm	N.G 5-15 mm	CEM I 42.5	FA, LSP
(Wang 2009)	Taiwan	N.G.	7.3-15.1			3,7,28,56,90d	Moist	dredged silt from reservoirs in southern Taiwan<9.5 mm, 12.7 mm	NRS<2.38 mm		CEM I	FA, slag
(Kim *et al.* 2010)	South Korea	PCB	0.7-1.3 % of cement weight	N.G.	0.005% of cement weight	3,7,28 d	Moist	LC1<20 mm by rhyolite fine powder, LC2<20 mm from by wastes (screening sludges)	Local NRS	CLS <20 mm	PC	N.G.
(Maghsoudi *et al.* 2011)	Iran	PCEP	4.675-4.95			3,7,28,90 d	Moist	Leca 4.75-9.5 mm	NRS<4.75 mm		CEM II	LSP and SF
(Bymaster 2012)	USA	ADVA 405, 408	15-26 floz/cwt	ADVA 575	5-11 fl oz/cwt	1,7, 28 d	Moist	EC, ES	NRS	CLS	CEM I for SCC and CEM III for LWSCC	FA
(Mazaheripour *et al.* 2011)	Iran	N.G.	17.18-19.02			7,14,28d	48 free and moist	LECA from EC 0-3,3-10 mm	NRS<4.75 mm	Natural gravel <10 mm	CEM II	SF, LSP
(Güneyisi *et al.* 2012)	Turkey	PCAE	5.3-6.4			28 d	Moist	Coarse cold-bonded FA 4-16 mm	Mix of CLS &NRS<5 mm		CEM I 42.5R	SF, FA class F
(Anwar *et al.* 2012)	Indonesia	N.G.	6.5-7.5	SIKA Viscocrete aqueous solution of modified polycarboxylate copolymers	4-10	3,7,28 d	Moist	Pumice 4.8-19 mm	NRS <9.6 mm	CLS<19 mm	CEM composite (PCC) Indonesian Standard (SNI) 15-7064-2004	FA, Indocement TBK
(Bogas *et al.* 2012)	Portugal	PCB	0.6-1.1% of fine agg. Weight			2,28,90d		Two Iberian EC: Leca from Portugal and Arlita from Spain	NRS	CLS <12.5 mm	CEM I 42.5R	FA (Pego thermoelectric power plant)
(Kaffetzakis and Papanicolaou 2012)	Greece	PCEP	1.06	N.G.	0.163-2.272	7, 28,56 d	Environmental chamber (21'c and 95% humidity)	Pumice 0-4 , 4-8 and 8-16 mm	NRS 0-4 mm		CEM II 42.5N	Pumice, LSP, S
(Andiç-Çakır and Hızal 2012)	Turkey	PCAE	2.4-10.2	Oil alcohol and ammonium salt based	1.4-3.9	7,28 d	Moist	Pumice 4-8, 4-16 mm	NRS <4 mm	CLS 4-16 mm	CEM I 42.5 R	industrial waste of olivine powder
(Juradin *et al.* 2012)	Croatia	Liquid PCAE	6-7.28			1,3,7,28 d	Moist	Liapor, EC granules 0-2, 1-8 mm	CLS 0-4 mm		PC	SF,FA, recycled concrete powder
(Soutsos *et al.* 2013)	North Ireland	PCB	3.3	SSA		3,6,12,24 hr 2,4,7,14,28 d	Moist	Lytag 4-14 mm	NRS <600 μm	Crushed Granite <20 mm	CEM I 42.5N	PFA, GGBS, LSP

the mixture. Expanded clay, granulated slag, perlite or vermiculite and polymer materials are frequently used as lightweight aggregate in LWC. Due to closed cavities in the mixture, especially in the light weight aggregates, water absorption is high. Hence, it is difficult to estimate the required water volume for hydration and workability in the mixture. Raising the extra water to surface during the mixing, in accompany with tendency of lightweight aggregates to float up, increases the segregation risk (Barrios 2010), (Juradin *et al.* 2012).

Since there is no instruction for LWSCC mixture design, some investigations (Mazaheripour *et al.* 2011) recommend to combine the mixture design consideration of high-performance concrete and LWC to avoid the segregation problem in LWSCC. Therefore, it will be possible to keep the strength of LWSCC high, in spite of applying

