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Self-compacting light-weight concrete; mix design and proportions

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Abstract. Utilization of mineral and chemical admixtures in concrete technology has led to changes in the formulation and mix design in recent decades, which has, in turn, made the concrete stronger and more durable. Lightweight concrete is an excellent solution in terms of decreasing the dead load of the structure, while self-compacting concrete eases the pouring and removes the construction problems. Combining the advantages of lightweight concrete and self-compacting concrete is a new and interesting research topic. Considering its light weight of structure and ease of placement, self-compacting lightweight concrete may be the answer to the increasing construction requirements of slender and more heavily reinforced structural elements. Twenty one laboratory experimental investigations published on the mix proportion, density and mechanical properties of lightweight self-compacting concrete from the last 12 years 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.

Keywords: self-compacting light weight concrete; compressive strength; mix proportion; admixtures; fillers; aggregates

1. Introduction

Workability, strength, and durability are three major characteristics of concrete. It is generally accepted 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 concerning the mechanical characteristics of hardened concrete (Domone 2006). The premature evaluation of hardened concrete properties is very important. The problem is that following the hardening process, the quality and mechanical properties do not recover. The structural behavior of concrete relies on mixing proportions and material properties of the

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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 (Aslani 2015). In recent years, some efforts have been made to combine the advantages of these two types of concrete in one package called Self-Compacting Light-Weight Concrete (SCLWC). There are a wide range of publications about LWC concerning different light weight aggregates and mix 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 SCLWC is combination of two materials and one part is not fully investigated, it needs much more market research (Vakhshouri and Nejadi 2015).

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 SCLWC mix design and its application. However, owing to the expected advantages of SCLWC 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 SCLWC is a fundamental parameter to estimate its other mechanical properties. In spite of available studies on the advantages of SCLWC 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. SCLWC is highly sensitive to changes in mix component properties and their proportions; therefore it requires increased quality control. The typical characteristics of SCLWC 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 2007). For instance, the compressive strength of the SCLWC is influenced by the aggregate type and the water to cement ratio and water to total powder ratio (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 SCLWC, this problem is even more obvious due to insufficiencies in the initial energy of lightweight aggregates in relation to moving along with the lightweight aggregates in the cement paste (Juradin *et al.* 2012, Vakhshouri and Nejadi 2016). To keep the balance among the proportions of SCLWC 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 SCLWC (Kaffetzakis and Papanicolaou 2012) by determining the optimum mortar to aggregates packing voids ratio. The main steps to attain the SCLWC 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.

The main part of this study is that of the SCLWC properties, mix proportions and component materials. However, the range of materials in different mixes and the general distribution of

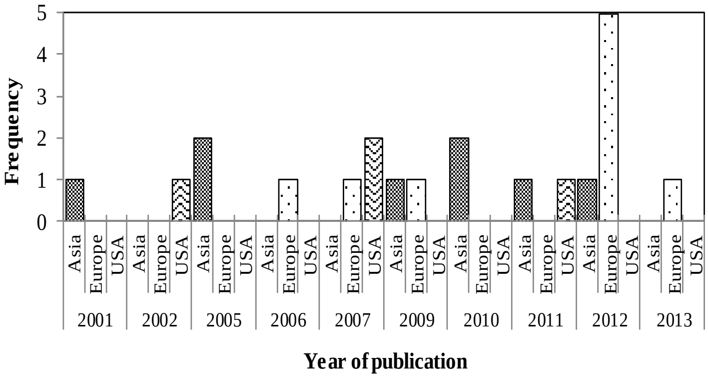

Fig. 1 Geographical distribution of case studies in SCLWC

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, SCLWC investigation is growing in European countries particularly in recent years. Noticeably no record of SCLWC 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 SCLWC in real projects.

2. Conflict of segregation problem and flowability requirements

Mix design of SCLWC contains both LWC and SCC proportions; however, its special mix design doesn't precisely follow the mix design for these types of concrete. Furthermore the technological considerations and mixing problems in LWC and SCC still govern the SCLWC 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 SCLWC mixes by slump flow tests, J ring tests and V funnel tests according to the Self-Compacting Concrete Committee of EFNARC (EFNARC 2002). Although the workability aspects of SCLWC could be improved by approved suggestions in SCC, the SCLWC shows specific features that have resulted from using the lightweight aggregate (Juradin *et al*. 2012).

Lower density and better flowability are two main advantages of SCLWC respect to normal concrete. 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 SCLWC, the heavier aggregates tend to considerably sink (Andiç-Çakır and Hızal 2012).

