Received: 3 April 2020 | Revised: 23 May 2020 | Accepted: 3 June 2020
DOI: 10.1002/suco.202000206

TECHNICAL PAPER

Infra lightweight concrete: A decade of investigation (a review)

Mahmoud Elshahawi[1,2] | **Alex Hückler**[1] | **Mike Schlaich**[1]

[1]Conceptual and Structural Design, Technische Universität Berlin, Berlin, Germany

[2]Structural Engineering Department, Mansoura University, Mansoura City, Egypt

Correspondence
Mahmoud Elshahawi, Conceptual and Structural Design, Technische Universität Berlin, Gustav-Meyer-Allee 25, 13355 Berlin, Germany.
Email: elshahawi@campus.tu-berlin.de; shahawi_m_1988@mans.edu.eg

Abstract
Around a decade ago, the first realistic mix of infra lightweight concrete (ILC) was developed and used in the construction of the façades of a family house in Berlin. Since then, it has been demonstrated that ILC represents a promising lightweight concrete material of dry density less than 800 kg/m^3 and possesses both good thermal insulation characteristics and a sufficient load bearing resistance. Such a unique combination makes it a competitive alternative to the conventional multilayer façades common nowadays in terms of robustness, durability, energy saving and ease of construction. In addition, it opens up innovative architectural horizons. The chief aim of this review is to present the current state of knowledge and the development of ILC over the last decade. A further and equally important consideration is to shed light on scientific gaps and issues that require additional investigation. Accordingly, wide comparisons between numerous mixes as to ingredients, density, strength and thermal conductivity are conducted. The review shows how the mechanical and thermal properties of ILC have improved considerably over time. It also reveals, however, how the understanding of the structural behavior of ILC could be improved through further discussions.

KEYWORDS
high performance lightweight aggregate concrete, infra lightweight concrete, ultra lightweight concrete

1 | INTRODUCTION

1.1 | Lightweight concrete

Buildings throughout the world have benefitted from how material and structural engineers have been improving material properties and behavior. In the last decades, Lightweight concrete (LWC), in particular, has become an important and versatile material that has been greatly improved, thanks to scientific efforts. LWC is considered

Discussion on this paper must be submitted within two months of the print publication. The discussion will then be published in print, along with the authors' closure, if any, approximately nine months after the print publication.

one of the promising materials in modern construction because of the enormous benefits that can be attained both structurally and ecologically [1].

Structurally, it has numerous applications, especially in heavy structures in which the self-weight governs the overall weight and where that self-weight is considerably higher than the expected service loads, as is the case for multistory buildings and bridges. The reduced weight that comes from utilizing LWC in multi-story buildings provides flexibility and significant cost saving; it also improves seismic structural response, provides longer spans, heightens fire resistance and lowers reinforcement ratios and foundation materials [2,3]. Moreover, precast elements constructed from LWC reduce transportation and placement cost [4]. With bridges, LWC may allow for more lanes and longer spans as well. In cantilever type bridges, LWC can be used on one side of the pier and Normal Weight Concrete (NWC) on the other to provide weight balance while accommodating a longer span on the LWC side [5].

Ecologically, LWC has a much lower thermal conductivity than NWC, and it can thus play a substantial role in energy saving when employed as insulation material. In other words, using LWC made with controlled thermal properties saves the energy consumed in air acclimatizing in both cold and warm countries [6,7]. Recently, energy shortage problems have been increasing at an alarming rate and energy has become a global concern. An additional benefit of LWC arises because many industrial and agricultural wastes may be utilized when it is being manufactured, presenting an economic and eco-friendly approach.

1.2 | Terminology

By adding the descriptive term "Lightweight" to concrete, it becomes a collective term for different sorts of concrete that are characterized by low specific weight. The reduced weight is achieved by either using certain types of aggregates (expanded materials) that have a specific gravity noticeably lower than that of the classic aggregate types (gravels or crushed stones) or by introducing air bubbles in the cementitious paste [8]. The former LWC type is designated as lightweight aggregate concrete (LWAC) while the latter type is known as Foamed Concrete (FC), which is usually used for nonstructural applications. The dilemma is that the lightness arises from the entrapped air within either the aggregates or the cement matrix: The more entrapped air, the lighter the weight and the better the insulation, but inversely, the lower the strength [9].

In many international design codes, LWC is defined as a concrete with a dry density of less than 2,000 kg/m^3. However, in the last decades, LWC could be made with a wide range of densities (300–2,000 kg/m^3) and corresponding strengths from 1.0 to 60 MPa [10]. Therefore, the descriptive terms "Structural" and "Infra" had to be introduced. Structural Lightweight Concrete (SLWC) is defined according to Eurocode 2 [11] as concrete with a mean cylinder compressive strength not less than 17 MPa and a unit weight not less than 800 kg/m^3 [11]. The Latin prefix "Infra" was first presented by the Chair of Conceptual and Structural Design at TU Berlin in 2006 to delineate the new LWC with a density lower than 800 kg/m^3 [12]. "Ultra" is used instead of "Infra" by many researchers. In the Netherlands, due to the high temperature arising from the hydration process, it is called a "warmbeton" or a warm concrete [13]. To sum up, Infra lightweight concrete (ILC), ultra lightweight concrete (ULWC) or "warmbeton" is the state-of-the-art concrete in terms of density and insulation properties and classifies concrete with a density below 800 kg/m^3. In this paper, the acronym ILC is used.

1.3 | Utilization of ILC

The rational and economic layout of buildings with relatively low energy consumption can be based on the respective mechanical and thermal properties of ILC, LWC, and NWC: ILC, with perfect insulation characteristics, can be best used for load bearing façades; LWC, with moderate insulation and strength, for floor slabs and NWC, with the greatest strength but poor insulation, for vertical interior members such as columns and shear walls [14].

Over the last few years, the strength, production and thermal properties of ILC have improved remarkably. For instance, Yu et al. [15] reported ILC with a compressive strength of 15 MPa, a corresponding dry density of 745 kg/m^3 and a thermal conductivity of 0.17 W m^{-1} K^{-1} [15]. Abd Elrahman et al. [16,17] developed ILC with a compressive strength of 15.2 MPa, a corresponding dry density of 810 kg/m^3 and a thermal conductivity of 0.19 W m^{-1} K^{-1} [16,17]. The ongoing improvements to the material, particularly in terms of strength, allow ILC to be used as a load bearing material. ILC has thus become a monolithic material providing both bearing resistance and thermal insulation. Therefore, it can be utilized in robust, durable and straightforward constructions. In comparison to the currently common multilayer wall constructions, these potentials make it a competitive alternative in respect of conceptual design, insulation, ease of construction, fire protection, energy saving and recyclability [18,19].

1.4 | Research objectives

The key objective of this paper is to compile the recent scientific efforts and standpoints related to ILC. This compilation offers a deeper understanding of the whole picture and bridges the gaps between viewpoints of researchers across the academic spectrum. Moreover, such a compilation can shed light on scientific gaps and encourage new researchers to effectively fill these gaps. In this context, 80 mixes of ILC are compared in terms of mix proportions, materials, admixtures and thermal and mechanical properties. In addition, this review includes a discussion on the limited efforts so far towards understanding the structural behavior of ILC.

2 | INFRA LIGHTWEIGHT CONCRETE

2.1 | Motivations towards the innovation of ILC

There are three main phases required for any novel material to be adopted by the industrial community and, hence, to be widely applied in different fields of construction: Phase 1, the problem statement and a feasible solution; Phase 2, material development and extensive investigations; and Phase 3, industrialization.

In Phase 1, to detect the problems that encouraged the innovation and development of ILC, for instance, the German thermal insulation composite system ("Wärmedämmverbundsysteme" [WDVS]) should be first mentioned. Figure 1 illustrates different types of the multi-layer insulation systems with thermal properties compared to ILC. The multi-layer system has many drawbacks, for example that installation is time-consuming and multipart, requiring highly qualified staff to perform special connections between the layers. In addition, the materials used, such as the polystyrene and mineral wool, are difficult to recycle and have a relatively short life cycle, which in turn cause a high long-term maintenance cost [20]. ILC could be a promising material for a new era of monolithic building by providing the following three merits [21]; (a) cost saving by eliminating the extra insulation layers, saving time and reducing the necessity of highly trained labor. (b) flexibility, since one single layer provides both bearing and insulation, no need for plastering or cladding is required and it can be cast in situ or as a precast element and (c) sustainability that is gained by such a monolithic structure with easy maintenance, recycling ability and energy saving. In this context, 50 cm wall thickness has been proven by many researchers to meet the insulation criteria and to provide a sufficient bearing resistance [13,14,18,19,22].

