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Case study

Mix design of light-weight self-compacting concrete

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ABSTRACT

In recent decades, the utilization of mineral and chemical admixtures in concrete technology has led to changes in the formulation and mix design which has, in turn, made the concrete stronger and more durable. Light weight concrete (LWC) is an excellent solution in terms of decreasing the dead load of the structure, while self-compacting concrete (SCC) eases the pouring and removes construction problems. Combining the advantages of LWC and SCC is a new field of research. Considering its light weight of structure and ease of placement, Light-weight self-compacting concrete (LWSCC) may be the answer to the increasing construction requirements of slender and more heavily reinforced structural elements. Twenty one laboratory experimental investigations on the mix proportion, density and mechanical properties of LWSCC have been published in the last 12 years and these are analyzed in this study. The collected information is used to investigate the mix proportions including the chemical and mineral admixtures, light weight and normal weight aggregates, fillers, cement and water. Analyzed results are presented in terms of statistical expressions. It is very helpful for future research to choose the proper components with different ratios and curing conditions to attain the desired concrete grade according to the planned application.

1. Introduction

Generally the three major characteristics of concrete are workability, strength, and durability. It is believed that strength and durability are related to the hardened concrete and workability is related to the fresh concrete, however hardened properties may be directly attributed to the mix design and fresh properties. In other words, mix design and the fresh properties of concrete are the most critical points to control in relation to the mechanical characteristics of hardened concrete (Domone, 2006). The early evaluation of hardened concrete properties is very important. The problem is that following the hardening process, the quality and mechanical properties do not improve. The structural behavior of concrete relies on mixing proportions and material properties of the composite system and these factors do not change after hardening.

Achievements in modern concrete technology have led to the introduction of light-weight concrete (LWC) and self-compacting concrete (SCC) as structure mass reducing and workable materials. LWC which is well known in the construction industry as opposed to SCC is an excellent solution for decreasing the dead load of the structure, while SCC is a modern material which facilitates the pouring and removal of construction problems. In recent years, some efforts have been made to combine the advantages of these two types of concrete in one package called light-weight self-compacting concrete (LWSCC). There are a wide range of publications about LWC concerning different light weight aggregates and mix

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proportions. However SCC is a completely new topic in the construction industry and it has therefore attracted increasing research interest especially during the last decade. Since LWSCC is combination of two materials and one part is not fully investigated, it needs much more market research.

Despite different codes of practice about LWC mix design and some rare publications about SCC in the literature, there is no reference and technical draft about LWSCC mix design and its application. However, owing to the expected advantages of LWSCC in terms of cost efficiency and reduced construction time, research to comprehend the complicated nature of this new material is increasingly growing in different parts of the world.

Generally, the compressive strength of LWSCC is a fundamental parameter to estimate its other mechanical properties. In spite of available studies on the advantages of LWSCC associated with its high performance in the fresh state, there are less available studies regarding the expected hardened properties for mechanical responses like compressive strength. LWSCC is highly sensitive to changes in mix component properties and their proportions, therefore it requires increased quality control. The typical characteristics of LWSCC mix proportions, which are necessary to ensure adequate fresh properties, can have significant effects on hardened properties like strength, dimensional stability and durability (Koehler and Fowler, 2015). For instance, the compressive strength of the LWSCC is influenced by the aggregate type and the water to cement and water to total powder (Andiç-Çakır and Hızal, 2012).

The relation between cement paste and aggregates is very important in the mix design of concrete. SCC has a higher paste amount than conventional concrete and LWC to facilitate the flowing of aggregates to fill any voids inside the formwork. Paste coating of aggregates to reduce the friction and direct touching between aggregates can improve the flowability of fresh concrete. Controlling the water to cement ratio, results in a denser and stronger concrete. In LWSCC, this problem is even more obvious due to insufficiencies in the initial energy of lightweight aggregates in relation to moving along with the light weight aggregates in the cement paste (Juradin et al., 2012). To keep the balance among the proportions of LWSCC is therefore important to achieve the required flowability in the fresh state and the planned density and high quality in the hardened state.

Packing density theory is a method of concrete mix design which has been successfully used in LWSCC (Kaffetzakis and Papanicolaou, 2012) by determining the optimum mortar to aggregates packing voids ratio. The main steps to attain the LWSCC mix design in this method are: (a) minimizing the voids volumes related to the coarse aggregate, (b) minimizing the water to cement ratio, (c) maximizing the density of the cementitious materials and (d) optimizing the flowability and requirements of the fresh concrete.

2. Conflict of segregation problem and flowability requirements

Although the mix design of LWSCC contains both LWC and SCC proportions, its special mix design does not exactly follow the mix design for these types of concrete. However the technological considerations and mixing problems in LWC and SCC still govern the LWSCC mix design. Fresh concrete is combined of fine and coarse aggregates suspended in a matrix of binder paste. Viscosity of the mortar and the volumetric fraction of the aggregates control the flow behavior. All studies evaluate the flowability of fresh LWSCC mixes by slump flow tests, J ring tests and V funnel tests according to the Self-Compacting Concrete Committee of EFNARC (Gencel et al., 2011). Although the workability aspects of LWSCC could be improved by approved suggestions in SCC, the LWSCC shows specific features that have resulted from using the lightweight aggregate (Juradin et al., 2012).

The common problem reported in almost all published studies in relation to combining LWC and SCC is to ensuring the flow-ability of the fresh state and the low density of hardened concrete without segregation. Aggregate shape has a beneficial influence on the flowability of fresh concrete; however, when mixing the light and normal aggregates in LWSCC, the heavier aggregates tend to considerably sink (Andiç-Çakır et al., 2009).

Expanded clay, expanded granulated slag, expanded perlite or vermiculite and expanded polymer materials are frequently used light weight aggregates in LWC. Due to closed cavities, water absorption is high and so it is difficult to estimate the required water volume. Rising the water to the surface during mixing, in association with the tendency of light weight aggregates to float up, increases the segregation risk (Juradin et al., 2012; Barrios Illidge, 2010).