Table 2 LWSCC mixture proportions of experimental studies

Reference	Cement	Water	Mineral powder	Chemical admixture	w/c	LWA	NWFA	NWCA	density	*f'c*
	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3		Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	MPa
(Andiç-Çakır and Hızal 2012)	395	257	232.5	8	0.65	546	449	0	1879	23.4
	395	237	233.6	10.2	0.6	467	467	0	1899	24.6
	394	217	234.8	13.4	0.55	587	484	0	1916	30.2
	367	202	236.8	2.4	0.55	147	544	0	1503	22.9
(Juradin *et al.* 2012)	380	185.6	120	6	0.49	469	0	0	1850	28.1
	380	185.44	110	6.37	0.49	470	0	0	1780	38.77
	430	172	90	6.76	0.4	479	0	0	1900	29.7
	380	185.6	120	6.5	0.49	366.3	197.8	0	1780	33.37
	380	185.44	110	6.86	0.49	367.6	198.5	0	1780	40.93
	380	185.44	120	7	0.49	469	0	0	1830	38.6
	380	185.44	120	7	0.49	470	0	0	1750	31.6
(Mazaheripour *et al.* 2011)	500	160	133	17.2	0.32	179	287	657	1700	24.6
	500	160	162	18.68	0.32	175	282	645	2000	26.3
	500	160	190	18.68	0.32	187	300	554	2000	24.6
	500	160	190	17.2	0.32	201	323	475	1700	21.7
	500	160	168	18.68	0.32	226	363	311	2000	22.8
	500	160	133	19.02	0.32	221	355	305	1989	25
	500	160	162	16.55	0.32	105	963	0	1994	23.8
	500	160	190	17.24	0.32	195	626	0	1927	26
	500	160	216	17.91	0.32	221	355	305	1861	23
	500	160	247	17.18	0.32	221	355	305	1872	24
	500	160	249	17.23	0.32	64	722	0	2026	22
(Kobayashi 2001)	265	147	245	10.6	0.55	230.8	433	0	2300	25
(Shi and Wu 2005)	420	200	165	3.5	0.48	546		0	1956	37
	420	200	165	3.7	0.48	546		0	1958	50
	420	200	231	2.9	0.6	546		0	1964	36
	420	200	231	2.8	0.6	546		0	1853	39
(Hubertova and Hela 2007)	370	160	148	2.76	0.43	543		0	1840	33
	370	170	148	3.7	0.46	507		0	1790	36
	370	170	148	5.6	0.46	533		0	1840	41
(Dymond 2007)	268	118.1	92	7.8	0.44	504	687	0	1896	61.78
(Ward 2010)	471.6	179.2	245	7.5	0.38	440	766	0	1861	47
	471.6	179.2	245	7.5	0.38	440	766	0	1861	43
(Yoğurtcu and Ramyar 2009)	350	173	296	7	0.49	0	884	578	2288	41.4
	399	198	239	5.8	0.5	0	863	546	2261	19.5
	401	196	240	5.8	0.49	0	867	551	2261	41.2
	397	199	237	11.1	0.5	0	858	546	2248	39.3
	399	200	240	8.2	0.5	187	746	0	1786	33.5
	395	197	242	6.3	0.5	186	743	0	1773	27.3
	395	198	228	5.5	0.5	188	714	0	1732	29.3
	419	210	245	3.5	0.5	0	506	569	1956	43.1
	396	198	232	3.66	0.5	69	471	362	1734	27.9
	393	196	228	4.1	0.5	136	472	180	1611	26.5
	400	200	233	5.4	0.5	197	509	0	1547	23.6

Table 2 Continued

(Wang 2009)	314	140	257.7	9.4	0.45	298.8	801	0	1562	42
	335	140	158.9	9.9	0.42	289.8	801	0	1584	42
	335	160	159	7.3	0.48	289.8	801	0	1584	27
	240	160	153.8	7.8	0.67	289.8	801	0	1484	14
	244	140	224.4	12.6	0.57	229.7	1200	0	1898	42
	280	140	226.7	14.7	0.5	229.7	1200	0	1936	42
(Maghsoudi *et al.* 2011)	360	256.4	194.95	4.95	0.71	103	672	0	1890	20.8
	450	240.3	104.7	4.67	0.53	103	684	0	1870	28.5

Table 2 Classification of LWC in some international codes of practice

Reference	Density (kg/m^3)	Compressive strength (MPa)	Application
(ACI-213R-03 2003)	800 to 2240	≥17	Structural
(ACI-211.2-98 2004)	≤1840	≥17	Structural
(ACI-213R 2014)	1350 to 1900	≥17	Structural
(TS-2511 1977)	≤1900	≥16	Structural
(EN-206-1 2000)	800 to 2000	8 to 80	Non structural
(AS-3600-09 2009)	1800 to 2100		Structural

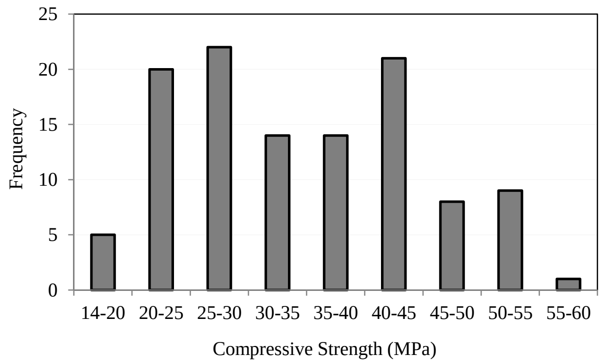

Fig. 1 The range of compressive strength in case studies

lightweight aggregates in the mixture.

2. Significance the study

It is vital to investigate that whether all the assumed hypotheses used to design the Conventional Concrete (CC), SCC and LWC structures are also valid for LWSCC structures. The objectives of this study are:

(a) Evaluation and comparison of the density and compressive strength of LWC and SCC in codes of practice with collected data of LWSCC;

(b) Evaluation and comparison of the different combination of components in the previously conducted experiments of 114 LWSCC mixtures in 21 investigations;

(c) Investigating the combined and individual effects of the mixture components on the mechanical properties of LWSCC;

(d) Proposing and verifying possible relationships by applying the best-fitting equation in regression analysis to predict the compressive strength of LWSCC from mixture proportions. Predictions of the proposed relationships are verified by the experimental values of the compressive strength in the literature;

(e) Evaluation and comparison of the effect of density of LWSCC mixture on the compressive strength;

(f) Comparing the components and their portioning in successfully tested mixtures of LWSCC to use in the future researches to attain a concrete with low-density and self-compacting capabilities without segregation, blocking and bleeding problems in designed mixtures.

It is worth mentioning that the proposed relationships can be used to initial estimation of the compressive strength from the utilized components and their relative volumes and weights in the mixture. However, each component has different effect on the mechanical properties of LWSCC that needs to be investigated by concrete technology and structural models in accompany with the laboratory test results.

3. Compressive strength of LWSCC

3.1 Experimental investigations

Database of experimental results from published investigations is effective tool to propose and verify new models and compare the exact and predicted values. Accurate application of the developed models on the particular mixture design of concrete needs to use the experiments consistent with the applied testing methodology.