2.2 | State of the art

Table 1 compares different ILC mixes in terms of ingredients, proportions, density, thermal conductivity and compressive strengths. The available data reflect the improvements in ILC properties over time. The Chair of Conceptual and Structural Design at TU Berlin has been practically investigating ILC since 2006. The first results, obtained by El Zareef [14], provided basic knowledge on the materials, on mix design and on the mechanical properties. The developed ILC has a dry density of 760 kg/m^3, a mean cube compressive strength of 7 MPa and a thermal conductivity of 0.18 W m^{-1} K^{-1}

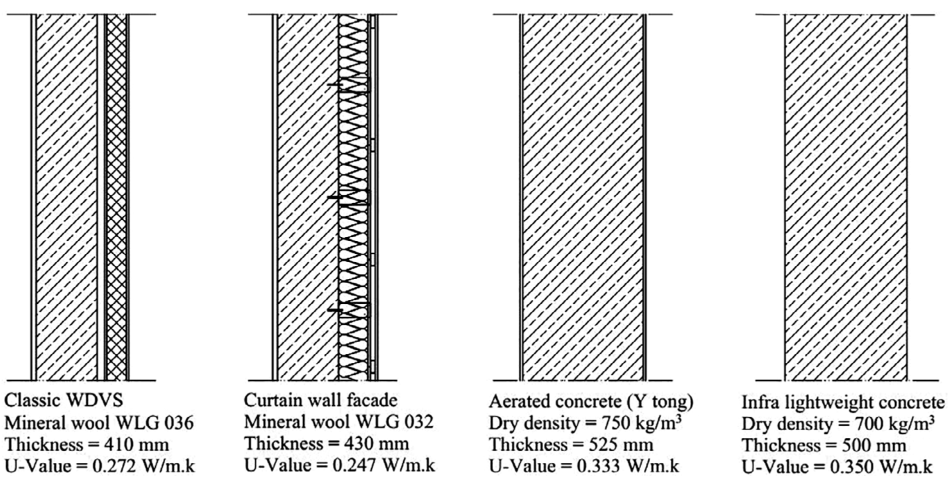

FIGURE 1 Standard insulation systems versus Infra lightweight concrete [20]

TABLE 1 Infra lightweight concrete mixes and properties[f]

Mix		Binder		LWAs kg/m³							Liquid		Admixtures							
					Size fraction									ST or Other additives	Fibers					
Ref.	mix	Type	Content kg/m³	Type	0.1-0.3 mm	0.3-0.5 mm	0.5-1.0 mm	1.0-2.0 mm	2.0-4.0 mm	4.0-8.0 mm	Type	Amount kg/m³	SP kg/m³		Type & content		Air Agent kg/m³	Dry density kg/m³	Thermal Conduc. w/m.k	Mean comp. Strength MPa
(Yu et al., 2016)	1	CEM I 52.5 R	350	EG	92.2	16.1	35.4	31.7	54.6	68.9	water	140	1.75	--	% vol. (LPF) + % vol. (SPF) [a]	0+0	--	750	0.165	10.5
	2															0.1+0		750	0.162	11.8
	3															0.2+0		750	0.165	12.1
	4															0.3+0		750	0.162	13.0
	5															0.15+0.05		750	0.170	13.0
	6															0.1+0.1		750	0.162	12.5
	7															0.05+0.15		750	0.168	12.3
	8															0.6+0		745	0.170	15.0
	9															0.9+0		735	0.168	14.0
	10															1.2+0		720	0.160	13.0
(Yu et al., 2015)	11	CEM II/B-V 42.5 N	450	EG	212.2						water	225	--	--	--	--	2.25	650-700	0.120	12.0
		Limestone powder	0																	
		Nano-silica	0																	
	12	CEM III/A 52.5 N	450		212.2							225	--						0.125	11.5
		Limestone powder	0																	
		Nano-silica	0																	
	13	CEM I 52.5 N	355		207.8							223.5	1.0 %[b]						0.130	11.0
		Limestone powder	52.6																	
		Nano-silica	40																	
	14	CEM II/B-V 42.5 N	405		212.2							225	1.0 %[b]						0.130	11.0
		Limestone powder	0																	
		Nano-silica	45																	
	15	CEM V/A (S-V) 42.5 N	405		212.2							225	1.0 %[b]						0.120	12.0
		Limestone powder	0																	
		Nano-silica	45																	
	16	CEM III/A 52.5 N	405		212.2							225	1.0 %[b]						0.125	11.5
		Limestone powder	0																	
		Nano-silica	45																	
	17	CEM I 52.5 N	315		205.4							228	1.0 %[b]						0.130	11.0
		Limestone powder	106																	
		Nano-silica	35																	
(Huiskes et al., 2016)	18	Alkali activated materials (Geopolymer): by mass 70% powder coal fly ash and 30% ground granulated blast furnace	450	EG	--	--	30	--	184	--	water (kg) + NaOH Molar	160+3M	3 l/m³ [c]		--	--	--	687	0.133	9.1
	19		492			29	43	33	57	70		140+3M						840	0.172	10.0
	20		492			29	43	33	57	69		150+3M						860	0.174	10.2
	21		492			28	42	32	56	68		160+3M						800	0.159	9.5
	22		492			27	41	32	54	66		175+3M						720	0.144	9.0
	23		492			29	43	33	57	69		150+3M						--	0.174	10.4
	24		492			29	43	33	127	--		150+3M						--	0.127	12.0
	25		400			31	46	36	61	74		140+3M						--	0.074	8.0
	26		400			31	46	36	136	--		140+3M						--	0.070	9.0
	27		492			29	43	33	127	--		150+3M						949	0.127	11.5
	28		457			27	40	31	118	--		139+3M					3	881	0.108	9.7
	29		388			122	34	68	54	--		174+3M					--	--	--	9.0
	30		388			122	34	68	54	--		174+2M						--	--	6.6
(Chung et al., 2017)	31	CEM III/A 42.5 N + Silica fume	216+ 24	EG	--	--	74.36	80.7	75.4	--	water	182.4	4.32	ST = 0.72 kg	--	--	--	485	0.132	6.1
	32						75.48	80.8	67.04									478	0.132	6.2
	33						68.7	80	80.1									498	0.145	6.8
	34						65.9	79.46	82.4									487	0.136	6.5
(Chen & Liu, 2013)	35	CEM I 72.5 N+ Silica fume+ High alumina cement	264+ 26.4+ 15.8	EPS: D= 1mm	--	--	23.5	--	--	--	water	79.8	0.245	13.2 kg Polymer Latex[d]	polypropylene of 10 mm length	0.3 kg	0	410 [e]	0.150	1.58
	36						22										0.85	406 [e]	0.130	1.76
	37						20.5										0.90	403 [e]	0.100	2.07
	38						19										0.93	405 [e]	0.090	2.76
	39						17.6										0.98	395 [e]	0.070	2.37
	40		529+ 52.9+ 31.7				17.1					160	0.49	26.4 kg Polymer Latex[d]			0	790 [e]	0.300	7.79
	41						15.6										0.85	805 [e]	0.280	8.82
	42						14.1										0.90	800 [e]	0.250	11.0
	43						12.6										0.93	803 [e]	0.220	10.75
	44						11.1										0.98	810 [e]	0.200	10.56
(Chung et al., 2018)	45	CEM III A 42.5 N	432	EG	--	--	67.1	46	47.7	--	water	206	4.80	ST = 0.66 kg	--	--	--	920	0.270	21
		Silica fume	48																	
		Limstone powder	155																	
	46	CEM III A 42.5 N	432															800	0.230	15.5
		Silica fume	48																	
		Liapor sand	96																	
	47	CEM III A 42.5 N	432															900	0.300	23
		Silica fume	48																	
		Fine fly ash	140																	
	48	CEM III A 42.5 N	432															890	0.280	21.5
		Silica fume	48																	
		Fly ash	131																	
	49	CEM III A 42.5 N	432															900	0.300	18.5
		Silica fume	48																	
		Fine sand	150																	
	50	CEM III A 42.5 N	432															900	0.290	17
		Silica fume	48																	
		Normal sand	150																	
(El Zareef & Schlaich, 2008)	51	CEM III-A 32.5 N	330	EC	200 kg (0-2mm) light sand				25 kg:1-4 mm + 170 kg: 2-9 mm		water	165	--	--	--	--	2	760	0.181	7.0
	52															polypropylene 1 kg/m3 6 mm				2.6
	53															12 mm				3.4
	54															20 mm				3.5

TABLE 1 (Continued)