Some investigations (Mazaheripour et al., 2011) in the LWSCC mix design recommend applying the mix design method of high performance concrete for LWC in the mix to avoid the segregation problem and to keep the strength of the concrete high, in spite of applying light-weight aggregates.

3. Research significance

It is vital to investigate whether or not all the assumed hypotheses used to design conventional concrete, SCC and LWC structures are also valid for LWSCC structures. Almost all the published case studies including detailed information about the selection of components, mix proportions and the resultant fresh and hardened properties have been presented in this study. Despite the limited number of publications, the collected data gives the impression of being adequate for valid and useful systematic assessment of the variety of mix parameters and properties in statistical expressions. Above all, this will develop the idea of what can be expected with LWSCC for prospective users and researchers. This also gives interested and involved people a context in which to assess their own practices and to inform other researchers about their products.

The main objectives of this study are:

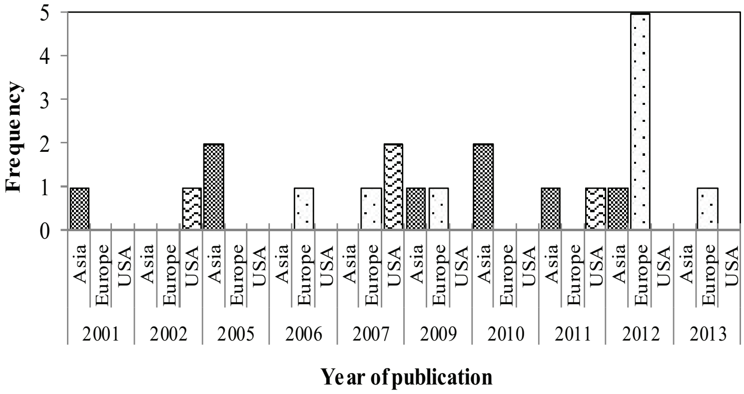

Fig. 1. Geographical distribution of case studies in LWSCC.

(a) Systematic evaluation of the experiments conducted by researchers in different parts of the world. Since LWSCC is a novel topic in the construction industry, comprehensive collection of data to date, accompanied by analytical comparisons will be a key starting point for upcoming investigations and the application of LWSCC in real projects.

(b) Evaluation and comparison of the effect of different components of the LWSCC mix design in terms of compressive strength.

4. Initial observations

The main part of this study is that of the LWSCC properties, mix proportions and component materials. However, the range of materials in different mixes and the general distribution of components are also presented. Fig. 1 shows the geographical distribution of the case studies in different years. In spite of the initiation of SCC research and its application in Japan, LWSCC investigation is growing in European countries particularly in recent years. Noticeably no record of LWSCC is found in Australia, Africa and South America.All the presented studies have been performed in laboratory conditions and there is no indication of the application of LWSCC in real projects.

5. Database for mix design, density and compressive strength of LWSCC

5.1. Experimental results

The resultant data of published experimental investigations is an effective tool to propose verifying new models and comparing the actual and predicted values. In spite of the effectiveness of experimental results from different sources, their use can be problematic owing to: (a) insufficient information concerning the exact composition of the concrete mixes; (b) the different size and numbers of the specimen, curing conditions and testing methodology; and (c) extracting the real data of experimental results from graphs and diagrams.The experimental database of this study has been collected mainly from the papers presented at conferences and the published articles on LWSCC. The database contains information about the composition of the mixes, type of chemical admixture as plasticizer and air entraining agent, curing method, curing age, type of fine and coarse aggregate, filler type, cement type, and the fresh and hardened properties of LWSCC i.e. density and compressive strength at the age of 28 days. However, the other mechanical properties of LWSCC have not been investigated as much as the above mentioned characteristics, and published empirical data in the literature is still very rare.

5.2. Range and type of case studies

The case studies for analysis have been selected on the basis of the concrete produced, cured and tested in laboratory conditions. One hundred and fourteen mix designs with sufficient detailed information in 21 published articles and dissertations have been reported. Table 1 points out the year of publication, the country of research, number of mixes of different concrete types, component materials, key mix proportions, curing type, testing ages and 28 day compressive strength for all the cases. Mix proportions include the chemical admixture (super plasticizer and air entraining agent), normal and light weight aggregates and cement and filler type. Different researches have applied different components by various proportions to attain the LWSCC by low-density and excellent flow-ability. Table 2 shows the reported mix proportions by presenting the cement, water, mineral powder (MN), and chemical admixture (CA), fine and coarse light weight aggregate (LWA) and normal weight fine and coarse aggregate in terms of weight in the volume of concrete mix, and

Table 1
Database for mix design of LWSCC.