In spite of effectiveness of the experimental results from different sources, using them can be problematic owing to (Vakhshouri and Nejadi 2014):

(a) Insufficient information concerning the exact composition of the concrete mixtures;

(b) Different size and number of the specimen, curing condition, and testing methodology; and

(c) Extracting real data of experimental results from graphs and diagrams.

The collected experimental database of this study is presented in Table 1. It has been taken mainly from the papers presented at conferences and published articles on LWSCC. The database contains information about the composition of the mixtures, type of chemical admixtures as plasticizer and air entraining, curing method, curing age, type of fine and coarse aggregate, filler type, cement type,

Table 3 LWSCC mixture proportions of experimental studies

Reference	Cement	water	Mineral powder	Chemical admixture	w/c	LWA	NWFA	NWCA	density	*f'c*
	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3		Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	MPa
(Güneyisi *et al.* 2012)	550	192.5	0	5.5	0.35	688	509	179	2124	48
	467.5	192.5	82.5	5.3	0.41	677	501	176	2101	44.6
	385	192.5	165	5.3	0.5	665	492	173	2078	41.7
	495	192.5	55	6.4	0.39	680	503	177	2109	54
	440	192.5	110	6.2	0.44	670	496	174	2090	48.2
	412.5	192.5	137.5	6.2	0.47	668	495	174	2085	47.9
	357.5	192.5	192.5	5.6	0.54	661	489	172	2070	42.5
	330	192.5	220	5.6	0.58	657	486	171	2062	42.9
(Anwar *et al.* 2012)	500	147	50	7.5	0.29	329	823	0	1995	28
	500	140	26.5	6.5	0.28	250	823	0	2091	34
	500	150	46.5	6.5	0.3	250	823	0	2091	34
	500	122	26.5	6.5	0.24	250	823	0	2095	30
	500	133	41.5	6.5	0.27	250	823	0	2095	30
	500	150	26.5	6.5	0.3	250	823	0	2052	35
(Kaffetzakis and Papanicolaou 2012)	326	153	114	4.9	0.47	139	318	310	1581	26.3
	349	157	122	5.2	0.45	129	343	287	1596	26.4
	400	172	139	6	0.43	103	398	229	1680	28.7
	428	175	149	6.4	0.41	91	344.5	202	1705	29.8
	379	125	124.5	5.4	0.33	120.5	363	268	1634	29.9
	400	124	132	6	0.31	114	413.5	253	1653	32.9
(Soutsos *et al.* 2013)	450	189	0	2.25	0.42	561	787	0	1890	44
	419	208	180	3.3	0.5	351	818	0	1890	37
(Papanicolaou and Kaffetzakis 2011)	310	197	216	7.9	0.64	345	681	0	1689	45
	303	132	199	4.5	0.44	409	434	0	1430	39
	386	136	150	14	0.35	577	736	0	1976	53
	460	175	198	5.75	0.38	469	861	0	1890	34
	325	168	218	4.9	0.52	405	235	0	1380	45
	451	183	43	7	0.41	434	672	0	1815	49
	455	195	195	3.5	0.43	420	406	0	1528	58
	370	170	148	5.5	0.46	380	625	0	1770	43
	382	180	68	3	0.47	528	873	0	1894	36.2
	315	145	228	15	0.46	209	1200	0	1952	43
	330	174	90	5	0.53	380	345	0	1334	26.6
	460	175	154	4.6	0.38	469	861	0	1990	31
(Andiç-Çakır and Hızal 2012)	395	257	232.5	8	0.65	546	449	0	1879	23.4
	395	237	233.6	10.2	0.6	467	467	0	1899	24.6
	394	217	234.8	13.4	0.55	587	484	0	1916	30.2
	367	202	236.8	2.4	0.55	147	544	0	1503	22.9
(Juradin *et al.* 2012)	380	185.6	120	6	0.49	469	0	0	1850	28.1
	380	185.44	110	6.37	0.49	470	0	0	1780	38.77
	430	172	90	6.76	0.4	479	0	0	1900	29.7
	380	185.6	120	6.5	0.49	366.3	197.8	0	1780	33.37
	380	185.44	110	6.86	0.49	367.6	198.5	0	1780	40.93
	380	185.44	120	7	0.49	469	0	0	1830	38.6
	380	185.44	120	7	0.49	470	0	0	1750	31.6

Table 3 Continued

(Mazaheripour *et al*. 2011)	500	160	133	17.2	0.32	179	287	657	1700	24.6
	500	160	162	18.68	0.32	175	282	645	2000	26.3
	500	160	190	18.68	0.32	187	300	554	2000	24.6
	500	160	190	17.2	0.32	201	323	475	1700	21.7
	500	160	168	18.68	0.32	226	363	311	2000	22.8
	500	160	133	19.02	0.32	221	355	305	1989	25
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	500	160	247	17.18	0.32	221	355	305	1872	24
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	420	200	165	3.7	0.48	546		0	1958	50
	420	200	231	2.9	0.6	546		0	1964	36
	420	200	231	2.8	0.6	546		0	1853	39
(Hubertova and Hela 2007)	370	160	148	2.76	0.43	543		0	1840	33
	370	170	148	3.7	0.46	507		0	1790	36
	370	170	148	5.6	0.46	533		0	1840	41
(Dymond 2007)	268	118.1	92	7.8	0.44	504	687	0	1896	61.78
(Ward 2010)	471.6	179.2	245	7.5	0.38	440	766	0	1861	47
	471.6	179.2	245	7.5	0.38	440	766	0	1861	43
(Yoğurtcu and Ramyar 2009)	350	173	296	7	0.49	0	884	578	2288	41.4
	399	198	239	5.8	0.5	0	863	546	2261	19.5
	401	196	240	5.8	0.49	0	867	551	2261	41.2
	397	199	237	11.1	0.5	0	858	546	2248	39.3
	399	200	240	8.2	0.5	187	746	0	1786	33.5
	395	197	242	6.3	0.5	186	743	0	1773	27.3
	395	198	228	5.5	0.5	188	714	0	1732	29.3
	419	210	245	3.5	0.5	0	506	569	1956	43.1
	396	198	232	3.66	0.5	69	471	362	1734	27.9
	393	196	228	4.1	0.5	136	472	180	1611	26.5
	400	200	233	5.4	0.5	197	509	0	1547	23.6
(Wang 2009)	314	140	257.7	9.4	0.45	298.8	801	0	1562	42
	335	140	158.9	9.9	0.42	289.8	801	0	1584	42
	335	160	159	7.3	0.48	289.8	801	0	1584	27
	240	160	153.8	7.8	0.67	289.8	801	0	1484	14
	244	140	224.4	12.6	0.57	229.7	1200	0	1898	42
	280	140	226.7	14.7	0.5	229.7	1200	0	1936	42
(Maghsoudi *et al*. 2011)	360	256.4	194.95	4.95	0.71	103	672	0	1890	20.8
	450	240.3	104.7	4.67	0.53	103	684	0	1870	28.5