(Chung et al., 2019)	55	CEM I 52.5 R+ Silica fume	198+22	EG	--	--	102	74	76	--	water	110	5.4	ST = 0.90 kg	--	--	--	500	0.140	6.0
	56		405+45		--		91	58	62			225	4.8	ST = 0.70 kg			--	700	0.210	13.5
	57		450+50		230 [f]		72	49	51			250	4.8	ST = 0.70 kg			--	930	0.330	17.2
	58		198+22	--	230 [f]		--	--	--			110	3.8	ST = 0.90 kg			670 [g] L/m^3	500	0.140	2.2
	59		405+45		210 [f]		--	--	--			225	2.6	ST = 1.9 kg			500 [g] L/m^3	780	0.240	6.5
	60		450+50		400 [f]		--	--	--			250	2.8	ST = 2.5 kg			420 [g] L/m^3	920	0.320	8.5
(Falliano et al., 2019)	61	CEM I 52.5 R	321	--							water	96	--	--	--	--	141 kg/m^3 [g]	423		2.24
	62		479									144					170 kg/m^3 [g]	636		6.5
	63		647									194					191 kg/m^3 [g]	824		13.38
(Hückler, 2016)	64	CEM III A 32.5 + Micro silica	190+74	EC	25 kg (0-2mm) light sand				139 kg:1-4 mm 243 kg: 2-6 mm		water	144	2.86	ST = 0.27 kg	--	--	--	619	0.141	6.49
	65		225+72		42 kg (0-2mm) light sand				132 kg: 1-4 mm 227 kg: 2-6 mm			154	3.03	ST = 0.36 kg				674	0.153	7.51
	66		260+70		59 kg (0-2mm) light sand				126 kg: 1-4 mm 212 kg: 2-6 mm			164	3.19	ST = 0.45 kg				711	0.166	9.60
	67		296+68		76 kg (0-2mm) light sand				120 kg: 1-4 mm 196 kg: 2-6 mm			175	3.36	ST = 0.53 kg				766	0.178	11.35
	68		333+66		93 kg (0-2mm) light sand				114 kg: 1-4 mm 180 kg: 2-6 mm			185	3.52	ST = 0.63 kg				809	0.193	13.36
(Abd Elrahman et al., 2019)	69	CEM III A 42.5 N+ Silica fume	216+24	EG	--	--	89.1	28.5	33.4	42.6	water	183.5	3.75	ST = 0.90 kg	--	--	--	580	0.13	6.50
	70			EC	72.7 kg (1-4mm) 267.9 kg (0-2mm)			95.2 kg: 2-8 mm 58.1 kg: 2-6 mm										850	0.22	8.30
	71			Ecog.	207.9			44 kg: 5-8 mm 62.4 kg: 2-5 mm										920	0.21	7.90
	72		405+45	EG	--	--	15.1	38.3	45	57.5		193.5	4.5	ST = 0.71 kg				810	0.19	15.20
	73			EC	93.1 kg (1-4mm) 45.5 kg (0-2mm)			128.4 kg: 2-8 mm 78.4 kg: 2-6 mm										1000	0.3	18.10
	74			Ecog.	35.3			59.4 kg: 5-8 mm 84.1 kg: 2-5 mm										1100	0.28	10.80
(Spiesz & Hunger, 2017)	75	CEM III-C 32.5 N+ Fly ash	350+100	EG	232 kg (0.25-8mm)						water	147	2.0	--	--	--	7.7	760	0.14	10.2
	76	CEM I 42.5 N+ Fly ash											2.2				7.7	703	0.15	7.90
	77	CEM I 42.5 N + Limestone powder											1.9				1.8	739	0.19	8.90
	78	CEM I 42.5 N + Fly ash											3.3				1.0	815	0.20	12.0
(Schulze & Breit, 2016)	79	CEM III-B 32.5 N	370	EG	74 kg (0.25-0.5 mm) + 74 kg (1-2 mm) + 62 kg (4-8 mm)						water	136	5.8	ST (0.5 kg)+ water proofing (1.3 kg) + shrinkage reducing agent (9.2)	--	--	7.4	650-700	0.15	6.30

Abbreviations: EC, expanded clay; Ecog, foamed glass; EG, expanded glass; EPS, expanded polystyrene; LPF, long polypropylene fiber; SP, superplasticizer; SPF, short polypropylene fiber; ST, stabilizer.

[a]LPF: ($L = 45$ mm, $D = 0.5$ mm) SPF: ($L = 18$ mm, $D = 22$ μm).

[b]SP is mass percentage based on the overall binder content.

[c]Polymer latex was added to improve the bond.

[d]Fresh density.

[e]Quartz sand.

[f]Special developed geopolymer additive.

[g]Foam.

FIGURE 2 (a) Lightweight concrete (Gartmann house) Schweiz 2003 density; 1,100 kg/m^3, thermal conductivity; 0.32 W m^{-1} K^{-1}, strength; 12.9 MPa [13]. (b) Infra lightweight concrete (Schlaich house) Berlin 2007 density; 760 kg/m^3, thermal conductivity; 0.18 W m^{-1} K^{-1}, strength; 7.4 MPa [32]. (c) Lightweight concrete (house H36) Stuttgart 2012 density; 1,000 kg/m^3, thermal conductivity; 0.23 W m^{-1} K^{-1}, strength; 10.9 MPa [13]. (d) Infra lightweight concrete (Pavilion) TU Eindhoven 2015 density; 780 kg/m^3, thermal conductivity; 0.13 W m^{-1} K^{-1}, strength; 10 MPa [13]

[14]. The mix was used in the construction of the exterior walls of a family house in Berlin in 2007 (Figure 2b). This stage inspired and opened a wide door for many researchers to complete what has begun (Phase 2). Hückler [22] developed ILC mixes with dry density ranges of 600–800 kg/m^3 with corresponding mean compressive strengths of 7–14 MPa and thermal conductivities of 0.14–0.19 W m^{-1} K^{-1}. Moreover, he investigated the structural behavior of ILC in terms of flexural, bond and cracking behavior.

At the Chair of Building Materials and Concrete Chemistry, TU Berlin, work has also been conducted into developing ILC in the last few years. Chung et al. [33,34] investigated the effect of different gradings of lightweight aggregates on the thermal and mechanical properties of ILC with a dry density below 500 kg/m^3. In 2018, the effects of various concrete additions such as fine fly ash, fine sand and fly ash on ILC properties were addressed [26]. Abd Elrahman et al. [16,17] compared the mechanical and physical properties of ILC mixes made of different expanded aggregates such as expanded clay, expanded glass and foamed glass. LWAC and FC share many properties. In addition, FC can be produced with a density range between 500 and 1,500 kg/m^3, which is lower than that of LWAC [35,36]. Accordingly, Chung et al. [28], compared the Infra LWAC and Infra Lightweight Foamed Concrete (ILFC). Moreover, the effect of incorporating LWAs in preparing and characterizing ILFC has been investigated [16,17].

Likewise, since 2012, efforts have been exerted at the Chair of the Built Environment (Eindhoven University of Technology) towards improving monolithic structures by developing ILC ready for both insulation and bearing applications. Yu et al. [23] investigated the influence of partially replacing the cement by secondary cementitious materials such as limestone powder and nano-silica. ILC with a dry density of about 650–700 kg/m^3 showed an excellent thermal conductivity of 0.12 W m^{-1} K^{-1}, and a mean compressive strength of about 10–12 MPa could be produced [23]. Huiskes et al. [24] developed a sustainable ILC by completely replacing the cement with alkali activated materials (geopolymer) [24]. Yu et al. [15] investigated the effect of polypropylene fiber on the mechanical and thermal characteristics of ILC. They developed ILC with a mean compressive strength of 15 MPa and a corresponding dry density of 745 kg/m^3 and a thermal conductivity of 0.17 W m^{-1} K^{-1}. The impact of fiber inclusion on the overall behavior of ILC has been widely addressed [27,29]. Recently, Falliano et al. [29] studied the effect of short polymer fibers and glass fiber reinforced polymer mesh on the mechanical and flexural behavior of ILFC with densities of 400, 600, and 800 kg/m^3.

To this end, despite a considerable number of applications utilizing LWC or ILC, as can be seen in Figure 2 [13,27], further investigations are still required to show more paramount features of this relatively new material and provide design engineers with complete guidelines containing information on all essential mechanical properties and the structural behavior. Moreover, such investigations could add to the reliability and confidence in the potentials of ILC, and hence to increased application. The scientific community approaches the industrialization phase.

However, more scientific investigations and comparisons related to the energy and economic efficiency are still crucial.

3 | LIGHTWEIGHT AGGREGATES

3.1 | General

Generally, as an alternative to the traditional aggregates, lightweight concrete could be produced using natural or artificial lightweight aggregates (LWAs). Different types of LWAs are available with various physical and mechanical properties that allow LWCs to be manufactured with a wide span of densities and strengths. With the commercial availability of several types of LWAs, researchers have pushed to study, compare and investigate them to develop high performance LWAC. Studies include LWAC with natural materials such as vermiculite [37] or perlite [38], with expanded argillaceous material such as shale [39], slate [40] and clay [41] and with recycled materials such as expanded glass [42], masonry rubble [43] or crushed glass [33,34]. In addition, research has been done into using agricultural wastes such as peach shells [44], coconut shells [45], palm kernel [45], and apricot shells [46]. Since most of these materials are wastes, incorporating them in the production of (Infra) lightweight concrete meets one of the critical environmental issues.

LWAs have a much higher level of porosity compared to normal weight aggregates (NWAs). Thus, they have low strengths and are more likely to experience large deformations. This implies that LWAs are the weakest components, and consequently, they play a great role in the final performance of the produced mix [47]. In addition, they occupy more than 50% of the concrete volume [33,34]. Therefore, LWAs should be used carefully to enhance the performance of the mix in both fresh and hardened states. Many researchers have performed detailed studies to understand the influence of LWAs' properties such as particle size, grading and absorption on the mechanical and thermal properties of LWAC and ILC, as described below.

3.2 | Effect of particle size

Table 1 shows how several LWAs have been applied to produce ILC with a wide range of densities, thermal conductivity and strengths. However, expanded glass was the most popular aggregate adopted. Abd Elrahman et al. [16,17] compared the performance of three different expanded materials as LWAs; expanded clay (Liapor®), expanded glass (Liaver®) and foamed glass (Ecoglas®) in the production of LWC with a density range from 580 to 1,100 kg/m^3. They confirmed the efficiency of expanded glass in terms of the final density, strength and thermal properties. In all mixes in Table 1, the LWAs have small particle sizes with a maximum aggregate size of 9 mm. This smallness is in line with literature that finds that the compressive strength of LWAC is greatly influenced by the size of the aggregates. In accordance with ACI 213R-14, reducing the maximum size of the coarse LWAs results in a noticeable increase in the compressive strength of the LWAC, especially in the weaker and friable aggregates [5]. The crushing resistance of structural Leca aggregates increased from 2.15 to 3.62 MPa when the mean particle size was reduced from 14 to 4 mm [48]. Huiskes et al. [24], reported an 11% increase in the compressive strength of ILC when replacing aggregates of 4–8 mm with aggregates of 2–4 mm. However, an assured balance between small and large sizes is recommended if lower thermal conductivity is the aim [24].