Expanded granulated slag, expanded clay, expanded perlite or vermiculite (Koksal *et al*. 2013) and expanded polymer materials are frequently used lightweight 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 lightweight aggregates to float up, increases the segregation risk (Illidge 2010, Juradin *et al*. 2012).

Some investigations (Mazaheripour *et al*. 2011) in the SCLWC 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 lightweight 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 SCLWC 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 SCLWC 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:

- Systematic evaluation of the experiments conducted by researchers in different parts of the world. Since SCLWC 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 SCLWC in real projects.
- Evaluation and comparison of the effect of different components of the SCLWC mix design in terms of compressive strength.

4. Database for mix design, density and compressive strength of SCLWC

4.1 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 SCLWC. 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 SCLWC i.e. density and compressive strength at the age of 28 days. However, the other mechanical properties of SCLWC have not been investigated as much as the above mentioned characteristics, and published empirical data in the literature is still very rare.

4.2 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 22 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 lightweight aggregates and cement and filler type.

Different researches have applied different components by various proportions to attain the SCLWC by low-density and excellent flow-ability. In general, the reported mix proportions include 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 the ratio of water to cement (W/C).

4.3 Curing condition

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

4.4 Compressive strength

The resultant compressive strength at the age of 28 days is reported for all mixes of SCLWC in the case studies. According to Fig. 2, compressive strength values ranged from 14 to 58 MPa, with about 34 percent of mixes having strength in excess of 40 MPa and 53 percent in excess of 32 MPa. This confirms the practicability of producing the SCLWC 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, lightweight and normal weight coarse and fine aggregates in the SCLWC mix designs.

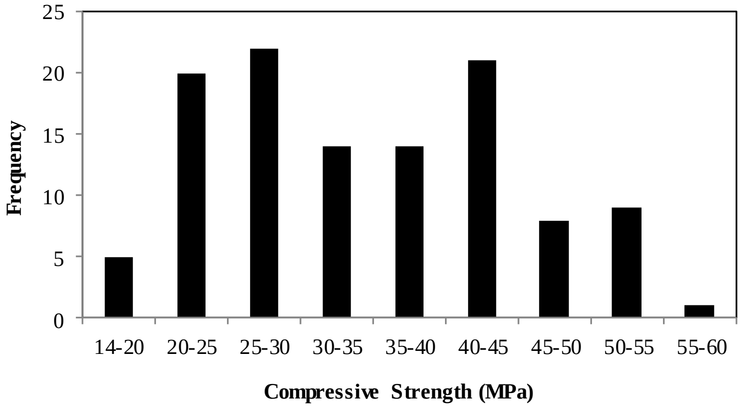

Fig. 2 The frequency of compressive strength ranges in the case studies

Table 1 Database for mix design of SCLWC

Ref	CA				Test age	No. of mixes				Curing type	LWCA	NWA		Cement	Filler
	SP		AEA												
	Type	Volume Kg/m^3	Type	Volume Kg/m^3	hr-day	CC	LWC	SCC	SCLWC			Fine	Coarse		
(Andiç-Çakır and Hızal 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, 4-16mm	NRS< 4mm	CLS 4-16mm	CEM I 42.5 R	industrial waste of olivine powder
(Juradin *et al*. 2012)	Liquid PCAE	6-7.28			1,3,7, 28 d				9	Moist	Liapor, EC granules 0-2, 1-8mm	CLS 0-4 mm		PC	SF,FA, recycled concrete powder
(Kaffetzakis and Papanicolaou 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 and Hızal 2012)	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) <5mm	N.G 5-15mm	CEM I 42.5	FA, LSP
(Illidge 2010)	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℃	crushed granite from Vulcan mine material	NRS		Type III and Class C Boral cement	SF, FA
(Mazaheri-pour *et al*. 2011)	N.G.	17.18-19.02			7,14,28 d				10	48 free and moist	LECA from EC 0-3,3-10mm	NRS <4.75 mm	Natural gravel <10mm	CEM II	SF, LSP
(Kobayashi 2001)	PCAE	1.5-1.8% of cement weight			28d			1	1	Moist	artificial LWA<15mm	NRS	CLS<15mm	PC	FA
(Shi and Wu 2005)	PCB	3.3	VRB	0.2	1,3,28, 90, 180d				5	fog room-23 ± 2 ℃	ES<9.5mm	NRS< 4.75mm		CEM I	FA class F
(Hwang and Hung 2005)	NLSB	2-26			3,7,28, 56, 91 d				13	N.G.	Made with sintering fine sediment from reservoir <13mm	Crushed Sand		CEM I -C150	FA class F
(Persson 2006)	MB	2.97-7.32	N.G*	0.106-1.203	28 d	1		2	2	N.G.		NRS <2 mm	Gravel<8 , Quartzite sandstone 8-16 mm		SF, LSP