fresh and hardened properties of LWSCC including the density and compressive strength at age 28 days.

The abbreviations in Table 1 are illustrated below:

Chemical Admixture (CA): Super-Plasticizer (SP), Poly-Carboxylate Based (PCB), Melamine Based (MB), Poly-Carboxylic Ether Polymer (PCEP), Poly Carboxylic Acid Ether (PCAE), and Naphthalene Lingo-Sulfonate Based (NLSB)

Air Entraining Agent (AEA): Sodium Sulphate Activator (SSA), Vinsol Resin based (VRB)

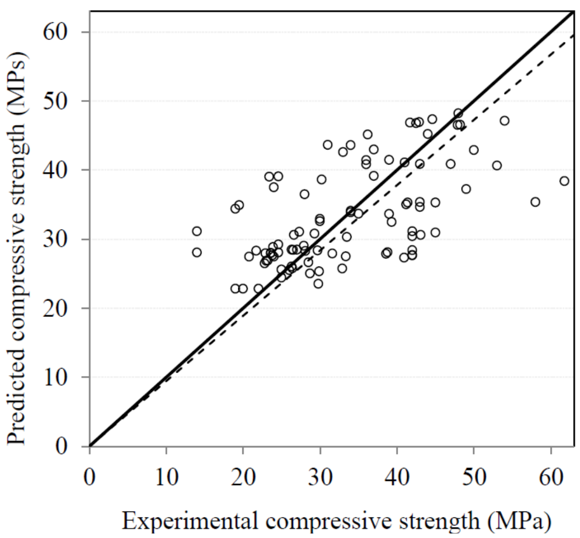

Fig. 2 Comparison of experimental compressive strength versus predictions of Eq. (1)

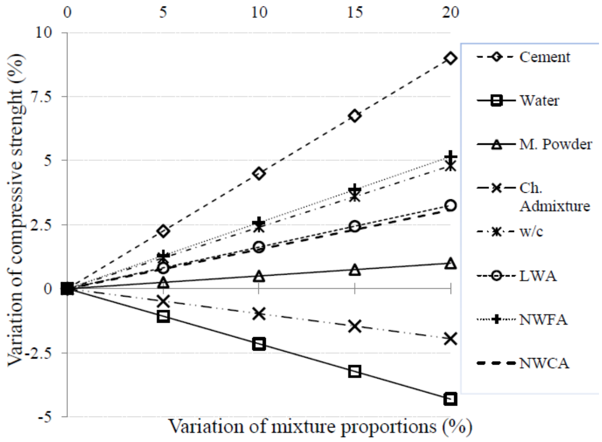

Fig. 3 Sensitivity of the compressive strength of LWSCC to mixture components in Eq. (1)

Light Weight Coarse Aggregate (LWCA): Expanded Clay (EC), Expanded Shale (ES)

Normal Weight Aggregate (NWA): Crushed Lime Stone (CLS), Natural River Sand (NRS)

Cement: Portland Cement (PC), Portland Cement type I and II (CEMI, CEMII)

Fillers: Fly Ash (FA), Limestone Powder (LSP), Silica Fume (SF), Pulverised Fuel Ash (PFA), Ground Granulated Blast furnace Slag (GGBS)

Not Given (N.G.) and gap in Table 1 indicates where no information is given and no application of the material in the mixture, respectively.

4. Analytical models

LWSCC is a new generation of construction materials that includes the advantages of both LWC and SCC. LWC has been used for years and its mixture designs to attain the desirable density and compressive strength for structural and non-structural applications can be found in some international codes and references. Moreover, although SCC is a new product to use in the construction industry, there are some significant researches and references to make the SCC mixture as a reliable material for construction. In the case of LWSCC as a new construction material, there is no instruction to select the components and how to mix the proportions to get the desired properties. Therefore, proposing an analytical model, based on the existing successfully examined laboratory test results can be as an instruction in mixture design of LWSCC.

5. Density and compressive strength of LWC, SCC and LWSCC

Generally, the density and compressive strength of structural LWC is less than those for CC. According to Table 2, definition of LWC in terms of density and compressive strength limitations varies in codes of practice and references. Applying different combination of components by various weights and volumes in the mixture has provided wide range of compressive strength and density in LWSCC mixtures. However, there are no guidelines for density and compressive strength limits of the combination of LWC and SCC. Compressive strength in 28 days age of the LWSCC is reported in all cases of study. According to Fig. 1, compressive strength values ranged from 14 to 58 MPa, with about 34% of mixtures having strength in excess of 40 MPa and 53% in excess of 32 MPa. This approves that it is possible to produce a concrete in almost all ranges of compressive strength as normal concreting with low density and self-consolidating capabilities. Density of concrete in those LWSCC mixtures vary between 1334 to 2361 kg/m^3 that is in good agreement with the density limits of structural and non-structural LWC presented in Table 2.