3.3 | Effect of particles grading

Generally, including LWAs reduces the material density, which in turn enhances the insulation characteristics but weakens the mechanical properties, that is, compressive strength and elastic modulus [37]. Reducing density and also keeping the workability and the strength are greatly desired. Therefore, many researchers have applied a dense packing model (the modified Andreasen and Andersen) [49,50] to achieve an optimum packing of the granular ingredients and to maximize the volume of LWAs in the mixture. The model concept highlights the importance of the particle size grading. By including all the solid particles in the mixture grading, that is, cement and other solids, many benefits can be attained such as minimizing the pores between the aggregates and thus the cement content, reducing the water demand and improving the mix workability [51]. The cumulative particles' fraction can be optimized following the modified Andreasen and Andersen model as [49,50]:

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \quad (1)$$

where $P(D)$ is the fraction of the particles smaller than D, D_{max} and D_{min} are the maximum and minimum particle sizes involved and q is the distribution factor. The factor q can be experimentally determined, and it depends mainly on the shape and the size of the particles. The higher the value of q is the coarser the mix and the lower the fine content are, and vice versa [33,34].

Several q values have been suggested and applied in different types of concrete. Funk and Dinger suggested a value of 0.37 to obtain an optimum packing [50]. Hüsken and Brouwers [52] successfully applied a q value of 0.28 to develop an earth-moist concrete. Hunger further developed a self-compacting concrete using the same value of 0.28 [53]. Yu et al. [23] developed a self-compacting ILC with excellent thermal conductivity and moderate mechanical properties by using a distribution factor of 0.32. Yu et al. [15] applied a distribution factor of 0.35 when developing Infra lightweight fiber reinforced concrete. The developed mix also showed high mechanical and thermal performance.

In a preliminary test, Huiskes et al. [24] examined the effect of bad packing by applying 90–95% large aggregates (2–4 mm) and 5–10% small aggregates (0–1 mm). The overall workability was poor and slumped to nearly zero. In addition, the resultant mix was sensitive to segregation upon increasing the liquid from 160 to 180 L/m^3, even though at 160 L/m^3, the mix was too stiff and unworkable [24]. Chung et al. [33,34] developed ILC with a low density below 500 kg/m^3 by maximizing the volume of LWAs (more than 70%) using different gradings and different distribution factors $q = 0.23$, 0.25, 0.30 and 0.45. They concluded that, for LWAC with equal volume content of LWAs, specimens that include larger fractions of fine aggregates display higher mechanical properties and a larger thermal conductivity [33,34].

3.4 | Effect of particle absorption

Water absorption is considered as one of the main factors that greatly affects the overall behavior of (Infra) LWC in both fresh and hardened state. For every separate particle, the amount and the rate of absorption are affected directly by the volume of pores, the distribution of pores inside the particle and the structure of the pore system, that is, whether the pores are linked or isolated [54]. The moisture stored inside LWAs is not immediately available to the cementitious paste and should be excluded from the mixing water [5,9]. The high degree of absorption negatively affects the workability, but afterwards it enhances the hydration process by providing additional internal curing and mitigates the autogenous shrinkage [55,56]. Generally, two choices are available: presoaking of the aggregates for 24 hr before mixing or adding an extra amount of water during the mixing [26,33,34].

Applying presoaked LWAs helps provide a stable, compactible mix and well-distributed particles. However, many researchers have validated the use of the oven-dry LWAs without presoaking but with adjusting the mixing water proportion to account for the LWAs' absorption. Golias et al. [57] pointed out that, when applying LWAs in the oven-dry case, the LWAs can absorb approximately 55% of the 24 hr absorption value. The discrepancy is attributed to the cement particles' ability to close some of the pores in the aggregates or to the resulting liquid viscosity being relatively higher than that of the water and hence resulting in the aggregate pores filling slowly. Chung et al. [26] and Abd Elrahman et al. [16,17] adopted adding an extra amount of water to the mix that equals 1 hr of absorption to help keep a workable mix for a longer time [16,17,26]. At the other end of the spectrum, Yu et al. [23] and Yu et al. [15] developed ILC by applying expanded glass with a comparatively smooth surface and a closed external shell that needs neither presoaking nor extra water [15,23]. The applied LWAs have low water absorption (less than 2% after 60 min presoaking).

4 | BINDER

Due to the availability of the raw materials, technology and the various types of cement that fulfill engineers' needs, Portland Cement (PC) has become the most utilized binder in the construction industry [58]. In contrast to NWC, cement paste is the strongest component and has the upper hand over the LWAs in the strength development of (Infra) LWC. The weakness of LWAs can be directly attributed to the cellular structure, which is needed to achieve the required low density and thermal properties as well. Unluckily, the fragile structure of LWAs circumscribes the strength of (Infra) LWC. And so, attention has been paid to the cement and its effect on the fresh and hardened properties of (Infra) LWC. Various issues have been considered, for example, the effect of binder type, binder content, heat of hydration and partial and complete replacement of the cement.

4.1 | Binder type

Yu et al. [23] compared the mechanical and thermal properties of ILC made using several types of cement at a fixed cement content of 450 kg/m^3, while keeping the apparent density of concrete. They reported the highest mechanical properties when using cements that incorporated ground granulated blast-furnace slag (GGBS), compared to only clinker-based cements. However, no influence of the cement type on the thermal properties was found [23]. This finding coincides with that of Neville who demonstrated a 38% increase in compressive strength with 40 wt.% cement replacement by GGBS [59]. This finding was confirmed by Spiesz and Hunger [30], who developed an ILC of density 760 kg/m^3 with a corresponding compressive strength of 10.2 MPa and a thermal conductivity of 0.14 W m^{-1} K^{-1} by applying CEM III/C 32.5 N [30], which has a high percentage of blast-furnace slag between 81 and 95% [60]. The developed mix showed a similar outstanding performance compared to a previous one made by the same authors but with Portland cement. However, no excessive overheating in the case of CEM III/C 32.5 N was reached.

4.2 | Binder content

Despite wide agreement among researchers that the compressive strength of (Infra) LWC increases as the cement content increases, finding an explicit relation between cement content and compressive strength of (Infra) LWC is not straightforward. Investigating the effect of cement content involves either changing the LWAs content or adding other fillers to keep the density value the same, as demonstrated by Chandra and Berntsson [8], who found a linear relation between concrete density and compressive strength of LWAC. Yu et al. [23] investigated the effect of binder dosage by utilizing three different contents, 450, 400 and 350 kg/m^3 [23]. To help keep the LWAs' content and achieve a fixed density of 650–700 kg/m^3, silica and limestone powder were added. They reported an increase in compressive strength from 10 to 12 MPa upon changing the CEM II/B-V 42.5 N content from 350 to 450 kg/m^3. However, equal strengths were obtained for CEM I 52.5 N. This finding can be interpreted by the strength ceiling made by the LWAs. Moreover, Spiesz and Hunger [30] indicated that increasing cement content leads to a high temperature during the hydration phase and, subsequently, cracks. Therefore, adopting the cement dosage may also be affected by many other factors such as the strength of LWAs and the cement characteristics.

4.3 | Heat of hydration

Whereas, with conventional NWC, the heat of hydration can be released to the surroundings due to the high thermal conductivity, the low heat conductivity of (Infra) LWC greatly contributes towards retaining the heat inside the concrete body. ILC's hydration temperature may rise up to 100°C accompanied by a temperature gradient across the cross section [10,30]. This results in a tensile stress on the outside of the cross section during the heating phase and then cracking [61]. Cracking can significantly limit the strength development and the durability of the structure. In addition, since ILC is a fair-faced concrete, cracks are undesirable. Schlaich and El Zareef [32] applied low heat cement CEM III-A 32.5 N to reduce the harmful effect of the hydration heat in one of the leading mixes of ILC and to control the early age cracks. Likewise, Schulze and Breit applied a CEM III/B 32.5 N, which has a slow heat of hydration, to develop ILC of dry density less than 700 kg/m^3 [31].

Donners [13] conducted experimental work to find an optimum solution to ILC's high hydration heat. In that work, he investigated many options such as reducing the starting temperature of the components, cooling the formwork or inserting cooling pipes. Although inserting cooling pipes meant the insulation criteria could be met, the most applicable and effective method that allowed the criteria (maximum temperature of 70°C) to be met was to reduce the cement content by 40% in addition to adopting a low heat cement CEM III-A 32.5 N. However, as a side effect, the mechanical properties were also reduced. Spiesz and Hunger [30] concluded that CEM III/C 32.5 N is a suitable selection for ILC, especially on larger scale, in terms of moderate strength, insulation and heat of hydration. The measured maximum temperature with 500 kg/m^3 cement content was 80°C. In addition, the temperature rose at a comparatively slower rate [30]. This slowness can be attributed to the slow hydration of GGBS as the composition of the applied CEM III/C 32.5 N contains large quantities of GGBS (87% GGBS and 11% cement clinker). Similarly, Callsen and Thienel [62] controlled the heat of hydration of ILC by adding ice flakes during the mix and by implementing a low heat cement.

4.4 | Cement replacement and environmental aspects

Cement production is one of the main sources of CO_2 emissions and other greenhouse gases. In addition, a great amount of energy is also consumed [63,64]. Since ILC is supposed to provide a sustainable and an eco-friendly approach, many researchers have started to mitigate the environmental impact and go towards green buildings by partially or completely replacing the cement with supplementary cementitious materials. In this regard, many supplementary materials have been used, for example, fly ash, GGBS and limestone powder.