Table 1 Continued

Ref	CA				Test age	No. of mixes				Curing type	LWCA	NWA		Cement	Filler
	SP		AEA												
	Type	Volume Kg/m^3	Type	Volume Kg/m^3	hr-day	CC	LWC	SCC	SCLWC			Fine	Coarse		
(Hubertova and Hela 2007)	PCB	1.5%	N.G.	0.4%	7,28 d		2	1	2			finely ground limestone, NRS<4mm			
(Dymond 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)	N.G.	4.9 mL/kg	N.G.	0.2 mL/kg	11,16 hr 7,28,90 d				2	Moist	EC<20 mm	NRS		PC	N.G.
(Wang 2009)	N.G.	7.3-15.1			3,7,28,56, 90d				10	Moist	dredged silt from reservoirs in southern Taiwan<9.5mm, 12.7 mm	NRS<2.38mm		CEM I	FA, slag
(Kim *et al.* 2010)	PCB	0.7-1.3 % of cement weight	N.G.	0.005% of cement weight	3,7,28 d				9	Moist	LC1<20mm By rhyolite fine powder, LC2<20mm by with wastes (screening sludges)	local NRS	CLS<20mm	PC	N.G.
(Maghsoudi *et al.* 2011)	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)	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 in SCC CEM III in SCLWC	FA

Table 1 Continued

Ref	CA				Test age	No. of mixes				Curing type	LWCA	NWA		Cement	Filler
	SP		AEA		hr-day	CC	LWC	SCC	SCLWC			Fine	Coarse		
	Type	Volume Kg/m^3	Type	Volume Kg/m^3											
(Güneyisi *et al.* 2012)	PCAE	5.3-6.4			28 d				9	Moist	Coarse cold-bonded FA 4-16mm	Mix of CLS &NRS <5 mm		CEM I 42.5R	SF, FA class F
(Anwar *et al.* 2012)	N.G.	6.5-7.5	SIKA Viscocrete modified polycarboxylate copolymers	4-10	3,7,28 d			1	2	Moist	Pumice 4.8-19mm	NRS <9.6mm	CLS <19mm	(PCC) Indonesian Standard (SNI) 15-7064-2004	FA, Indocement TBK
(Bogas *et al.* 2012)	PCB	0.6-1.1% of fine agg.			2,28,90d		2	1	2		Two Iberian EC: Leca from Portugal and Arlita (Spain)	NRS	CLS <12.5mm	CEM I 42.5R	FA (Pego thermoelectric power plant)
(Soutsos *et al.* 2013)	PCB	3.3	SSA		3,6,12,24 hr 2,4,7,14, 28d		5	1	2	Moist	Lytag 4-14 mm	NRS <600 μm	Crushed Granite<20mm	CEM I 42.5N	PFA, GGBS, LSP
(Choi *et al.* 2006)	PCB	0.005%	N.G	0.5-2 % of cement weight	3,7,28 d		6		5	Moist	<20mm	NRS	CLS <20mm	PC	Rhyolite
(Andiç-çakır et al. 2009)	PCB	3.5-11.1 kg/m^3	N.G	2.34-6.09 kg/m^3	7,28 d			5	10	N.G.	Pumice 4-8, 8-16 mm	<5 mm	<15 mm	CEM I 42.5N	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)
*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.

Table 2 Classification of LWC in some codes of practice

Reference	Density (kg/m^3)	Compressive strength (MPa)	Application
(213R-03 2003)	1350 to 1900	≥17	Structural
(Bilir *et al*. 2015)	800 to 2240	16≥,<19	Structural
(TS-2511 1977)	≤1900	≥16	Structural
(EN-206-1 2000)	800 to 2000	8 to 80	Structural and Non structural

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

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. However there is no guideline for density and compressive strength limits of the combination of LWC and SCC in SCLWC. Applying different combination of components by various weights and volumes in the SCLWC mixture provides wide range of compressive strength and density. Table 2 shows some classification of LWC.

6. Mix proportions

6.1 Admixtures

SCLWC 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 SCLWC (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 percent of the case studies don’t include AEA. The main reason to apply AEA i.e.; providing freeze-thaw resistance or improving the rheology of SCLWC is not clearly defined in the case studies.