Ref.	Country	Year	CA				Test age	No. of mixes				Curing type	LWCA	NWA		Cement	Filler
			SP Type	Volume (Kg/m^3)	AEA Type	Volume (Kg/m^3)	h-day	CC	LWC	SCC	LWSCC			Fine	Coarse		
Andiç-Çakır and Hızal (2012)	Turkey	2012	PCAE	2.4–10.2	Oil alcohol and ammonium salt based	1.4-3.9	7, 28 d			2	3	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	2012	Liquid PCAE	6–7.28			1, 3, 7, 28 d				9	Moist	Liapor, EC granules 0–2, 1–8 mm	CLS 0–4 mm		PC	SF,FA, recycled concrete powder
Kaffetzakis and Papanicolaou, (2012)	Greece	2012	PCEP	1.06	N.G.	0.163-2.272	7, 28, 56 d				11	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, SF
Andiç-Çakır et al. (2009)	Turkey	2009	PCB	4.9–11.1	Not given	2.88-6.09	7, 28 d			5	10	N.G	Pumice 4–8, 8–16 mm	Crushed sand (SSD) < 5 mm	N.G 5–15 mm	CEM I 42.5	FA, LSP
Barrios Illidge (2010)	USA	2002	PCB Eucon SPJ	1.96–3.91 mL/kg	DARAVAIR 1000, AIR MIX 250 and AIR 30	2.1-2.61 mL/kg	28, 56 d				18	Humid heat room 32–35 °C	Crushed granite from Vulcan mine material	NRS		Type III and Class C Boral cement	SF, FA
Mazaheripour et al. (2011)	Iran	2011	N.G.	17.18–19.02			7, 14, 28 d				10	48 free and moist	LECA from EC 0–3, 3–10 mm	NRS < 4.75 mm	Natural gravel < 10 mm	CEM II	SF, LSP
Kobayashi (2001)	Japan	2001	PCAE	1.5–1.8% of cement weight			28 d			1	1	Moist	Artificial LWA < 15 mm	NRS	CLS < 15 mm	PC	FA
Shi and Wu (2005)	China	2005	PCB	3.3	VRB	0.2	1, 3, 28, 90, 180 d				5	Fog room-23 ± 2 °C	ES < 9.5 mm	NRS<4.75mm		CEM I	FA class F
Hwang and Hung (2005)	Taiwan	2005	NLSB	2–26			3, 7, 28, 56, 91 d				13	N.G.	Manufactured with sintering fine sediment excavated from reservoir < 13 mm	Crushed sand		CEM I -C150	FA class F
Persson (2006)	Sweden	2006	MB	2.97–7.32	N.G[a]	0.106-1.203	28 d	1		2	2	N.G.		NRS < 2 mm	Gravel < 8, quartzite sandstone 8–16 mm		SF, LSP
Hubertova and Hela (2007)	Czech republic	2007	PCB	1.5%	N.G.	0.4%	7, 28 d		2	1	2			Finely ground limestone, NRS < 4 mm			
Dymond (2007)	USA	2007	N.G.	11.86	N.G.	0.6	7, 14, 28 d				2	Moist	Aggregate of Carolina Stalite Company	NRS < 2 mm		PC	FA
Ward (2010)	USA	2007	N.G.	4.9 mL/kg	N.G.	0.2 mL/kg	11, 16 h 7, 28, 90 d				2	Moist	EC < 20 mm	NRS		PC	N.G.
Yung (2009)	Taiwan	2009	N.G.	7.3–15.1			3, 7, 28, 56, 90 d				10	Moist	Dredged silt from reservoirs in southern Taiwan < 9.5 mm, 12.7 mm	NRS < 2.38 mm		CEM I	FA, slag
Kim and Choi (2010)	South Korea	2010	PCB	0.7–1.3% of cement weight	N.G.	0.005% of cement weight	3, 7, 28 d				9	Moist	LC1 < 20 mm By rhyolite fine powder, LC2 < 20 mm by with wastes (screening sludges)	Local NRS	CLS < 20 mm	PC	N.G.

Maghsoudi et al. (2011)	Iran	2010	PCEP	4.675–4.95			3, 7, 28, 90 d				Moist	Leca 4.75–9.5 mm	NRS < 4.75mm		CEM II	LSP and SF
Bymaster (2012)	USA	2011	ADVA 405, 408	9.78–16.95 mL/kg	ADVA 575	3.26-7.17 mL/kg	1, 7, 28 d		1	2	Moist	EC, ES	NRS	CLS	CEM I inSCCCEM III in LWSCC	FA
Gűneyisi et al. (2012)	Turkey	2012	PCAE	5.3–6.4			28 d			9	Moist	Coarse cold-bonded FA 4–16 mm	Mix of CLS and NRS < 5 mm		CEM I 42.5R	SF, FA class F
Syaiful Anwar et al. (2012)	Indonesia	2012	N.G.	6.5–7.5	SIKA Viscocrete modified polycarboxylate copolymers	4-10	3, 7, 28 d		1	2	Moist	Pumice 4.8–19 mm	NRS < 9.6 mm	CLS < 19 mm	(PCC) Indonesian Standard (SNI) 15-7064-2004	FA, Indocement TBK
Bogas et al. (2012)	Portugal	2012	PCB	0.6–1.1% of fine agg.			2, 28, 90 d	2	1	2		Two Iberian EC: Leca from Portugal and Arlita (Spain)	NRS	CLS < 12.5 mm	CEM I 42.5R	FA (Pego thermoelectric power plant)
Soutsos et al. (2013)	NorthIreland	2013	PCB	3.3	SSA		3, 6, 12, 24 h 2, 4, 7, 14, 28 d	5	1	2	Moist	Lytag 4–14 mm	NRS < 600 μm	Crushed Granite < 20 mm	CEM I 42.5N	PFA, GGBS, LSP

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).

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).

[a] Not Given (N.G.) in Table 1 indicates where there is no information and the blank space means the material is not used in that case study.

the ratio of water to cement (W/C). The resultant density and compressive strength from the mix proportions are also shown in Table 2.

5.3. Curing condition

Curing the hardened concrete after 24 and 48 h and after curing in the lime saturated water is the most common method (66%) among the reported studies. Fog room, heat room and the environmental chamber are equally used in about 14% of the studies and there is no information about the remaining 20%.

5.4. Compressive strength

The resultant compressive strength at the age of 28 days is reported for all mixes of LWSCC in the case studies. According to Fig. 2, compressive strength values ranged from 14 to 58 MPa, with about 34% of mixes having strength in excess of 40 MPa and 53% in excess of 32 MPa. This confirms the practicability of producing the LWSCC in almost all ranges of compressive strength as normal concrete manufacturing.

Table 1 presents a statistical and technical analysis of the components which takes into account the mineral and chemical admixture, light weight and normal weight coarse and fine aggregates in the LWSCC mix designs.