To accelerate the hardening and keep the foam within the matrix of ILC, Chen and Liu [25] partially replaced the cement by high alumina cement, which is limestone based [25], while Yu et al. [23] stated that limestone powder is the best replacer because it shares the same particle distribution with cement. Chung et al. [26] investigated the effect of different fillers on the overall properties of (Infra) LWAC with a dry density range from 800 to 950 kg/m^3. They reported the best mechanical properties for the mix that incorporated fly ash, while the limestone powder mix achieved both the required thermal and mechanical properties [26]. To achieve a high level of sustainable and green structures, Huiskes et al. [24] developed ILC with a compressive strength of 10 MPa and a thermal conductivity of 0.11 W m^{-1} K^{-1} by completely replacing the cement with alkali activated materials [24]. The precursor utilized was premixed by mass 30% GGBS and 70% fly ash activated by blending water with sodium hydroxide (NaOH) to achieve a desired molarity of 2–3.

Generally, considerable attention has been paid to reduce the carbon footprint associated with the manufacturing of ILC by partially or completely replacing the cement with supplementary cementitious materials. Important also is the high rate of carbonization of ILC due to its high level of porosity. ILC has a much higher carbonization coefficient than NWC; it can absorb back about 55 kg of CO_2 per cubic meter during its service life [19]. Consequently, ILC represents a relatively eco-friendly concrete material. However, steel corrosion should be carefully considered with ILC.

5 | ADMIXTURES

5.1 | General

ILC is a novel material that can cater for contradictory aims, that is, high void content to meet insulation criteria and a moderately compressive strength, which is negatively affected by the existence of voids. Accordingly, many researchers have been trying to enhance the overall behavior of ILC by adopting methods such as including fiber or nano-silica. Moreover, owing to the wide density difference between the LWAs and the matrix, ILC is more likely to experience segregation and bleeding, particularly upon vibration. Consequently, a high level of workability is also crucial to ensure a self-leveling without vibration. In this context and as is shown in Table 1, almost all researchers have recommended using superplasticizer and stabilizers to improve the workability and keep the stability of the mixes.

5.2 | Fibers

Basically, when fibers are used in concrete, many benefits arise in terms of flexural capacity, ductility, crack control and energy absorption [65]. Moreover, fibers can play a considerable role in reducing the dry shrinkage [66,67]. The influence of fiber inclusion on the mechanical properties of ILC has been also addressed by researchers. However, due to the limited discussions and contradictory results on the topic, no assured outcomes can be considered here.

First, there is a wide agreement among researchers that polypropylene fiber (PP) is the best choice for ILC. It is rustproof and has a comparatively lower density and lower thermal conductivity. El Zareef and Schlaich [27] investigated the effect of PP fibers (nearly 0.1% vol. and with three different lengths of 6, 12, and 20 mm) on the mechanical properties of ILC. They reported an increase in the tensile strength of ILC by 10, 23, and 30%, respectively. Conversely, a relatively high reduction in the compressive strength of, respectively, 56, 43, and 41%, was reported. They interpreted this as being caused by the early micro cracks that may develop upon using PP fiber in low compressive strength materials. The same general tendency was found by Falliano et al. [29], who reported a considerably enhanced tensile and flexural capacity of ILFC. However, the improvement of compressive strength due to fibers was negligible, despite the relatively high proportions of fibers; (0.7, 2.0, and 5% vol.). Yu et al. [15] investigated the effect of both short PP fibers (length of 18 mm, diameter of 22 μm) and long PP fibers (length of 45 mm, diameter of 0.5 mm) on the mechanical and thermal properties of ILC. They underlined the importance of hybridization between long and short PP fibers, especially in low fiber dosage (below 0.3%). The compressive strength obtained when the hybrid fibers of 0.2% vol. composed of 75% of long PP and 25% of short PP was 13 MPa, compared to 12.1 MPa with only long PP fibers of the same volume content. According to the authors, this difference can be attributed to the ability of the short PP fiber to bridge the macro-cracks, while the long PP fibers become more effective after crack propagation. The study was also extended to compare the effect of relatively high fiber dosages; 0.6, 0.9,*** and 1.2% vol. The highest compressive strength of 15 MPa was achieved by using 0.6% vol. long PP fibers. However, a further increase in the fiber content resulted in compressive strength being reduced due to the possible disturbance in the matrix.

Despite the beneficial effects in terms of the mechanical performance that may be achieved by including fibers in ILC, a recyclability problem may emerge. This problem arises partially because the fibers cannot be easily separated from the concrete body. Therefore, Prof. Schlaich, who is considered one of the influential scholars in this area and had the opportunity to apply ILC in the construction of a family house in Berlin 2007, recommends using the galvanized normal reinforcement (RFT) rather than fibers or glass fiber reinforcement (GFR). Nevertheless, bars of GFR have been utilized in the construction of that house to overcome the rust problem that might occur from the high porosity of ILC.

5.3 | Micro-/nano-silica

Broadly speaking, it has been demonstrated that micro- and nano-silica have a positive impact on the mechanical properties of concrete by introducing pozzolanic reactions due to the high SiO_2 content and the high degree of fineness [18,68,69]. By observing the ILC mixes described in Table 1, many researchers have sought enhancements and have applied silica fume. Micro- and nano-silica play a significant role in ILC by improving the mix consistency, reducing the risk of bleeding or segregation and increasing the cohesion between the LWAs and the matrix [16,17,26,33,34]. Moreover, they can effectively help develop the strength at an early age. Yu et al. [23] studied the effect of replacing different amounts of cement with nano-silica on the mechanical and thermal properties of ILC. They reported a positive trend on the strength. For example, applying 10% replacement of CEM II/B-V 42.5 N by nano-silica resulted in a compressive strength increase of 21% and 22% for a cement content of 450 and 400 kg/m^3, respectively. Nonetheless, they found no influence on the thermal conductivity upon employing different dosages of nano-silica.

6 | SHRINKAGE BEHAVIOR OF ILC

Initial experimental tests of ILC's shrinkage behavior have shown that ILC can experience a high shrinkage strain value relative to NWC. The shrinkage strain was around 0.9 mm/m after 2 years. However, 70% of this value was reached after only 3 weeks [32]. An ongoing study shows that this value may exceed 1.2 mm/m compared to (0.2–0.8) mm/m for NWC. Among several parameters, the quantity and the lower elastic modulus of LWAs play a significant role on the shrinkage behavior of (Infra) LWAC [70]. The role of LWAs can be analyzed by separating the overall shrinkage into two stages; autogenous shrinkage and drying shrinkage [71]. In the early ages of concrete, saturated LWAs provide the cement paste with additional moisture during the hydration process, hence compensating the loss of water, and may further result in swelling of concrete at an early age [72]. On the other hand, the drying shrinkage of ILC is significantly high due to the less restrains provided by the LWAs to the cement paste deformation [70].

High shrinkage strain of ILC in constrained conditions produces tensile stress and contributes towards the initiation and propagation of cracks that may impair the quality of concrete and reduce the service life. Several practices can reduce the ILC's shrinkage. Applying low heat cement helps reduce the hydration heat and, accordingly, the early age shrinkage [32]. An experimental investigation demonstrated that adding shrinkage-reducing admixtures can reduce the shrinkage up to 50% [73,74]. Fiber reinforcement has a positive effect on reducing the early age cracks and enhancing the tensile strength of ILC, as well [66]. In the exterior walls of the family house in Berlin, (Figure 2b) GFR bars were used on both sides, which has helped to minimize the cracks so far and keep the shrinkage to the NWC level. Moreover, the structural system adopted was of minimum redundancy and less restraining stresses [14].

Time dependent deformations, such as shrinkage and creep are sensitive in such a special type of concrete being contained a high cement content, a high w/c ratio and weak aggregates. Thus, shrinkage and creep of ILC must be carefully considered by engineers. In addition, further investigations are required to present prediction models of shrinkage and creep that consider all the factors involved in ILC.

7 | STRUCTURAL BEHAVIOR OF ILC

7.1 | Bond behavior

An adequate bond between reinforcement bars and concrete is necessary [75], as it directly contributes towards a) achieving an effective beam action, b) controlling the cracks and c) developing ductility. Moreover, all the derived design equations implemented in codes of practice fundamentally rely on a sufficient bond. Thus, the loss of the bond would render all the design basics invalid [76]. Building-up of bond strength may be achieved by two mechanisms: physio chemical (adhesion) and mechanical (friction and bearing action). The adhesion force comes from the chemical interaction between the cementitious paste and the steel bar surface. The friction force arises from the rough contact and the bearing force, that is, it is a direct result of the interlocking between the steel ribs and the surrounding concrete [77].

Many researchers have investigated the bond behavior of LWAC and reported factors that may affect the bond strength of LWAC such as aggregate type, water to cement ratio w/c, curing, admixtures, type and surface texture of reinforcing bars, diameter of reinforcing bars, bond length and the effect of lateral confinement. Many equations for predicting the bond strength of LWAC have been proposed, as given for Equation (2) in Bogas et al.