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

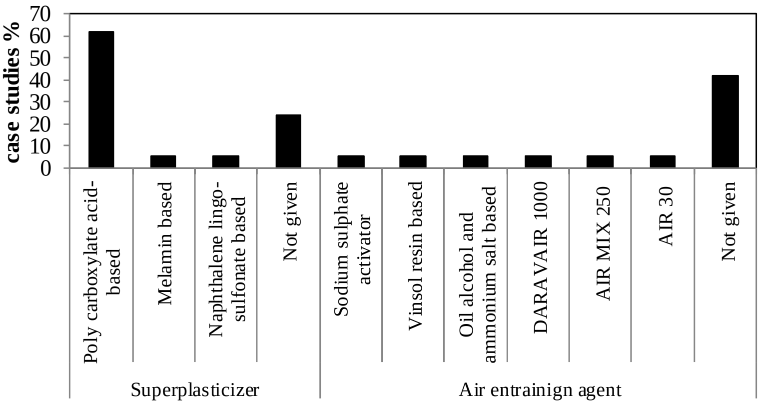

Fig. 3 Type of chemical admixtures and relative number of case studies using each type

1.06 to 26 kg/m^3 in the concrete mixes. Besides the weight of AEA 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. 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 SCLWC and reduce the cost of project (Gencel *et al*. 2011); however fillers may increase the density of concrete.

Addition of the mineral powders in the mixture to produce a flow-able concrete, accompanied by replacement of normal weight coarse aggregate with light weight powder and light weight aggregate to produce a lighter concrete makes the powder content of SCLWC higher than those for conventional concrete, LWC and SCC.

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 percent of the case studies, while 14 and 9 percent 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 percent 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.

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 percent 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 percent of the case studies. No information is given about the fillers in the remaining 10 percent of the case studies. It worth mentioning that 57 percent of the studies have used the combination of two or more fillers in the SCLWC mixes.

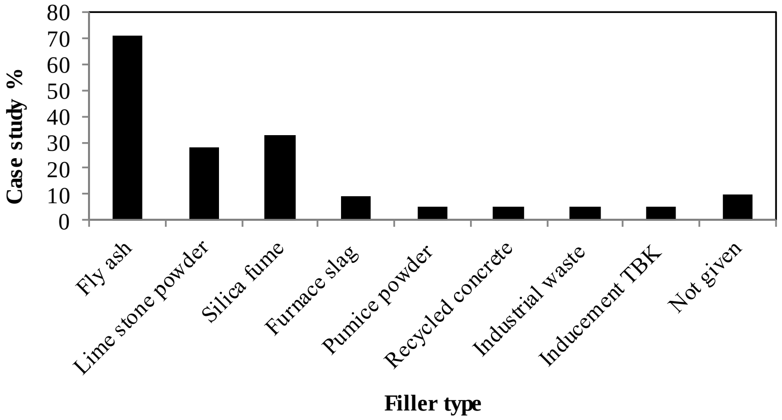

Fig. 4 Filler types and relative number of case studies using each type

Table 3 Powder combinations in different case studies

Powder combinations	No. of cases
Portland Cement	22
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

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 lightweight powder and lightweight aggregate to produce a lighter concrete. This makes the powder content of the SCLWC 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.

6.6 Lightweight aggregate

According to Table 1, a lightweight 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 lightweight aggregates.

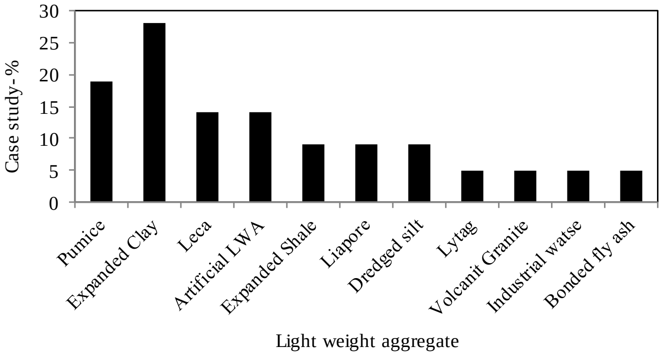

Fig. 5 Distribution of different types of lightweight aggregate in case studies

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

Both types of natural and manufactured chemical lightweight 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 some local aggregates dredged from reservoirs and industrial wastes are amongst the wide range of lightweight aggregates applied in the studies.

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

6.7 Normal weight aggregate

6.7.1 Coarse aggregate

The presence of a normal weight coarse aggregate is always a reason for the increased concrete density. Replacing whole or part of the natural coarse aggregate with lightweight aggregate is a major part of SCLWC mixture design. Reaching a higher strength by lowered density in SCLWCC requires the application of different types of cementitious materials like fly ash in the mixture. While, the effect of different types of coarse aggregate on the density, compressive strength and slump flow of SCLWC may change in combination with the cementitious materials (Gencel *et al*. 2012).