6. Mix proportions

6.1. Admixtures

LWSCC is a type of SCC, so it is inevitable that we use chemical and mineral admixtures as: (a) a combination of high-range water-reducing admixture (HRWRA) and viscosity-modifying admixture (VMA) with or without the defoaming agent and (b) a 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 improves the durability of LWSCC (Gencel et al., 2011).

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. Super plasticizer has been applied in all case studies, while 38% of the case studies do not include AEA. The main reason to apply AEA i.e.; providing freeze-thaw resistance or improving the rheology of LWSCC is not clearly defined in the case studies.

The majority of the case studies (62%) apply Poly carboxylate acid-based super plasticizer in the mixes. The type of super plasticizer is not given in 24% of the case studies. Melamine based and Naphthalene lingo-Sulphonate based super plasticizers have been applied equally in 5% of the case studies.

Despite the limited types of super plasticizers, it appears that there is extensive range of AEA applied in the mixes. There is no information about the AEA type in 42% of the case studies. In the remaining mixes, sodium sulphate activator, vinsol resin based, oil alcohol and ammonium salt based and DARAVAIR-1000, AIR MIX-250 and AIR-30 of ASTM standard are equally used in 5% of the case studies.

Based on the required performance in the mixes, different dosages of the chemical admixtures have been used in the mixes. As shown in Table 1, the volume of super plasticizer varies from 1.06 to 26 kg/m^3 in the concrete mixes. Besides the weight of AEA

Table 2
LWSCC mix proportions of experimental studies.

Ref.	Cement (kg/m^3)	Water (kg/m^3)	Mineral powd. (kg/m^3)	Chem. admix. (kg/m^3)	w/c	LWA (kg/m^3)	NWFA (kg/m^3)	NWCA (kg/m^3)	γ (kg/m^3)	f'c (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	0.60	567	467	0	1899	24.6
	394	217	234.8	13.4	0.55	587	484	0	1916	30.2
	367	202	236.3	2.4	0.55	147	544	0	1503	22.9
Juradin et al. (2012)	380	185.6	120	6	0.49	469.00	0.00	0	1850	28.1
	380	185.44	110	6.37	0.49	470.80	0.00	0	1780	38.77
	430	172	90	6.76	0.40	479.60	0.00	0	1900	29.7
	380	185.6	120	6.5	0.49	366.30	197.80	0	1820	33.37
	380	185.44	110	6.86	0.49	367.60	198.50	0	1780	40.93
	380	185.44	120	7	0.49	469.00	0.00	0	1830	38.6
	380	185.44	120	7	0.49	470.00	0.00	0	1750	31.6
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
Andiç-Çakır et al. (2009)	350	173	296	7	0.49	0	884	578	2288	41.4
	399	198	239	5.8	0.50	0	863	546	2261	19.5
	401	196	240	5.8	0.49	0	867	551	2261	41.2
	397	199	237	11.1	0.50	0	858	546	2248	39.3
	399	200	240	8.2	0.50	187	746	0	1786	33.5
	395	197	242	6.3	0.50	186	743	0	1773	27.3
	395	198	228	5.5	0.50	188	714	0	1732	29.3
	369	184	224	4.9	0.50	177	612	0	1575	23.9
	400	200	233	5.4	0.50	197	509	0	1547	23.6
	419	210	245	3.5	0.50	0	506	569	1956	43.1
	396	198	232	3.66	0.50	69	471	362	1734	27.9
	393	196	228	4.1	0.50	136	472	180	1611	26.5
	400	200	233	5.4	0.50	197	509	0	1547	23.6
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	17.25	0.32	169	772	0	1965	23.2
	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
	500	160	249	17.23	0.32	64	722	0	1868	20
	500	160	249	17.23	0.32	64	722	0	1805	19
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	624	0	1956	37
	420	200	165	3.7	0.48	546	624	0	1958	50
	336	200	231	2.9	0.60	546	624	0	1964	36
	336	200	231	2.8	0.60	546	624	0	1853	39
Hubertova and Hela (2007)	370	160	148	2.76	0.43	543	639	0	1840	33
	370	170	148	3.7	0.46	507	627	0	1790	36
	370	170	148	5.6	0.46	533	635	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
Yung (2009)	314	140	157.7	9.4	0.45	289.8	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	0.50	229.7	1200	0	1936	42
	315	150	228.1	15.1	0.48	208.8	1200	0	1952	42
	170	160	220.3	10.9	0.94	208.8	1200	0	1799	14
Maghsoudi et al. (2011)	360	256.4	194.95	4.95	0.71	103	672	0	1890	20.8
	450	240.3	104.675	4.67	0.53	103	684	0	1870	28.5
Gϋneyisi et al. (2012)	550	192.5	0	5.5	0.35	688.00	509.00	179.00	2124	48
	467.5	192.5	82.5	5.3	0.41	677.00	501.00	176.00	2101	44.6

Table 2 (*Continued*)

Ref.	Cement (kg/m^3)	Water (kg/m^3)	Mineral powd. (kg/m^3)	Chem. admix. (kg/m^3)	w/c	LWA (kg/m^3)	NWFA (kg/m^3)	NWCA (kg/m^3)	γ (kg/m^3)	f'c (Mpa)
	385	192.5	165	5.3	0.50	665.00	492.00	173.00	2078	41.7
	495	192.5	55	6.4	0.39	680.00	503.00	177.00	2109	54
	440	192.5	110	6.2	0.44	670.00	496.00	174.00	2090	48.2
	412.5	192.5	137.5	6.2	0.47	668.00	495.00	174.00	2085	47.9
	357.5	192.5	192.5	5.6	0.54	661.00	489.00	172.00	2070	42.5
	330	192.5	220	5.6	0.58	657.00	486.00	171.00	2062	42.9
Syaiful 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	0.30	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	0.30	250	823	0	2052	35
Soutsos et al. (2013)	450	189	0	2.25	0.42	561	787	0	1890	44
	419	208	180	3.3	0.50	351	818	0	1980	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
	450	180	150	15.6	0.40	492	722	0	1938	24
	330	174	90	5	0.53	380	345	0	1334	26.6
	400	203	133.4	9.1	0.51	403	590	0	1396	19
	460	175	154	4.6	0.38	469	861	0	1990	31

is less than the weight of the super plasticizer and it differs from 0.2 to 10 kg/m^3 in the mixes.