Experts for Specialized Construction and Concrete Systems (EFNARC 2005) classifies the concrete with density of 800 to 2000 kg/m^3 and compressive strength in the range of 8 to 80 MPa as light-weight structural SCC.

6. Proposed analytical models

Mechanical properties of LWSCC in the hardened stage are result of the fresh state properties. Understanding the interaction of components in the mixture and their combination with the resultant hardened concrete can ease the estimation of the mechanical characteristics prior to mixture design. This will enable the operators and designers to modify the mixture to reach the desired hardened properties. The heterogeneous nature of concrete in fresh and hardened state in addition to its non-linear behavior, especially at higher stress levels makes difficult to investigate the relationship between all the effective parameters in one package. However, some simplified approaches can predict the hardened properties from mixture proportions and fresh concrete proprieties, reasonably. Mixture proportions in majority of the presented case studies include the following components:

Chemical and mineral admixtures: LWSCC is type of SCC, so it’s inevitable to use chemical and mineral admixtures as: a) combination of High-Range Water-

Reducing Admixture (HRWRA) and Viscosity-Modifying Admixture (VMA) with or without defoaming agent and b) combination of HRWRA and high content of mineral powders (Shi and Wu 2005). Pozzolanic admixtures extend the hydration reaction and create good micro-pore structures, which improve durability of LWSCC (Gencel *et al.* 2011).

Addition of supplementary mineral powders and cementitious materials to the cement in the mixture may reduce the water demand and enhance the compressive strength, durability and workability (Liu *et al.* 2013). They also can optimize the viscosity of LWSCC and reduce the cost of project (Gencel *et al.* 2011), however, fillers may increase the density of concrete.

The admixtures in this study are divided into two main categories of: a) chemical (Super Plasticizer (SP) and Air Entraining Agent (AEA)) and b) mineral admixtures. The main reason to apply AEA is providing freeze-thaw resistance or improving the rheology of LWSCC (Vakhshouri and Nejadi 2016).

Powder components: Powder in the mixtures includes cement and filler. All case studies use the blend of cement with one or more types of mineral powder as illustrated in Table 1. Addition of the mineral powders in the mixture to produce a flow-able concrete, accompanied by replacement of normal-weight coarse aggregate with lightweight powder and lightweight aggregate to produce a lighter concrete makes the powder content of LWSCC higher than those for conventional concrete, LWC and SCC.

Light-Weight Aggregate (LWA): In spite of lower density and better thermal insulation of LWC, the interfacial transition zone, paste-aggregate bonding and segregation problems should be considered (Yoğurtcu and Ramyar 2009) with the application of LWA especially in LWSCC mixture.

Replacement of LWA with whole or part of the Normal Weight Coarse Aggregate (NWCA) is the main parameter to attain a lighter concrete. In the presented case studies in Table 1, both types of natural and manufactured chemical LWA have been used.

Normal weight aggregate: Along with the improving effect of NWCA on compressive strength, it raises the density of LWSCC. Therefore, it is necessary to balance out between the higher strength and lower density demands in the mixture design of LWSCC.

Ratio of water to binder (w/b): The water to binder ratio indicates the effective water available for cement hydration. It also influences the flow-ability and compressive strength of LWSCC. This study investigates the effect of water to cement (w/c) and water to total cementitious material (w/tc) as the effect of water to binder ratio on the compressive strength of LWSCC. Self-compacting requirement of the mixture also limits the volumetric ratio between the water and fine materials content to reduce the volume of cementitious materials as much as possible (Bogas *et al.* 2012). By increasing the cementitious materials, the relative distance between particles decreases, which increases the internal friction.

Cement content: Cement paste provides an adhesive cover for aggregates and works as conveyance agent to pass them through the formwork and fill the cavities. In LWSCC mixture due to presence of LWA, this paste should also be able to provide the sufficient rheology coefficients to prevent the segregation problem and supply the initial energy to move the light aggregates (Juradin *et al.* 2012). Increasing the cement content leads to a considerable rise of concrete cost and often has negative effects on shrinkage and increased thermal stress (Güneyisi and Gesoğlu 2008).

A multiple least-squares regression analysis was conducted to determine the most important effective components of the mixture that can be used to predict the compressive strength of LWSCC. The least-squares model calculates the best-fitting line for the observed data by minimizing sum of the squares of the vertical deviations from each point to the line. Table 3 shows more 114 mixture proportions of LWSCC from the previously conducted experimental investigations. In order to quantify the effect of each component of the mixture on the compressive strength of LWSCC, multiple regression analysis was applied to obtain the Eq. (1).

$$f_c' = 0.028944(c) - 0.04472(w) + 0.0096866(MP) - 0.41833(CHA) + 19.90325\left(\frac{w}{c}\right) + 0.0036688(LWA) + 0.016039(NWFA) + 0.015607(NWCA) \quad (1)$$

Where; *c*: cement (kg/m^3), *w*: water (kg/m^3), *MP*: mineral powder (kg/m^3), *CHA*: chemical admixture (kg/m^3), *w*/*c*: water to cement ratio, *LWA*: lightweight coarse aggregate (kg/m^3), *NWFA*: normal-weight fine aggregate (sand) (kg/m^3) and *NWCA*: normal-weight coarse aggregate (kg/m^3). Units of the components are given in Table 3 as well.

As shown in Fig. 2 there is a good agreement between the predictions of Eq. (1) versus the experimental data of compressive strength. However, sensitivity of the compressive strength to each component is different. The comparative statistical coefficients of the model proposed in Eq. (1) are described in next parts of this study. Fig. 3 is illustrative presentation of the percentage variation of the compressive strength due to percentage variation of each component in the mixture. It is assumed that in studying the effect of each component, variation of the other components in the mixture remains intact.