Among all case studies, 70 percent have not implemented this type of aggregate in the mixes and have instead replaced it by a lightweight 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 percent 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 millimeters. Crushed limestone is applied in the major part of the studies.

6.7.2 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 percent have used crushed limestone and the remaining 9 percent have used a combination of natural river sand and crushed Limestone in the SCLWC mix design.

7. Mix proportions

Table 2 contains the following key proportions for mix design of SCLWC in different studies:

- Cement content (by weight in 1m3 of concrete volume)
- Water content (by weight in 1m3 of concrete volume)
- Mineral powder (by weight in 1m3 of concrete volume)
- Chemical admixture, super plasticizer and AEA (by weight in 1m3 of concrete volume)
- Water/cement ratio by weight
- Lightweight fine and coarse aggregates (by weight in 1m3 of concrete volume)
- Normal weight fine and coarse aggregate (by weight in 1m3 of concrete volume)
- Density of concrete (in Kg/m^3)
- Compressive strength (in MPa)

If we compare the SCLWC mix designs with: a) Conventional Concrete (CC), 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 SCLWC 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 SCLWC 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 SCLWC mixes.

Fig. 6 shows a typical comparative amount of Normal Weight Coarse aggregate (NWCA), paste content, powder content, chemical admixture, LWA and water to powder ratio in SCLWC to their amount in CC, SCC and LWC.

SCLWC has lower or sometimes zero content of normal weight coarse aggregate which needs

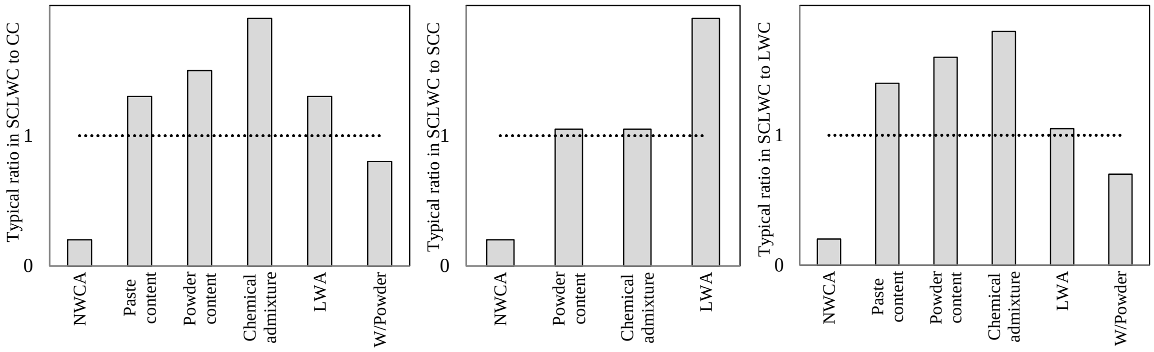

Fig. 6 Comparative amount of mixture components in SCLWC to those amounts in CC, SCC and LWC

to be lubricated by a layer of fine/mortar paste. Even in the case of lightweight 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 SCLWC. However consideration should be taken to prevent the segregation problem while mixing the lightweight 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 distribution of them is an instructive way of presenting the range of key proportions and their variations in the mixes. Figs. 7, 8 and 10 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. 7. 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 to 29.77 percent and 1.26 to 15.79 percent respectively. While the ratio variation for combined weight of cement and mineral powder is between 18.98 and 42.53 percent in the SCLWC 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 SCLWC 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 SCLWC, the mix design may be changed by replacing or combining the powder based and viscosity modifying