Fig. 3 shows the types of the chemical admixtures together with the relative number of case studies that use each type of chemical admixture.

6.2. Powder components

Powder in the mixes 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. The majority of the cement employs different types of Portland cement. Different classes of Portland cement type I (CEM I) are used in 43% of the case studies, while 14 and 9% of the case studies have used Portland cement type II (CEM I) and Portland cement type III (CEM III) respectively. The class of Portland cement is not mentioned in 23% of the case studies. Five percent of the case studies have used local (Indonesian) produced cement and the cement type is not mentioned in the rest of case studies.

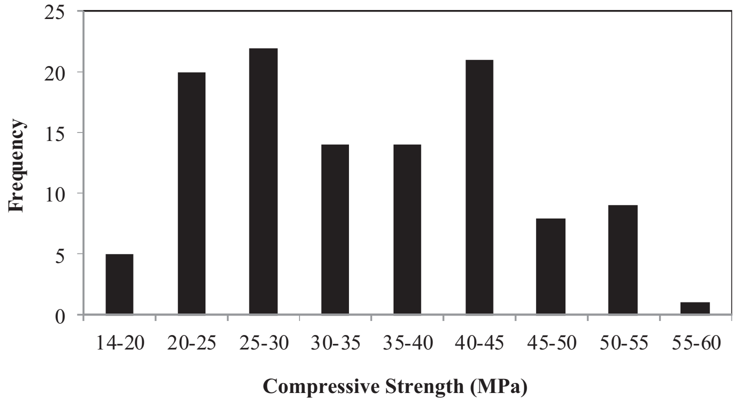

Fig. 2. The frequency of compressive strength ranges in the case studies.

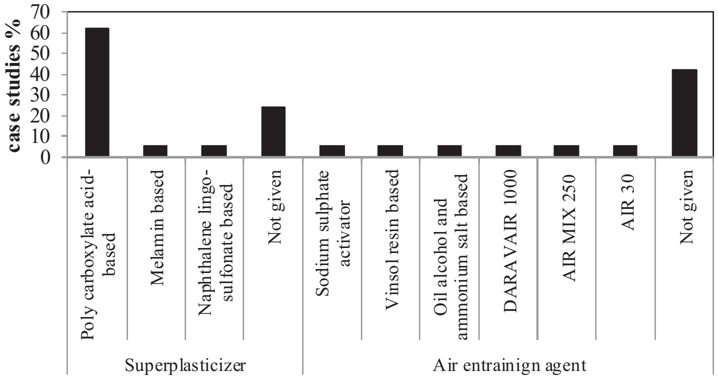

Fig. 3. Type of chemical admixtures and relative number of case studies using each type.

The range of used mineral admixtures like filler powders is more extensive than the cement types. Fly ash, lime stone powder, silica fume, furnace slag and pumice powder have been used in 71, 28, 33, 9 and 5% of the case studies respectively. Other types of powders like recycled concrete powder, industrial waste of olivine powder and Inducement TBK (Indonesian made filler) have been applied equally in 5% of the case studies. No information is given about the fillers in the remaining 10% of the case studies. It worth mentioning that 57% of the studies have used the combination of two or more fillers in the LWSCC mixes.

Fig. 4 shows the components of filler powders together with the relative number of case studies that use each type of filler.

The addition of the mineral powders in the mix design to produce a flowable concrete is accompanied by the replacement of normal weight coarse aggregate with a light weight powder and light weight aggregate to produce a lighter concrete. This makes the powder content of the LWSCC higher than that of conventional concrete, LWC and SCC. Table 3 shows the components of the powder part together with the number of case studies using each combination of powders. Portland cement is a constant part of the powders in almost all the mixtures that is combined with different powders (mineral fillers and cementitious materials)

6.3. Light weight aggregate

According to Table 1, a light weight aggregate is used in all case studies with different types and various ranges of minimum and maximum size. Not only have all the case studies applied normal weight fine aggregate and mineral powders, but they have also used coarse and fine light weight aggregates.

The maximum size of coarse and fine light weight aggregates varies in different studies. In 33% of the case studies, together with the coarse light weight aggregates, a fine light weight aggregate with a maximum size of 1, 2, 3, 4 and 4.8 mm has been used. By contrast, the maximum size of the coarse light weight aggregate is limited to 8, 9.5, 10, 12.7, 13, 14,15,16,19 and 20 mm in the case studies.

Both types of natural and manufactured chemical light weight aggregates have been used in the studies. Pumice, lytag, leca, expanded clay, expanded shale, liapor, crushed volcanic granite, coarse cold bonded fly ash, artificial aggregate and

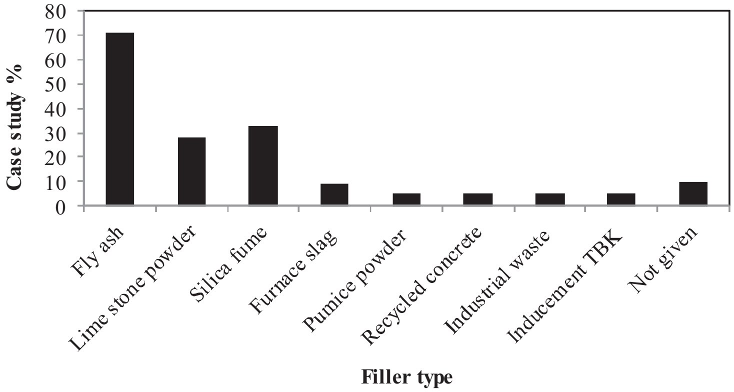

Fig. 4. Filler types and relative number of case studies using each type.