According to Fig. 3 with constant values of all other parameters in Eq. (1), the increased cement content causes the highest growing rate of the compressive strength. While, the increased water content has the most negative effect on the compressive strength of LWSCC. The positive effect of cement content is about twice the negative effect of water content. Mineral powder and the chemical admixture have both increasing and decreasing effects on the compressive strength. Increasing effect of LWA and NWCA on the compressive strength is very similar. In addition, NWFA and w/c ratio have higher increasing effect on the compressive strength than the effect of normal weight and light weight coarse aggregates.

Fig. 3 shows a rational effect of the components depending on their importance in the proposed Eq. (1). Apart from the combined effect of each component of the mixture on the compressive strength in Eq. (1), the individual relationship between the compressive strength

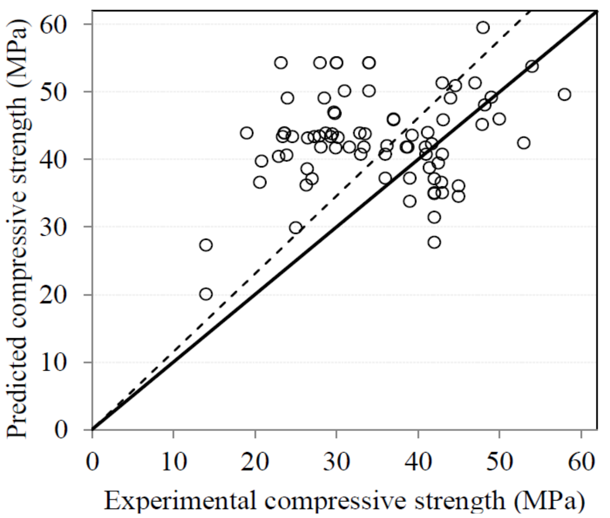

Fig. 4 Comparison of experimental compressive strength vs. predictions of $f_c' = f(c)$

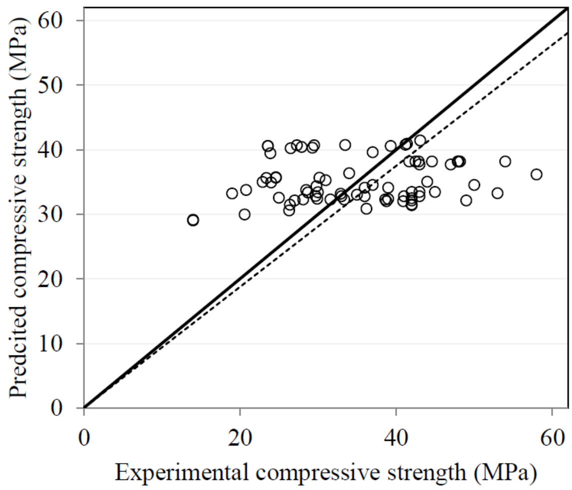

Fig. 6 Comparison of experimental compressive strength vs. predictions of $f_c' = h(tc)$

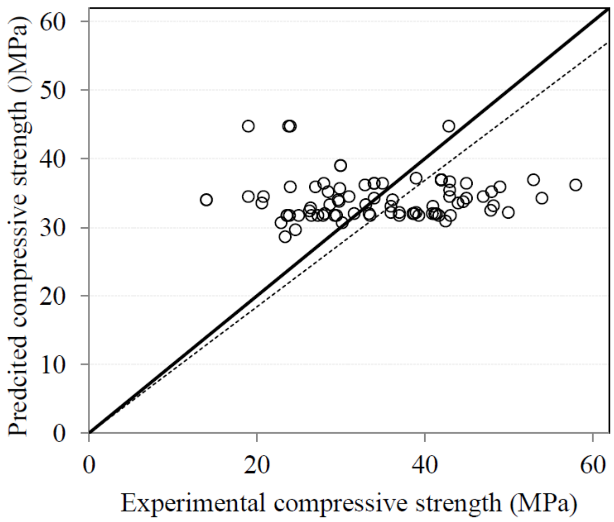

Fig. 5 Comparison of experimental compressive strength vs. predictions of $f_c' = g(w/c)$

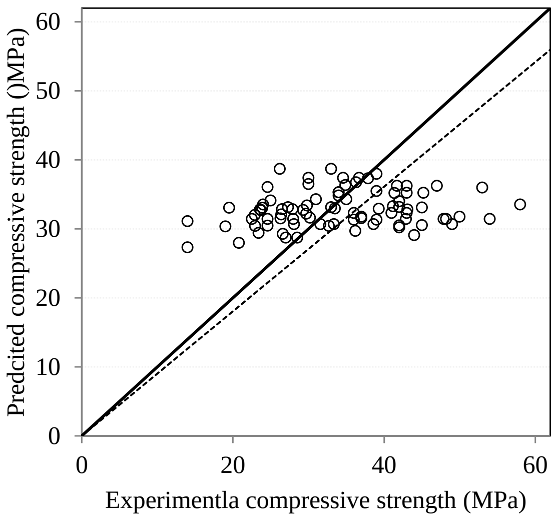

Fig. 7 Comparison of experimental compressive strength vs. predictions of $f_c' = i(w/tc)$

and mixture components have been investigated also.

There is a polynomial-type relationship between the compressive strength and cement content (c) in the mixture. Fig. 4 compares the experimental values of the compressive strength with predictions of the best fitting relationship between the compressive strength and the cement content ($f_c' = f(c)$).

The compressive strength of LWSCC has an exponential relationship with the ratio of water to cement (w/c). Fig. 5 shows the relationship between the experimental compressive strength and the predictions of established exponential relationship between the compressive strength and w/c ratio ($f_c' = g(w/c)$).