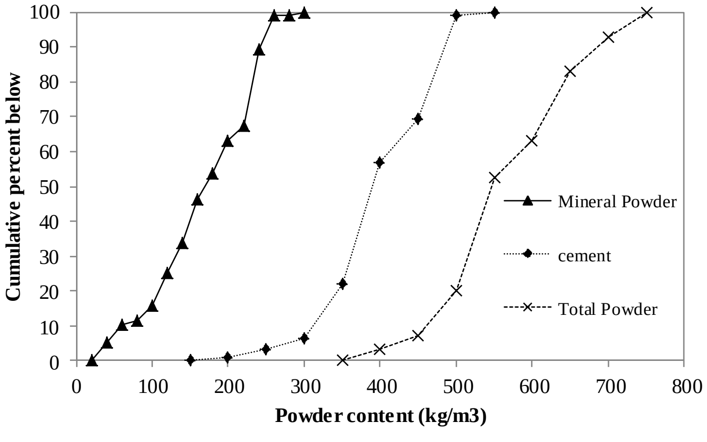

Fig. 7 Distribution of powder contents in SCLWC mix designs

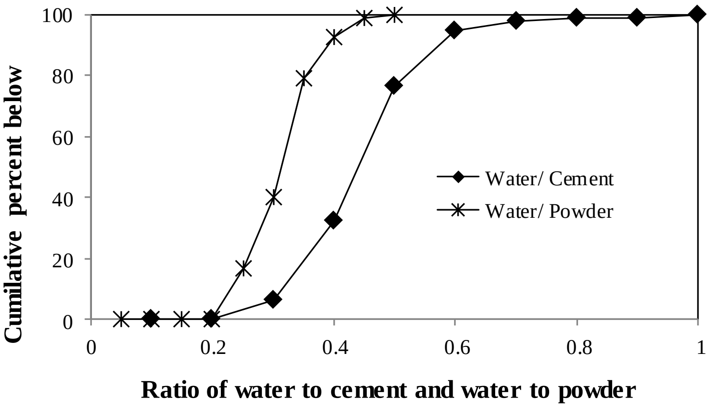

Fig. 8 Distribution of water/powder and water/cement ratio in SCLWC mixes

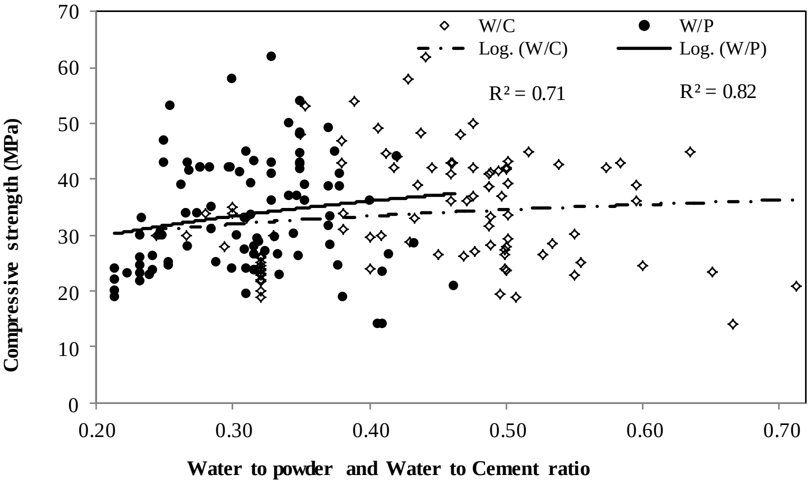

Fig. 9 Effect of water to powder and water to cement ration on the compressive strength

agent based methods. Choosing each method requires different volumes and combinations of binder, water, super plasticizer and filler in the mix design. According to Fig. 7, the *W/C* and *W/P* (water to cement plus mineral powder) ratios range between 0.25-0.94 (mainly between 0.25-0.72) and 0.21-0.46 respectively. The water/powder ratio in the majority of the mixes is between 0.25-0.40, while most of the mixes have used the water/cement ration in the range of 0.25-0.60.

The *W/C*=0.94 (Wang 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 SCLWC mixes are different. According to the detailed information of the SCLWC 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. A considerable part of the mineral powders

Table 4 Weight limits of aggregates in SCLWC mixes

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

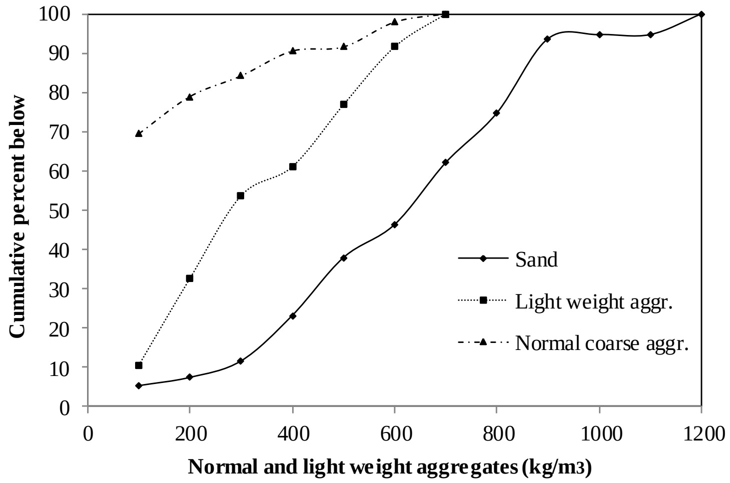

Fig. 10 Corresponding weight distribution of aggregates in case studies

in all mixes are cementitious materials, hence the water to powder ratio (*W/P*) could be evaluated as the water to binder ratio (*W/B*). Fig. 9 compares the effect of these ratios on the compressive strength of the SCLWC. According to the established logarithmic relationship, it is obvious that both ratios influence the compressive strength in a similar manner; however increasing the ratio of water to total powder achieves more growth in the compressive strength of SCLWC. It should be noted that the water to cement ratio is limited to 0.71 in Fig. 10 and the effect of *W/C*=0.94 (Wang 2009) is ignored.