Table 3
Powder combinations in different case studies.

Powder combinations	No. of cases
Portland cement	21
Portland cement + fly ash	6
Portland cement + limestone powder + fly ash	1
Portland cement + limestone powder + silica fume	3
Portland cement + limestone powder + fly ash + pumice powder	1
Portland cement + silica fume + fly ash	2
Portland cement + silica fume + fly ash + recycled concrete powder	1
Portland cement + silica fume + fly ash + Metakaolin	1
Portland cement + slag + fly ash	1
Portland cement + slag + fly ash + limestone powder	1
Portland cement + industrial waste	1
local standard cement (TBK + PCC) + fly ash	1

some local aggregates dredged from reservoirs and industrial wastes are amongst the wide range of light weight aggregates applied in the studies.

Fig. 5 shows the relative number of case studies using each type of the above mentioned light weight aggregates.

6.4. Normal weight aggregate

6.4.1. Coarse aggregate

The presence of a normal weight coarse aggregate is always a reason for the increased weight of concrete. Among all case studies, 70% have not implemented this type of aggregate in the mixes and have instead replaced it by a light weight aggregate to produce a lighter concrete. Crushed granite, crushed limestone, quartzite sandstone and gravel are types of the coarse aggregate used in the remaining 30% of the studies. The maximum size of the normal weight coarse aggregate in the studies is limited to 8, 12.5, and 15, 16 19 and 20 mm. Crushed limestone is applied in the major part of the studies.

6.4.2. Fine aggregate

The variety of normal weight fine aggregate is the least among all components used in the mixes. Natural river sand and finely crushed limestone have been used in all case studies. Eighty six percent of the case studies have used crushed or natural river sand, 5% have used crushed limestone and the remaining 9% have used a combination of natural river sand and crushed limestone in the LWSCC mix design.

7. Mix proportions

Table 2 contains the following key proportions for mix design of LWSCC in different studies: cement content (by weight in 1 m^3 of concrete volume)

- Water content (by weight in 1 m^3 of concrete volume).
- Mineral powder (by weight in 1 m^3 of concrete volume).
- Chemical admixture, super plasticizer and AEA (by weight in 1 m^3 of concrete volume).
- Water/cement ratio by weight.
- Light weight fine and coarse aggregates (by weight in 1 m^3 of concrete volume).

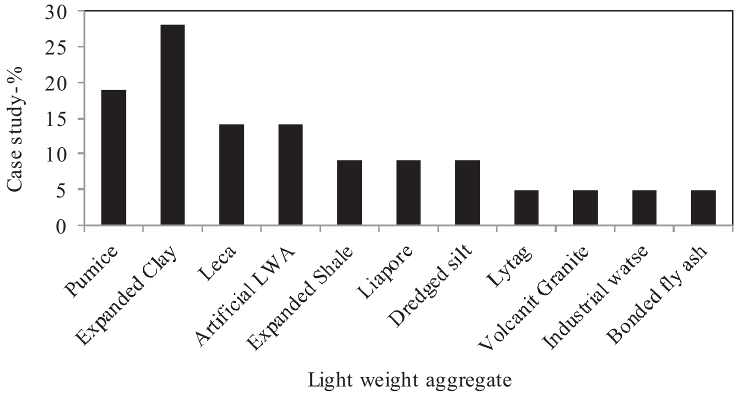

Fig. 5. Distribution of different types of light weight aggregate in case studies.

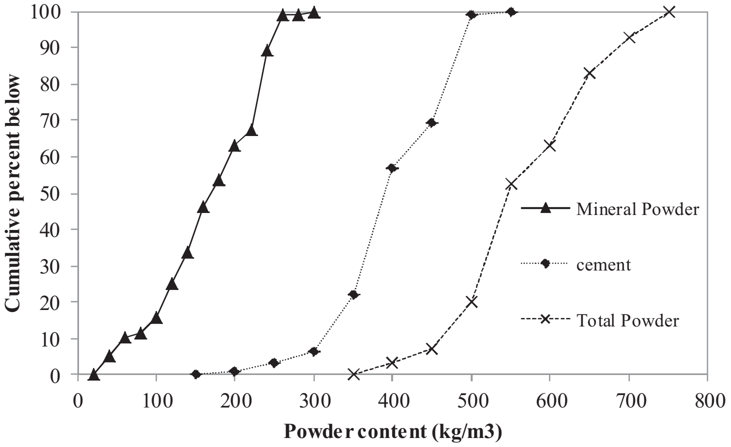

Fig. 6. Distribution of powder contents in LWSCC mix designs.

- Normal weight fine and coarse aggregate (by weight in 1 m^3 of concrete volume).
- Density of concrete (in Kg/m^3).
- Compressive strength (in MP).

If we compare the LWSCC mix designs with: (a) conventional concrete, (b) SCC and (c) LWC, we can conclude that there is:

a) Lower or probably no content of normal weight coarse aggregate, increased paste content, increased powder content, increased light weight aggregate content, lower water to powder ratio, and the addition of chemical and mineral admixtures (air entraining, viscosity modifying agent and filler) in the LWSCC mix designs.
b) Lower or even no content of normal weight coarse aggregate, increased powder content (in some cases), and the addition of light weight aggregate in LWSCC mixes.
c) Lower or possibly no content of normal weight coarse aggregate, increased paste content, amplified powder content, reduced water to powder ratio, and the addition of chemical and mineral admixtures (air entraining, viscosity modifying agent and filler) in LWSCC mixes.

LWSCC has lower or sometimes zero content of normal weight coarse aggregate which needs to be lubricated by a layer of fine/mortar paste. Even in the case of light weight aggregates, fine aggregates or a combination of fine and coarse aggregates are used to facilitate the lubrication process.