[78], for Equation (3) in Kim et al. [79], and for Equation (4) in Tang [80];

$$\tau = \left[171.9\left(\frac{h}{d}\right)^2 - 24.24\left(\frac{h}{d}\right) + 1.2981\right] f'_c \quad (2)$$

$$\tau = \left[\frac{37.5}{(d+l_d)^{0.25}} - 9.4\right] f'^{0.5}_c \quad (3)$$

$$\tau = K \cdot [44.5 - 60(w/c)] \cdot \frac{\rho_d}{2200} \quad (4)$$

where; h is the rib height, d is the bar diameter, l_d is the embedment length, f'_c is the compressive strength of concrete, w/c is the water to cement ratio and ρ_d is the dry density of concrete. The question that may arise is whether these equations are applicable to ILC. In other words, will the bond behavior of ILC differ from that of LWC? This is a vital issue. Bond of ILC has been addressed by many researchers. El Zareef and Schlaich [27] compared the bond behavior of ILC reinforced with two types of reinforcement: RFT and GFR. In addition, they inspected the effect of PP fibers on improving the bond capacity of ILC. They highlighted the significance of the bars' ribs, especially in low strength materials such as ILC. Owing to more ribs per unit length in the case of RFT compared to GFR, they reported a 20% increase in bond strength for RFT. Additionally, for the same reason, the use of PP fibers of 20 mm length gave more effective results for RFT than for GFR. Upon employing the PP fibers, they reported a 25.3% increase in bond strength for RFT compared to only 4.6% increase for GFR. Moreover, adding PP fibers resulted in a relative reduction of the bar slip at the maximum bond stress, and consequently, a better crack control.

Those results were confirmed later by Marinus [81], who investigated the bond behavior as a part of a wide study related to the structural behavior of ILC. He attributed the low bond strength of ILC to LWAs that cannot withstand large compressive forces and pulverize at rib location. Therefore, an optimization of the ribs' configuration is required to reduce the stress on the LWAs. In line with El Zareef and Schlaich [27], he recommended the use of normal reinforcement in ILC in comparison to GFR, based on the possibility of wider cracks when using GFR due to the lower elastic modulus. Recently, Hückler and Schlaich [82] conducted experimental work to explore the structural behavior of ILC [82]. For the bond behavior, they concluded that the bond-slip relationship of ILC is totally different compared to that of LWC. In addition, the bond strength of ILC mainly depends on the grade of ILC, that is, the higher the tensile strength, the higher the bond strength. The experimental results were employed to develop an ILC bond model in which the mathematical idealization is similar to that of CEB-FIB [83] and fib Model Code for concrete structures 2013 [84] while the governing peaks were modified. The proposed model was expressed by three linear parts in which the high rigidity of ILC was strongly reflected; a sharp gradient till the peak strength τ_{max} at a comparatively small slip value s_1 followed by an abrupt decline with no plateau compared to that of NWC or LWC. The model is shown in Figure 3 and the governing equations can be expressed as [82]:

$$\tau = \begin{cases} \left(\frac{\tau_{\max}}{s_{1,2}}\right) & s\,0 \le s \le s_{1,2} \\ \tau_{\max} - \frac{\tau_{\max} - \tau_f}{s_3 - s_{1,2}} & (s - s_{1,2})\, s_{1,2} < s \le s_3 \\ \tau_f & s_3 < s \end{cases} \quad (5)$$

where $\tau_{max} = 0.3\, f_{ck}^{0.82}$, $\tau_f = 0.045 f_{ck}^{0.82}$, $s_{1,\,2} = 0.1\tau_{max}$, f_{ck} is the characteristic compressive strength of concrete and s_3 is equal to the spacing between the ribs. To the authors' knowledge, this is the first ILC bond model. In addition, testing the previous bond models adopted for LWC reveals that the bond models for LWC are not applicable for ILC, although they consider the limited density or strength.

7.2 | Flexural behavior

The common use of ILC is in monolithic load bearing façades, in which the load from a NC or LWC slab is transferred to the foundations. So, for ILC walls with openings (windows), it is essential to ensure the structural safety of the whole wall, particularly the part of the walls above the opening, that is, lintels, which, for relatively wide openings, may act as a beam carrying a distributed load from the slab and are subjected to flexural

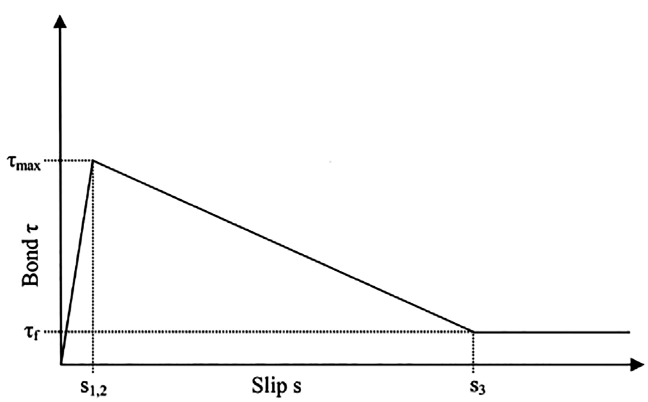

FIGURE 3 Bond model of Infra lightweight concrete [82]

and shear stresses. Therefore, the flexural behavior of ILC must be understood in detail. In this context, since ILC cannot survive alone without reinforcement under bending action, different reinforcement strategies had been investigated. Falliano et al. [29] investigated the flexural strength of ILFC of densities 400, 600 and 800 kg/m^3 using either short PP fibers alone or short PP fibers plus GFR mesh at the tensile stress zone. They recommend an optimum arrangement consisting of GFR mesh plus 2% short PP fibers, which could ensure optimum enhancement of flexural strength. The bending behavior of ILC beams has been also investigated by Hückler and Schlaich, who considered two types of reinforcement; RFT and GFR [82,85]. Owing to the linear elastic behavior of ILC under compressive stress, a triangular stress block has been assumed in the compression zone instead of a parabola-rectangle or Whitney block. In this way, the lever arm between the equivalent compressive force and the steel tension force is equal to ($d - c/3$) where d is the effective depth of the section and c is the height of compression zone. Accordingly, applying the internal equilibrium and the strain compatibility conditions has allowed a proposal for the first design aid for ILC sections reinforced with either RFT or GFR under bending action.

Recently, seeking a high level of efficiency and sustainability, Lösch et al. [86] investigated the flexural behavior of inhomogeneous ILC beams. The inhomogeneity arises from incorporating ILC with different properties in the same cross section to meet the principle of "properties follow function." Accordingly, ILC with a relatively high strength was adopted for the outer shells of the cross section as a bearing element while the inner core was made of highly porous ILC with perfect insulation characteristics. By following approximately the approach used by Hückler and Schlaich [82], an analytical solution was proposed that allowed the maximum moment capacity of inhomogeneous ILC beams under bending to be estimated.

7.3 | Bearing behavior

Monolithic façades made of ILC may experience bending moments or shear, as explained before, or a uniform centric or eccentric compression. In this context, the complete wall behavior has to be considered. Marinus [81] reported a bearing problem of ILC upon testing ILC wall beams in 4-points bending. The key aim of that study was to find the best anchorage technique in ILC. However, almost all specimens failed at one of the end supports, although the bearing stress was still lower than the compressive strength of concrete. This failure (Figure 4)

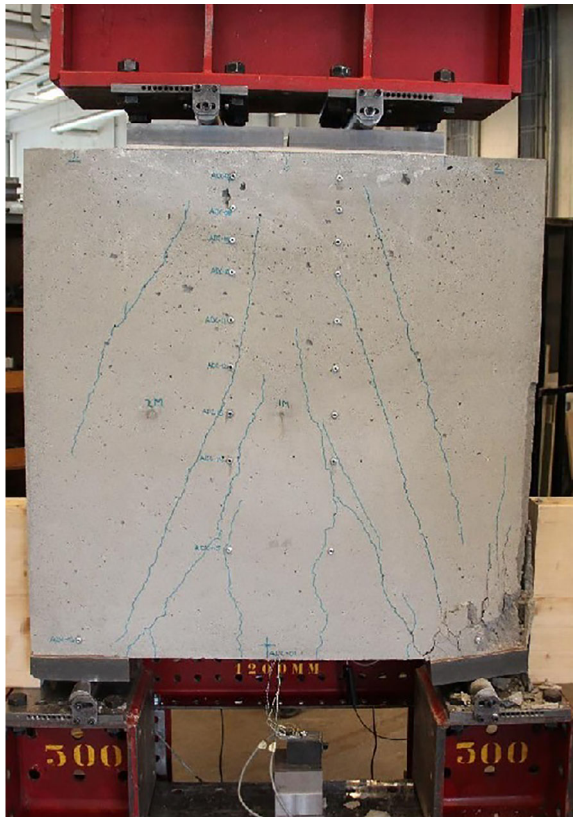

FIGURE 4 Bearing failure of Infra lightweight concrete wall beam [81]

was unpredictable since all specimens were designed to fail at the fracture of the main reinforcement. The reasons behind this failure have not been examined. The failure may, however, present direct evidence that the bearing strength of ILC is lower than the compressive strength. Hence, further investigation is required to predict precisely the bearing strength of ILC. Recently, Lösch et al. [86] conducted experimental work to predict the maximum load-bearing capacity of inhomogeneous ILC walls under centric vertical pressure. They provided clear evidence that the bearing strength of ILC walls is lower than the corresponding mean cylinder compressive strength. Based on the analytical and experimental findings, they presented a reduction factor of 0.74 when calculating the maximum load bearing capacity, based on the mean cylinder compressive strength of ILC.

7.4 | Shear behavior of ILC

So far, there has been no investigation into the shear behavior of ILC. Therefore, comprehensive analytical and experimental investigations should be conducted in future research projects. Over the last century, efforts have been devoted towards the proper understanding of the shear behavior of NWC. Accordingly, many theories have been formulated, for example the truss model, the tooth model and the modified compression field theory. In addition, many affecting factors have been reported such as the shear span, aggregates' interlock, longitudinal reinforcement ratio and the size effect. When it comes to ILC, many questions are brought up for discussions and need further investigation. For instance: is the shear behavior of ILC similar to that of NWC? Are the international codes' provisions related to the shear capacity applicable to the ILC or should additional modifications be implemented? Since the Strut and Tie Model (STM) is a typical method for dealing with shear problems, is the strut strength of ILC similar to that of NWC?