7.3 Aggregate content

According to Table 4, two types of normal and lightweight 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 to 38.64 percent by the weight of the concrete mix. Sand content varies between 10.86 to 66.7 percent by the weight of the concrete mix and the content of the lightweight aggregate varies between 3.15 to 32.3 percent. Evidently, the variation of normal weight aggregates is greater than that for lightweight aggregates. In other words, different researchers have tried to produce the SCLWC 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 to 78.31 percent. The upper limits of total aggregates content in the mixes mainly consist of the sand aggregate.

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

Fig. 10 shows the distribution of different ranges of aggregates in the SCLWC 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 SCLWC mix designs varies between 100 kg to 1200 kg. The weight range of the lightweight aggregate in the SCLWC mix designs is similar to that of the normal weight coarse aggregate; however the distribution is different in the mixes.

8. Conclusions

SCLWC 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 SCLWC, in order to extract worthwhile conclusions for researchers and practitioners.

Analyzing 141 SCLWC mix designs of 22 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 SCLWC. In this investigation, 53 and 34 percent 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 percent of mixes don’t apply the normal weight coarse aggregate to produce SCLWC.

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 SCLWC mix designs. The variation of filler types is more than that of the cement types in the SCLWC mix designs.

Mix proportions: Some key notes on the mix design of SCLWC are presented as follows:

Just 30 percent 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 percent.

Water/cement and water/total powder ratios vary between 0.25 to 0.85 and 0.25 to 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 SCLWC 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 to 29.77 percent, 1.26 to 15.79 percent and 18.98 to 42.53 percent respectively in all the SCLWC mix designs.

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

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

References

ACI-213R-03 (2003), “Guide for Structural Lightweight-Aggregate Concrete”, American Concrete Institute.

Andiç-Çakır, Ö. and Hızal, S. (2012), “Influence of elevated temperatures on the mechanical properties and microstructure of self consolidating lightweight aggregate concrete”, *Constr. Build. Mater.*, **34**, 575-583.

Andiç-çakır, Ö., Yoğurtcu, E., Yazıcı, Ş. and Ramyar, K. (2009), “Self-compacting lightweight aggregate concrete: design and experimental study”, *Mag. Concrete Res.*, **61**(7), 519-527.

Anwar, M.S., Pramono, A.W., Judarta, V.I. and Manaf, A. (2012), “The role of pumice in self-compacting lightweight aggregate concrete manufacture”, *Asian Tran. Basic Appl. Sci.*, **4**, 14-20.

Aslani, F. (2015), “Creep behaviour of normal-and high-strength self-compacting concrete”, *Struct. Eng. Mech.*, **53**(5), 921-938.

Bilir, T., Gencel, O. and Topcu, I.B. (2015), “Properties of mortars with fly ash as fine aggregate”, *Constr. Build. Mater.*, **93**, 782-789.

Bogas, J.A., Gomes, A. and Pereira, M. (2012), “Self-compacting lightweight concrete produced with expanded clay aggregate”, *Constr. Build. Mater.*, **35**, 1013-1022.

Bymaster, J. (2012), *Prestress losses in lightweight self-consolidating concrete*, Masters Abstracts International.

Choi, Y.W., Kim, Y.J., Shin, H.C. and Moon, H.Y. (2006), “An experimental research on the fluidity and mechanical properties of high-strength lightweight self-compacting concrete”, *Cement Concrete Res.*, **36**(9), 1595-1602.

Domone, P. (2006), “Self-compacting concrete: An analysis of 11 years of case studies”, *Cement Concrete Compos.*, **28**(2), 197-208.

Dymond, B.Z. (2007), *Shear strength of a PCBT-53 girder fabricated with lightweight, self-consolidating concrete*, Virginia Polytechnic Institute and State University.

EFNARC, F. (2002), “Specification and Guidelines for Self-Compacting Concrete”, Farnham, Surrey GU9 7EN, UK.

EN-206-1 (2000), “Specification, performance, production and conformity”, European Standard, 72.

Gencel, O., Koksal, F., Ozel, C. and Brostow, W. (2012), “Combined effects of fly ash and waste ferrochromium on properties of concrete”, *Constr. Build. Mater.*, **29**, 633-640.