The relationship between the compressive strength and the total volume of cementitious materials (tc) in LWSCC mixture can be best explained by a power type equation. Fig. 6 compares the experimental compressive strength and predictions of the power type established relationship between the compressive strength and total cementitious materials ($f_c' = h(tc)$.

The effect of the ratio of water to total cementitious materials (w/tc) on the compressive strength of LWSCC can be described by a power type relationship. Fig. 7 compares the predicted and experimental compressive strength of LWSCC considering the effect of w/tc ratio. The relationship can be explained as $f_c' = i(w/tc)$.

Fig. 8 shows the power type variation of compressive strength with the changes of chemical admixture content (CHA) in the mixture. This relationship can be explained as $f_c' = j(CHA)$.

The proposed Eq. (1) is a linear relationship between the compressive strength and all the measured parameters presented in Table 4. However, it is obvious that some parameters such as w/c ratio are dependent on the other parameters. Therefore, including the most effective parameters of the mixture proportion to develop a relationship with the compressive strength will be more reliable. Among the independent variables in Eq. (1), the chemical admixture, mineral powder and water content are included in other parameters or have very low effect on the compressive strength. Consequently, cement content, w/c

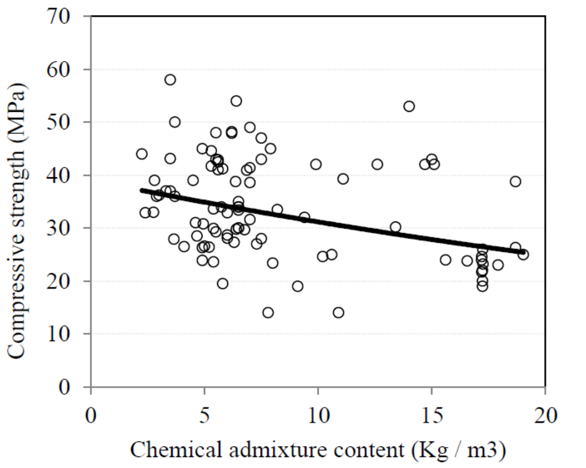

Fig. 8 Effect of chemical admixture on the compressive strength of LWSCC

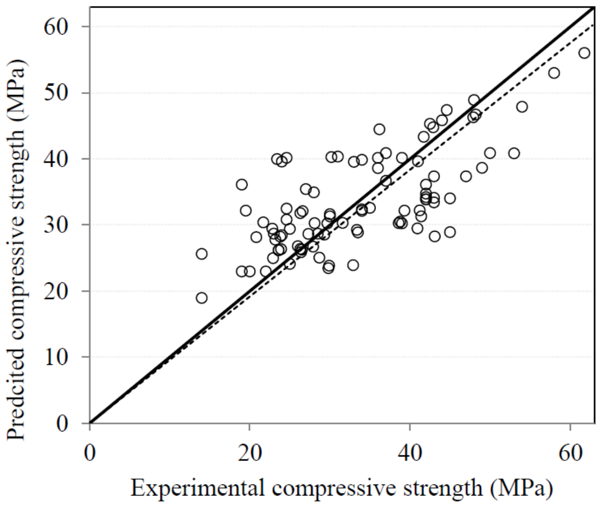

Fig. 9 Comparison of experimental compressive strength vs. predictions of Eq. (2)

Table 4

Proposed model	Multiple R	R square	Adjusted R square	Standard error
Eq. (1)	0.9723	0.9454	0.9296	8.55
Eq. (2)	0.9711	0.943	0.9294	8.6011

ratio or the ratio of water to total cementitious materials, LWA, NWCA and NWFA are included in Eq. (2) to predict different combination the compressive strength from the other most effective mixture components of LWSCC.

$$f_c' = 0.011969(c) + 24.73055(w) +0.0096866(w/tc) + 0.035253(LWA) + 0.013057(NWFA) + 0.015477(NWCA) \quad (2)$$

Where; *c*: cement (Kg/m^3), *w/tc*: water to total cementitious material ratio, *LWA*: light weight coarse aggregate (Kg/m^3), *NWFA*: normal weight fine aggregate (sand) (Kg/m^3) and *NWCA*: normal weight coarse aggregate (Kg/m^3).

Fig. 9 compares the experimental compressive strength with the predictions of Eq. (2) for different combination of mixture components. According to Figs. 2 and 9, results from the both equations are in good agreement with the measured compressive strength of LWSCC from mixture proportions.

Table 4 compares the statistical coefficients of proposed Eqs. (1) and (2) compared to the experimental values of the compressive strength of LWSCC.

Table 5 Range of the mixture components, density and compressive strength

	Water content (kg/m^3)	Cement content (kg/m^3)	Density (kg/m^3)	Compressive strength (MPa)
Minimum	110	170	1334	14
Maximum	257	550	2361	62

7. Comparison of the results and discussion

Figs. 2 and 9 show the comparison of the measured experimental results versus the predictions of Eqs. (1) and (2) for the compressive strength, respectively. In addition, the statistical coefficients of the equations confirm the accuracy of the proposed equations to estimate the compressive strength of LWSCC from the mixture proportions. However, since the most effective parameters are included in Eq. (2), it will be more efficient in prediction of the compressive strength from mixture proportions of LWSCC.

It is worth to mention that the proposed equations are based on the mass or volume limits of the component shown in Tables 1 and 3. Considering lack of any instruction or reference for mixture design of LWSCC, the proposed equations can be useful starting point to select the proper components and their volume and mass limits by a reasonable estimation of compressive strength for design purposes.

Table 5 indicates the range of cement content, water content, density and compressive strength of the LWSCC mixtures utilized in this study. The range of other proportions can be obtained from Table 3.