8 | FURTHER STUDIES

The conducted survey provides clear evidence that the mechanical and thermal properties of ILC have been widely investigated and developed. It highlights, however, limited studies related to the structural behavior of ILC. Therefore, it recommends widening the scope of research by studying the structural behavior of ILC and providing complete guidelines for the design engineers, furnishing them with all necessary data and design aids. Further investigations, especially on the mechanics side, would bring trust and confidence to the potentials of ILC and hence increase its use. Also important is the high values of the time dependent deformations of ILC, which require further investigations.

9 | CONCLUSION

The major findings of this survey can be summarized as follows:

1. Smaller aggregate size and proper grading play an important role in developing ILC strength.
2. Blast furnace cements with lower clinker content are the optimum choice for producing ILC because they deliver moderate strength, lower thermal conductivity and hydration heat.
3. Increasing the cement dosage will not necessarily ensure a corresponding increase in the mechanical properties of ILC due to the strength ceiling caused by the LWAs. In addition, high cement dosage results in a high hydration temperature, which in turn induces cracks.
4. There is a universal trend towards mitigating the environmental impact by partially or completely replacing the cement with supplementary cementitious material. In this regard, limestone powder has been confirmed as the best replacer when it comes to moderate compressive strength and low thermal conductivity.
5. The results on fiber inclusion in ILC are conflicting. Moreover, it may cause a recyclability problem in the long run.
6. Micro- and nano-silica can significantly improve the fresh properties of ILC by reducing the risk of bleeding or segregation and increasing the cohesion between the LWAs and the matrix. They could also enhance the mechanical properties by introducing pozzolanic reactions.
7. The bond strength of ILC is much lower than that of NWC or LWC, while the behavior is completely different due to the high level of rigidity.
8. It has been widely accepted that normal reinforcement (RFT) is the best reinforcement strategy in bond and economic terms. Nevertheless, precautions against rust problems must be considered due to the high porosity of ILC.
9. Due to the linear elastic behavior of ILC, the compressive stress block under bending action can be expressed by a triangle instead of by a parabola-rectangle so that the lever arm between the internal compression and tension force is equal to $(d-c/3)$. Consequently, the flexural formulas of ILC can be easily derived.
10. The bearing capacity of ILC obtained experimentally is lower than the mean cylinder compressive strength. Hence, further investigation is required to predict precisely ILC bearing strength.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the Deutscher Akademischer Austauschdienst (DAAD) for their regular support.

ORCID

Mahmoud Elshahawi https://orcid.org/0000-0003-1921-938X

REFERENCES

1. Narayanan N, Ramamurthy K. Structure and properties of aerated concrete: A review. Cement Concr Compos. 2000;22(5):321–329.
2. ACI 213R-87. Guide for structural lightweight aggregate concrete. American Concrete Institute International (Reapproved 1999); 1987
3. Ke Y, Beaucour AL, Ortola S, Dumontet H, Cabrillac R. Influence of volume fraction and characteristics of lightweight aggregates on the mechanical properties of concrete. Construct Build Mater. 2009;23(8):2821–2828.
4. Dinelli G, Belz G, Majorana CE, Schrefler BA. Experimental investigation on the use of fly ash for lightweight precast structural elements. Mater Struct. 1996;29(10):632–638.

5. ACI 213R-14. Guide for structural lightweight aggregate concrete; 2003.
6. Real S, Gomes MG, Rodrigues AM, Bogas JA. Contribution of structural lightweight aggregate concrete to the reduction of thermal bridging effect in buildings. Construct Build Mater. 2016;121:460–470.
7. Roberz F, Loonen R, Hoes P, Hensen JLM. Ultra-lightweight concrete: Energy and comfort performance evaluation in relation to buildings with low and high thermal mass. Energ Buildings. 2017;138:432–442.
8. Chandra S, Berntsson L. Lightweight aggregate concrete. Berlin: Elsevier, 2002.
9. Clarke JL. Structural lightweight aggregate concrete. Boca Raton, FL: Taylor & Francis CRC Press, 1993.
10. Newman JB. 2 properties of structural lightweight aggregate. Struct Lightweight Aggreg Concr. London: Chapman & Hall; 1993;19.
11. Eurocode 2. Design of Concrete Structures-Part 1–1: General Rules and Rules for Buildings; 2004.
12. Schlaich M, Hillemeier B, Schubert K. Infraleichtbeton–Potenzial für den Sichtbetonbau. *Proceedings*, 51; 2007.
13. Donners MM. Warmbeton: De invloed van hydratatiewarmte op de toepassing in de praktijk. Technische Universiteit Eindhoven, 2015.
14. El Zareef M.. Conceptual and structural design of buildings made of lightweight and infra-lightweight concrete (PhD). Conceptual and Structural Design Department, TU Berlin, (2010).
15. Yu R, Van Onna DV, Spiesz P, Yu QL, Brouwers HJH. Development of ultra-lightweight fibre reinforced concrete applying expanded waste glass. J Clean Prod. 2016;112: 690–701.
16. Abd Elrahman M, Chung S-Y, Stephan D. Effect of different expanded aggregates on the properties of lightweight concrete. Magaz Concr Res. 2019a;71(2):95–107.
17. Abd Elrahman M, Chung S-Y, Sikora P, Stephan D. Preparation and characterization of ultra-lightweight foamed concrete incorporating lightweight aggregates. Appl Sci. 2019b;9(7): 1447.
18. Schlaich M, Hückler A. Infraleichtbeton 2.0. Beton Stahlbetonbau. 2012;107(11):757–766.
19. Schlaich M, Hückler A. Infraleichtbeton: Reif für die Praxis. Beton Stahlbetonbau. 2017;112(12):772–783.
20. Lösch C, Rieseberg P, Schlaich M, Leibinger R, Ballestrem M, Forum E. Infra-lightweight concrete in multi-story residential buildings. Bern, Switzerland: 10th Conference on Advanced Building Skins; 2015; p. 932–941.
21. Liang YQ, Przemek S, Jos B. Design of ultra-lightweight concrete: Towards monolithic concrete structures. Вестник МГСУ. 2014;4:98–106.
22. Hückler A. Trag- und Verformungsverhalten von biegebeanspruchten Bauteilen aus Infraleichtbeton (ILC) [dissertation]. Sierke Verlag: Göttingen; 2016.
23. Yu QL, Spiesz P, Brouwers HJH. Ultra-lightweight concrete: Conceptual design and performance evaluation. Cement Concr Compos. 2015;61:18–28.
24. Huiskes DMA, Keulen A, Yu QL, Brouwers HJH. Design and performance evaluation of ultra-lightweight geopolymer concrete. Mater Des. 2016;89:516–526.
25. Chen B, Liu N. A novel lightweight concrete-fabrication and its thermal and mechanical properties. Construct Build Mater. 2013;44:691–698.
26. Chung S-Y, Elrahman MA, Stephan D, Kamm PH. The influence of different concrete additions on the properties of lightweight concrete evaluated using experimental and numerical approaches. Construct Build Mater. 2018;189:314–322.
27. El Zareef M, Schlaich M. Bond behaviour between GFR bars and infra-lightweight concrete. Amsterdam, Netherlands: Proceeding of FIB International Conference, Tailor Made Concrete Structures - New Solutions for our Society; 2008; p. 161.
28. Chung S-Y, Elrahman MA, Kim J-S, Han T-S, Stephan D, Sikora P. Comparison of lightweight aggregate and foamed concrete with the same density level using image-based characterizations. Construct Build Mater. 2019;211:988–999.
29. Falliano D, De Domenico D, Ricciardi G, Gugliandolo E. Compressive and flexural strength of fiber-reinforced foamed concrete: Effect of fiber content, curing conditions and dry density. Construct Build Mater. 2019;198:479–493.
30. Spiesz PR, Hunger M. Structural ultra-lightweight concrete—From laboratory research to field trials. *11th High Performance Concrete Conference, HPC Tromso, Norway*, 1–10; 2017.
31. Schulze J, Breit W. Experimentalgebäude aus infraleichtbeton–monolithisch und hochwärmedämmend. Beton Stahlbetonbau. 2016;111(6):377–384.
32. Schlaich M, El Zareef M. Infra-lightweight concrete. . Amsterdam, Netherlands: Proceeding of FIB International Conference, Tailor Made Concrete Structures - New Solutions for our Society; 2008; p. 159.
33. Chung S-Y, Abd Elrahman M, Stephan D. Effect of different gradings of lightweight aggregates on the properties of concrete. Appl Sci. 2017a;7(6):585.
34. Chung S-Y, Abd Elrahman M, Sikora P, Rucinska T, Horszczaruk E, Stephan D. Evaluation of the effects of crushed and expanded waste glass aggregates on the material properties of lightweight concrete using image-based approaches. Materials. 2017b;10(12):1354.
35. Lim SK, Tan CS, Lim OY, Lee YL. Fresh and hardened properties of lightweight foamed concrete with palm oil fuel ash as filler. Construct Build Mater. 2013;46:39–47.
36. Pan Z, Li H, Liu W. Preparation and characterization of super low density foamed concrete from portland cement and admixtures. Construct Build Mater. 2014;72:256–261.
37. Schackow A, Effting C, Folgueras MV, Güths S, Mendes GA. Mechanical and thermal properties of lightweight concretes with vermiculite and EPS using air-entraining agent. Construct Build Mater. 2014;57:190–197.
38. Sengul O, Azizi S, Karaosmanoglu F, Tasdemir MA. Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete. Energ Buildings. 2011;43 (2–3):671–676.
39. Cui HZ, Lo TY, Memon SA, Xu W. Effect of lightweight aggregates on the mechanical properties and brittleness of lightweight aggregate concrete. Construct Build Mater. 2012;35:149–158.
40. Harmon KS. Physical characteristics of rotary kiln expanded slate lightweight aggregate. Proceedings of 2nd International Symposium on Structural Lightweight Aggregate Concrete. Norway: Kristiandsand, 2000.