Comparable to the mix design of SCC, limiting the fine aggregate content and water to powder ratio together with the inclusion of super plasticizer and viscosity modifying and air entraining agents in the mix design prepares the required fluidity and viscosity of mortar in LWSCC. However consideration should be taken to prevent the segregation problem while mixing the light weight aggregate and increasing the fluidity to reach the desired flowability.

The range and distribution of light and normal weight aggregates are explained above. Moreover the powder content of mixes like cement and fillers are illustrated. The above information is illustrated individually; however the cumulative

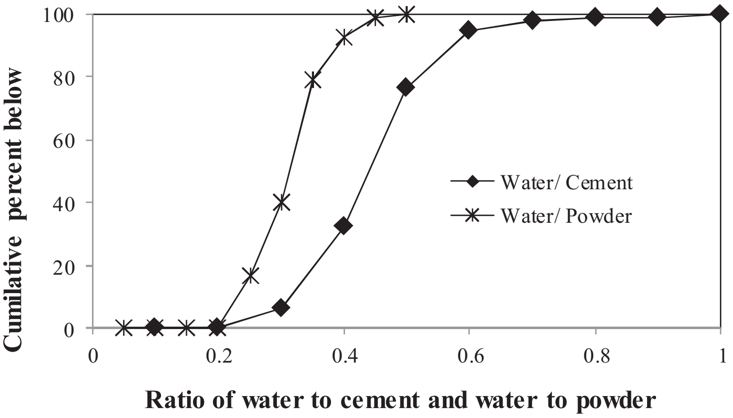

Fig. 7. Distribution of water/powder and water/cement ratio in LWSCC mixes.

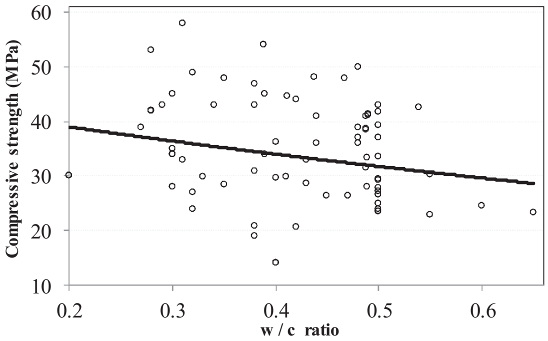

Fig. 8. Effect of water to powder and water to cement ration on the compressive strength.

distribution of them is an instructive way of presenting the range of key proportions and their variations in the mixes. Figs. 6, 7 and 9 show the cumulative distribution of coarse aggregate content, powder content and the water to powder ratio.

7.1. Powder content

The cumulative percentage of powder content (cement and mineral powder) below the specified ranges of weight in the concrete volume is presented in Fig. 6. It shows the wider variety of cement content in the mixes. The weight ratio of cement and mineral powder to the concrete density varies between 9.44–29.77% and 1.26–15.79% respectively. While the ratio variation for combined weight of cement and mineral powder is between 18.98 and 42.53% in the LWSCC mix designs.

7.2. Water/powder and water/cement ratios

Water/total powder (W/P) and water/cement (W/C) ratios are critical factors in the LWSCC mix design which affect both the fresh and hardened properties such as the hydration process, flowability and compressive strength. Considering the required fresh properties of LWSCC, the mix design may be changed by replacing or combining the powder based and viscosity modifying agent based methods. Choosing each method requires different volumes and combinations of binder, water, super plasticizer and filler in the mix design. The W/C and W/P (water to cement plus mineral powder) ratios range between 0.25 and 0.94 (mainly between 0.25 and 0.72) and 0.21 and 0.46 respectively. The water/powder ratio in the majority of the mixes is between 0.25 and 0.40, while most of the mixes have used the water/cement ration in the range of 0.25–0.60. Fig. 7 shows the cumulative wt% of W/C and W/P in unit volume of the mixtures.

The W/C = 0.94 (Yung, 2009) is out of the normal range in the mixing design of concrete. The W/P ratio below 0.25 may bring some difficulties to hydrating the cement part. However the upper limit of W/P = 0.46 is appropriate to use in the mixes.

As previously mentioned, the distribution of cement, mineral powder and water, and their ratio in LWSCC mixes are different. According to the detailed information of the LWSCC mix design in Table 2, there is no distinct fraction between the cement, mineral powder and even the total powder content in the mixes. Both the cement and mineral powder have considerable fluctuations, though the cement content has slightly higher change.

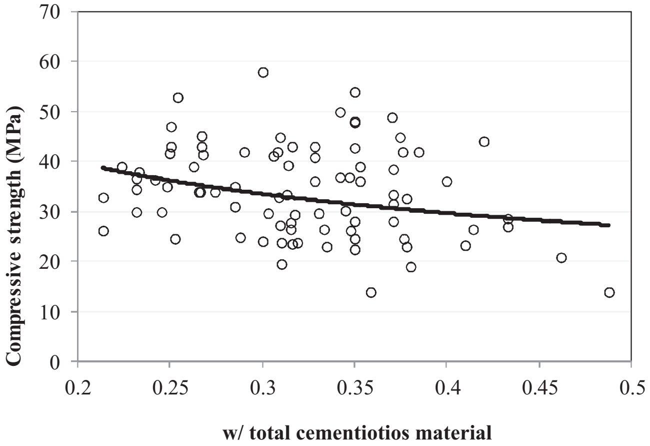

Fig. 9. Effect of water to powder and water to cement ration on the compressive strength.

Table 4
Weight limits of aggregates in LWSCC mixes.