Gencel, O., Ozel, C., Brostow, W. and Martínez-Barrera, G. (2011), “Mechanical properties of self-compacting concrete reinforced with polypropylene fibres”, *Mater. Res. Innov.*, **15**(3), 216-225.

Güneyisi, E., Gesoğlu, M. and Booya, E. (2012), “Fresh properties of self-compacting cold bonded fly ash lightweight aggregate concrete with different mineral admixtures”, *Mater. Struct.*, **45**(12), 1849-1859.

Hubertova, M. and Hela, R. (2007), “The effect of metakaolin and silica fume on the properties of lightweight self consolidating concrete”, ACI Special Publication, **243**.

Hwang, C.L. and Hung, M.F. (2005), “Durability design and performance of self-consolidating lightweight concrete”, *Constr. Build. Mater.*, **19**(8), 619-626.

Illidge, F.B. (2010), “Acoustic emission techniques and cyclic load testing load testing for integrity evaluation of self-compacting normal and self-compacting”, PhD Thesis, University of South Carolina, USA.

Juradin, S., Baloević, G. and Harapin, A. (2012), “Experimental testing of the effects of fine particles on the properties of the self-compacting lightweight concrete”, *Adv. Mater. Sci. Eng.*, **2012**, Article ID 398567, 8.

Kaffetzakis, M. and Papanicolaou, C. (2012), *Mix Proportioning Method for Lightweight Aggregate SCC (LWASCC) Based on the Optimum Packing Point Concept, Innovative Materials and Techniques in*

Concrete Construction, Springer.

Kim, Y.J., Choi, Y.W. and Lachemi, M. (2010), “Characteristics of self-consolidating concrete using two types of lightweight coarse aggregates”, *Constr. Build. Mater.*, **24**(1), 11-16.

Kobayashi, K. (2001), “Characteristics of self-compacting concrete in fresh state with artificial light-weight aggregate”, *J. Soc. Mater. Sci.*, **50**(9), 1021-1027.

Koehler, E.P. and Fowler, D.W. (2007), “ICAR Project 108: Aggregates in Self-Consolidating Concrete. Aggregates Foundation for Technology, Research, and Education (AFTRE)”, International Centre for Aggregates Research (ICAR), The University of Texas at Austin.

Koksal, F., del Coz, D., Juan, J., Gencel, O., Alvarez, R. and Felipe, P. (2013), “Experimental and numerical analysis of new bricks made up of polymer modified-cement using expanded vermiculite”, *Comput. Concrete*, **12**(3), 319-335.

Liu, X., Ye, G., De Schutter, G. and Yuan, Y. (2013), “Simulation of the microstructure formation in hardening self-compacting cement paste containing limestone powder as filler via computer-based model”, *Mater. Struct.*, **46**(11), 1861-1879.

Maghsoudi, A.A., Mohamadpour, S. and Maghsoudi, M. (2011), “Mix design and mechanical properties of self compacting light weight concrete”, *Int. J. Civil Eng.*, **9**(3), 230-236.

Mazaheripour, H., Ghanbarpour, S., Mirmoradi, S. and Hosseinpour, I. (2011), “The effect of polypropylene fibers on the properties of fresh and hardened lightweight self-compacting concrete”, *Constr. Build. Mater.*, **25**(1), 351-358.

Persson, B. (2006), “On the internal frost resistance of self-compacting concrete, with and without polypropylene fibres”, *Mater. Struct.*, **39**(7), 707-716.

Shi, C. and Wu, Y. (2005), “Mixture proportioning and properties of self-consolidating lightweight concrete containing glass powder”, *ACI Mater. J.*, **102**(5), 355.

Soutsos, M., Turu’allo, G., Owens, K., Kwasny, J., Barnett, S. and Basheer, P. (2013), “Maturity testing of lightweight self-compacting and vibrated concretes”, *Constr. Build. Mater.*, **47**, 118-125.

TS-2511 (1977), “Mix Design for Structural Lightweight Aggregate Concrete”, Turkish Standards Institution TSI, Ankara, Turkey.

Vakhshouri, B. and Nejadi, S. (2015), “Predicition of compressive strength in light-weight self-compacting concrete by ANFIS analytical model”, *Arch. Civil Eng.*, **61**(2), 53-72.

Vakhshouri, B. and Nejadi, S. (2016), “Mix design of light-weight self-compacting concrete”, *Case Stud. Constr. Mater.*, **4**, 1-14.

Wang, H.Y. (2009), “Durability of self-consolidating lightweight aggregate concrete using dredged silt”, *Constr. Build. Mater.*, **23**(6), 2332-2337.

Ward, D. (2010), *Performance of prestressed double-tee beams cast with lightweight self-consolidating concrete*, University of arkansas.

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