41. Muñoz-Ruiperez C, Rodríguez A, Gutiérrez-González S, Calderón V. Lightweight masonry mortars made with expanded clay and recycled aggregates. Construct Build Mater. 2016;118:139–145.
42. Nemes R, Józsa Z. Strength of lightweight glass aggregate concrete. J Mater Civil Eng. 2006;18(5):710–714.
43. Mueller A, Schnell A, Rübner K. The manufacture of lightweight aggregates from recycled masonry rubble. Construct Build Mater. 2015;98:376–387.
44. Wu F, Liu C, Sun W, Zhang L, Ma Y. Mechanical and creep properties of concrete containing apricot shell lightweight aggregate. KSCE J Civil Eng. 2019b;23(7): 2948–2957.
45. Olanipekun EA, Olusola KO, Ata O. A comparative study of concrete properties using coconut shell and palm kernel shell as coarse aggregates. Build Environ. 2006;41(3): 297–301.
46. Wu F, Liu C, Sun W, Ma Y, Zhang L. Effect of peach shell as lightweight aggregate on mechanics and creep properties of concrete. Eur J Environ Civ Eng. 2019a;1–19. https://doi.org/10.1080/19648189.2018.1515667.
47. Chi JM, Huang R, Yang CC, Chang JJ. Effect of aggregate properties on the strength and stiffness of lightweight concrete. Cement Concrete Compos. 2003;25(2):197–205.
48. Ardakani A, Yazdani M. The relation between particle density and static elastic moduli of lightweight expanded clay aggregates. Appl Clay Sci. 2014;93:28–34.
49. Andreasen AHM. Über die Beziehung zwischen Kornabstufung und Zwischenraum in Produkten aus losen Körnern (mit einigen Experimenten). Kolloid-Zeitschrift. 1930;50(3): 217–228.
50. Funk JE, Dinger DR. Predictive process control of crowded particulate suspensions: Applied to ceramic manufacturing. Berlin: Springer Science & Business Media, 2013.
51. Abd Elrahman MA, Hillemeier B. Combined effect of fine fly ash and packing density on the properties of high performance concrete: An experimental approach. Construct Build Mater. 2014;58:225–233.
52. Hüsken G, Brouwers HJH. A new mix design concept for earth-moist concrete: A theoretical and experimental study. Cem Concr Res. 2008;38(10):1246–1259.
53. Hunger M. An integral design concept for ecological self-compacting concrete. Eindhoven, The Netherlands: *Eindhoven University of Technology*, 2010.
54. Chia KS, Zhang M-H. Water permeability and chloride penetrability of high-strength lightweight aggregate concrete. Cem Concr Res. 2002;32(4):639–645.
55. Bentz DP. Internal curing of high-performance blended cement mortars. ACI Mater J. 2007;104(4):408.
56. Kohno K, Okamoto T, Isikawa Y, Sibata T, Mori H. Effects of artificial lightweight aggregate on autogenous shrinkage of concrete. Cem Concr Res. 1999;29(4):611–614.
57. Golias M, Castro J, Weiss J. The influence of the initial moisture content of lightweight aggregate on internal curing. Construct Build Mater. 2012;35:52–62.
58. Schneider M, Romer M, Tschudin M, Bolio H. Sustainable cement production-present and future. Cem Concr Res. 2011; 41(7):642–650.
59. Neville AM. Properties of concrete. Vol 4. London: Longman, 1995.
60. European Committee for Standardization. Cement. Part 1: Composition, Specifications and Conformity Criteria for Common Cements. Brussels: European Committee for Standardization, 2011.
61. Byard BE, Schindler AK. Cracking tendency of lightweight concrete. Auburn, AL: *Highway Research Center, Auburn University*, 2010.
62. Callsen B, Thienel K-C. Besondere Aspekte bei der Entwicklung und Ausführung eines hochwärmedämmenden Hochleistungs-Leichtbetons mit sehr niedriger Betonrohdichte. Beton. 2017;67(4):128–134.
63. Mehta PK, Monteiro PJM. Concrete Microstructure, Properties and Materials. New York, NY: McGraw-Hill Professional; 2005.
64. Paris JM, Roessler JG, Ferraro CC, DeFord HD, Townsend TG. A review of waste products utilized as supplements to portland cement in concrete. J Clean Prod. 2016;121:1–18.
65. Ding Y, Kusterle W. Compressive stress–strain relationship of steel fibre-reinforced concrete at early age. Cem Concr Res. 2000;30(10):1573–1579.
66. Banthia N, Gupta R. Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete. Cem Concr Res. 2006;36(7):1263–1267.
67. Mirza FA, Soroushian P. Effects of alkali-resistant glass fiber reinforcement on crack and temperature resistance of lightweight concrete. Cement Concr Compos. 2002;24(2):223–227.
68. Jo B-W, Kim C-H, Tae G, Park J-B. Characteristics of cement mortar with nano-SiO_2 particles. Construct Build Mater. 2007; 21(6):1351–1355.
69. Qing Y, Zenan Z, Deyu K, Rongshen C. Influence of nano-SiO_2 addition on properties of hardened cement paste as compared with silica fume. Construct Build Mater. 2007;21(3):539–545.
70. ACI 209.1R. Report on factors affecting shrinkage and creep of hardened concrete; 2005.
71. CEB-FIB Model Code 1990: Design Code. London, Telford; 1993.
72. Lura P, Bisschop J. On the origin of eigenstresses in lightweight aggregate concrete. Cement Concr Compos. 2004;26(5): 445–452.
73. Shh SP, Krguller ME, Sarigaphuti M. Effects of shrinkage-reducing admixtures on restrained shrinkage cracking of concrete. Mater J. 1992;89(3):289–295.
74. Shoya M, Sugita S, Sugawara T. Improvement of drying shrinkage and shrinkage cracking of concrete by special surfactants. Proceedings of the International Symposium, Barcelona, 1990.
75. Prince MJR, Singh B. Bond behaviour of deformed steel bars embedded in recycled aggregate concrete. Construct Build Mater. 2013;49:852–862.
76. Zhao Y, Lin H, Wu K, Jin W. Bond behaviour of normal/recycled concrete and corroded steel bars. Construct Build Mater. 2013;48:348–359.
77. ACI 408R-03. Development of straight reinforcing bars in tension; 2003.
78. Bogas JA, Gomes MG, Real S. Bonding of steel reinforcement in structural expanded clay lightweight aggregate concrete: The influence of failure mechanism and concrete composition. Construct Build Mater. 2014;65:350–359.
79. Kim D-J, Kim MS, Yun GY, Lee YH. Bond strength of steel deformed rebars embedded in artificial lightweight aggregate concrete. J Adhes Sci Technol. 2013;27(5–6):490–507.

80. Tang C-W. Local bond stress-slip behavior of reinforcing bars embedded in lightweight aggregate concrete. Comput Concrete. 2015;16(3):449–466.
81. Marinus P. Ultra-Lichtbeton voor Monoliete Gevelconstructies. Technische Universiteit Eindhoven, Eindhoven, Nog Uit Te Brengen. 2016.
82. Hückler A, Schlaich M. Structural behavior of reinforced infra-lightweight concrete (ILC). ACI Struct J. 2019;116(2):3–14.
83. CEB-FIB. Lightweight aggregate concrete: Recommended extensions to model code 90. Lausanne: International Federation for Structural Concrete 8, 2000.
84. CEB-FIB. Fib model code for concrete structures 2010; Ernst & Sohn. Berlin, Germany: Wiley, 2013.
85. Hückler A, Schlaich M. Zur Biegung von Infraleichtbetonbauteilen–Werkstoff-, Verbund-, Trag-und Verformungsverhalten. Beton Stahlbetonbau. 2017;112(5):282–292.
86. Lösch C, Richter A, Schlaich M. Multifunctional inhomogeneous lightweight concrete elements—Outline and structural behavior. 40th IABSE Symposium. Nantes, France: Curran Associates, Inc.; 2018; p. 3.45–3.52.

AUTHOR BIOGRAPHIES

Mahmoud Elshahawi
Conceptual and Structural Design
Technische Universität Berlin
Berlin, Germany
Structural Engineering Department
Mansoura University
Mansoura City, Egypt
elshahawi@campus.tu-berlin.de
shahawi_m_1988@mans.edu.eg

Alex Hückler
Conceptual and Structural Design
Technische Universität Berlin
Berlin, Germany

Mike Schlaich
Conceptual and Structural Design
Technische Universität Berlin
Berlin, Germany

How to cite this article: Elshahawi M, Hückler A, Schlaich M. Infra lightweight concrete: A decade of investigation (a review). *Structural Concrete*. 2020;1–17. https://doi.org/10.1002/suco.202000206