Hardened properties of concrete, particularly the compressive strength are strongly influenced by the volume of the cement paste in the mixture. In this regard, effects of the cement content and total cementitious materials content on the compressive strength are investigated, separately. According to Fig. 4, increasing the cement content in the mixture improves the compressive strength, exponentially. This effect is similar to the effect of total cementitious materials in the mixture as presented in Fig. 7. However, the cement content solely has somewhat stronger effect on the compressive strength.

The ratio of water to the cementitious materials in the mixture is another effective factor that directly affects the mechanical properties. According to Fig. 5 the water to cement ratio has an inverse effect on the compressive strength; i.e., by increasing the water to cement ratio, compressive strength is decreasing, exponentially. The compressive strength is similarly influenced by the water to

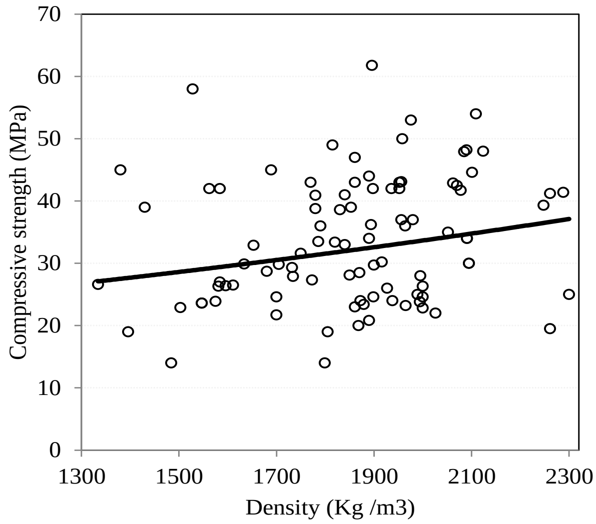

Fig. 10 Density versus compressive strength of LWSCC

Table 6 Individual relationships between compressive strength and mixture proportions of LWSCC

	Equation	R square
$f_c' = f(c)$	$f_c' = -0.0001c^2 + 0.1109c + 7.655$	0.853
$f_c' = g(w/c)$	$f_c' = 44.73e^{-0.686\,(\frac{w}{c})}$	0.792
$f_c' = h(tc)$	$f_c' = 2.224(tc)^{0.4305}$	0.832
$f_c' = i(w/tc)$	$f_c' = 20.179(w/tc)^{-0.422}$	0.813
$f_c' = j(CHA)$	$f_c' = 39.062e^{-0.023\,(CHA)}$	0.871

total cementitious materials ratio in Fig. 7. However, variation of the water to total cementitious materials ratio has greater effects on variation of the compressive strength. Although the water-reducing and viscosity-modifying characteristics of the chemical admixtures and super-plasticizers may affect the mechanical properties, they are included in the major effective parameters of mixture design such as cement paste and water to cementitious materials ratio. However the effect of chemical admixture on the compressive strength is studied individually. According to Fig. 6, along with the advantages of super-plasticizer to improve the workability and viscosity requirements of the fresh concrete, it has a decreasing effect on the compressive strength of the hardened concrete.

7.1 Density-compressive strength relationship in LWSCC

In accompany with the advantages of self-compacting capability of LWSCC, proper lightweight aggregates can optimize the structural efficiency by improving the strength to weight ratio. The density of concrete has significant influence on the compressive strength. Generally, the higher density of fresh concrete results a higher strength concrete. Some investigations on LWSCC relay on the bulk density of the mixture. This fact can be a matter of conflict in LWSCC mixture design while the higher strength must be optimized by lower density.

Fig. 10 shows the increasing rate of compressive strength with density of the fresh concrete. The value of density in majority of the mixtures presented in Table 3 is under 2000 kg/m^3. In this range of concrete density, the compressive strength is more influenced by the density. However, for all ranges of LWSCC density, the higher density in fresh state, results a higher compressive strength in hardened state of the concrete.

Despite a considerable agreement of the developed relationships between the compressive strength and different components and their ratio in the mixture, they are different accuracy and efficiency to estimate the compressive strength. However, this study recommends the equations proposed in Table 6 to estimate the compressive strength of LWSCC in relation to each mixture components. The estimation should be confirmed by the general Eq. (2) also.

8. Conclusions

There are not adequate instructions and guidelines about the mixture design and proportioning of components of LWSCC in the literature. This study provides a useful platform to optimize the mixture design with high strength and low density and avoid the problems such as segregation, blocking and bleeding.

The previously conducted experiments on the 114 mixture design of LWSCC form 21 investigations are evaluated. The combined and individual effects of the mixture components on the mechanical properties of LWSCC, especially the compressive strength are investigated and the following conclusions are drawn:

• New models are developed and verified to estimate the compressive strength of LWSCC from mixture components and their ratio;

• Sensitivity analysis of the mixture components in the proposed models indicate the minor effect of the mineral powders and chemical admixture on the compressive strength of LWSCC.

• The cement content and water content have the most increasing and decreasing effect on the compressive strength of LWSCC.

• Improving effect of the lightweight aggregate on the compressive strength are more than the normal-weight coarse aggregate.

• Increasing effect of cement content on the compressive strength of LWSCC is to some extent higher than the effect of total cementitious materials in the mixture.

• Decreasing effect of water to cement ratio on the compressive strength of LWSCC is slightly higher than the effect of water to total cementitious materials ratio in the mixture.

• The ratio of water to cement and lightweight aggregate content in the mixture show similar positive effect on the compressive strength of LWSCC.

• Individual relationship between the compressive strength and the mixture parameters (cement content, powder content, chemical admixtures and water to binder) are proposed and verified.

• According to the collected experimental data, it is possible to get wide range of low and high compressive strength in LWSCC by proper combination of SCC and

LWC.

• Wide range of chemical admixtures and mineral powders can be used in LWSCC mixture to optimize the rheological and structural requirements of LWSCC mixture.

• The increasing effect of mixture density on the compressive strength is higher in the range of density under 2000 kg/m^3.

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