	Sand	Normal coarse aggregate	Light weight aggregate	Total aggregate
Min. weight in mix (%)	10.86	0	3.15	25.24
Max. weight in mix. (%)	66.7	38.64	32.3	78.31

The powders in this study include mineral fillers and cementitious materials. To find a better relationship between compressive strength and water/binder ratio, all the non-cementitious powders (mineral fillers) are omitted from binder portion of the mixes. According to the case studies used in this study, Pumice powder, limestone powder, recycled concrete powder and industrial waste are mineral fillers. In other hand, fly ash, metakaolin and slag are considered as cementitious powders. Fig. 8 shows the exponential relationship between water/cement ratio and the compressive strength. Fig. 9 shows the power type variation of compressive strength with changes in the ratio of water to total cementitious materials (Portland cement + fly ash + metakaolin + slag).

According to Fig. 8, the water to cement ratio has 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 total cementitious materials ratio in Fig. 9. However variation of the water to total cementitious materials ratio has greater effects on the compressive strength.

7.3. Aggregate content

According to Table 4, two types of normal and light weight aggregates in fine and coarse states have been used in the mixes. Table 4 shows the ratio of aggregate weight to the total weight of 1 m^3 concrete. The normal weight coarse aggregate content varies between 0 and 38.64% by the weight of the concrete mix. Sand content varies between 10.86 and 66.7% by the weight of the concrete mix and the content of the light weight aggregate varies between 3.15 and 32.3%. Evidently, the variation of normal weight aggregates is greater than that for light weight aggregates. In other words, different researchers have tried to produce the LWSCC by applying a wide range of normal weight fine and coarse aggregates in the mix design. The total weight of aggregates in all the mixes varies between 25.24 and 78.31%. The upper limits of total aggregates content in the mixes mainly consist of the sand aggregate.

Considering the mix proportions and components of LWSCC in Table 2, a normal weight coarse aggregate is not used in 70% of the mixes. In addition, the weight ratio of fine to coarse aggregate as well as normal to light weight aggregates is not constant and varies in different LWSCC mix designs.

Fig. 10 shows the distribution of different ranges of aggregates in the LWSCC mix designs. The weight range of normal weight coarse aggregate varies between 100 kg to about 700 kg in the mix design; however this type of aggregate has been used in only 30 mix designs. By contrast, the weight of sand aggregate which has been used in all the LWSCC mix designs varies between 100 kg and 1200 kg. The weight range of the light weight aggregate in the LWSCC mix designs is similar to that of the normal weight coarse aggregate; however the distribution is different in the mixes.

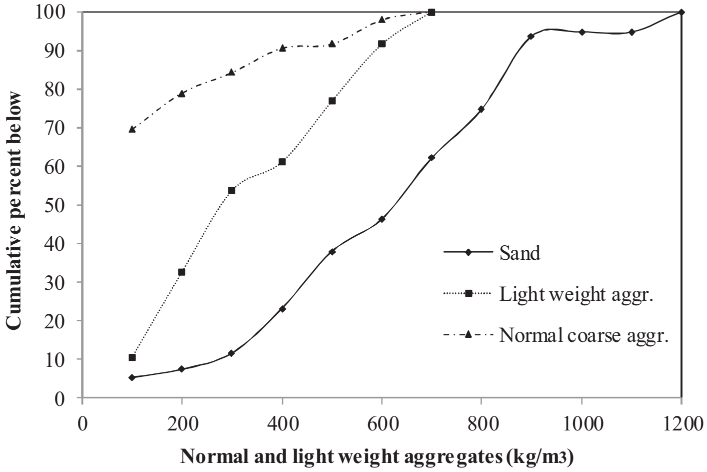

Fig. 10. Corresponding weight distribution of aggregates in case.

8. Conclusion

LWSCC is new type of concrete that combines the advantages of both LWC and SCC. However, publications about mix design, mechanical properties, component materials and the curing condition are very rarely found in the literature. This study has collected almost all the published investigations with sufficient details in terms of country and year of research, mix proportions, components, curing condition, density and compressive strength of LWSCC, in order to extract worthwhile conclusions for researchers and practitioners.

Analyzing 114 LWSCC mix designs of 21 recent laboratory investigations from 2001 to 2013, the following conclusions can be reached:

Compressive strength: different ranges of low and high compressive strength are achievable in LWSCC. In this investigation, 53 and 34% of the mix designs give the compressive strength in excess of 32 MPa and 40 MPa respectively.

Aggregate: both types of light and normal weight aggregates have been used in the mixes; however 70% of mixes do not apply the normal weight coarse aggregate to produce LWSCC.

Admixtures: different types and ranges of mineral and chemical admixtures (super plasticizer, air entraining agent and viscosity modifying agent) have been used in the mixes to attain the desired flowability and the fresh and hardened properties.

Powder: fillers and cement are two types of powder applied in all LWSCC mix designs. The variation of filler types is more than that of the cement types in the LWSCC mix designs.

Mix proportions: some key notes on the mix design of LWSCC are presented as follows:

- Just 30% of the mixes use the normal weight coarse aggregate, and the maximum weight ratio of this type of aggregate in the mix volumes is 38.6%. Water/cement and water/total powder ratios vary between 0.25–0.85 and 0.25–0.5 respectively.
- Different ranges of chemical admixtures have been used in the mixes, however despite the inclusion of super plasticizer in the mixes; the air entraining agent and viscosity modifying agent are not used in all LWSCC mix designs.
- The weight ratio of cement, mineral powder and the combined weight of cement and mineral powder to the mix weight vary between 9.44 and 29.77%, 1.26 and 15.79% and 18.98–42.53% respectively in all the LWSCC mix designs.

Curing condition: lime saturated water, fog room; heat room and environmental chamber have been applied in 66, 14, 14 and 14% of the studies respectively to cure the concrete for 24 or 48 h after pouring.

Overall, laboratory investigations confirm the feasibility of producing LWSCC with different ranges of flowability, compressive strength and density and with no risk of segregation or blocking. However, the application of LWSCC in real construction projects may result in more problems to solve.

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