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Infra-Lightweight Concrete: Ready for practice*

*Hormigón infraligero: Listo para la práctica***

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ABSTRACT

After ten years of research at the *Technische Universität Berlin* (TU Berlin) and a first house, which has proved itself successful for ten years, Infra-Lightweight Concrete is now ready for practice. The risks associated with any innovation are now manageable. For those who want to use or further explore this high-performance concrete as a load-bearing thermal insulation material, this paper first summarizes the most important things about such very light concretes which allow for fair-faced structures without any additional heat insulation measures. The further results of our recent and ongoing research are presented in detail. The material-compatible development of structural details and the design potential of such new concretes are discussed as well as the project-specific approval still required in practice in each individual case. At the end, the paper presents the small number of buildings that have been built until now and are currently being planned.

KEYWORDS: Infra-Lightweight Concrete; structural design; structural details; approval in the individual case; application

RESUMEN

Hormigón infraligero: después de diez años de investigación en la *Technische Universität Berlin* (TU Berlin) y tras la construcción de una vivienda piloto hace diez años como prueba de la eficacia de este innovador material, el hormigón infraligero está listo para la práctica. Los riesgos implicados que toda innovación lleva consigo son ahora previsibles. Para aquellos que quieran usar este hormigón estructural de alto rendimiento o investigarlo más a fondo, encontrarán en este artículo un resumen de lo más importante acerca de este material, el cual permite estructuras de hormigón visto que prácticamente no necesitan ninguna medida adicional de aislamiento térmico. Los resultados alcanzados hasta ahora por los autores y la investigación en curso son presentados en detalle. El diseño estructural apropiado con este material y su potencial de forma serán también discutidos, así como los requisitos necesarios para su aprobación, ya que su uso no está cubierto por los Eurocódigos. Finalmente, se presentan algunos edificios de hormigón infraligero construidos hasta ahora y otros que están siendo actualmente planificados.

PALABRAS CLAVE: hormigón infraligero; diseño estructural; detalles estructurales; aprobación en casos singulares; aplicaciones

1. INTRODUCTION - THE MOST IMPORTANT THINGS ABOUT INFRA-LIGHTWEIGHT CONCRETE

A revolution in construction, like it was triggered by reinforced concrete around the year 1900 or pre-stressed concrete in the middle of the last century, is certainly not to be expected from infra-lightweight concrete (ILC). However, infra-lightweight concrete is not just light, but also heat-insulating in a way that allows for fair-faced concrete structures which meet today's energy saving regulations without the need for additional heat insulation material. Such buildings with exterior walls made of virtually only one mineral material – a load-bearing thermal

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Fig. 1. Detached house made of Infra-Lightweight Concrete in Berlin-Pankow (2007).

insulation - allow for a freer design, because the structural details are drastically simplified. They offer a pleasant room climate because of the porous material, and they are reusable at the end of their lifetime because they are not permanently bonded with other materials. The detached house with ILC exterior walls (Fig. 1) built in Berlin in 2007 [1] also shows that the light-weight material resists weather conditions very well.

Infra-lightweight concrete nowadays achieves mean compressive strengths of up to f_{lcm} = 13 MPa [2], which according to the conformity criteria corresponds to an LC8/9 and allows its use for multi-storey buildings. ILC offers the advantages of structural concrete, like free-form surfaces on a façade and enables structural elements, e.g. spandrel beams or lintels above large openings, which are subject to bending. Within the scope of a current project of the TU Berlin (see section. 2.2.1), an improved composition with up to 18 MPa mean cube compressive strength at a dry density just below 800 kg/m³ is currently being tested on mock-up walls (Fig. 3). At the same time, depending on the strength, the thermal conductivity can be between $\lambda_{tr}10°_{dry}$ = 0.14 and 0.19 W/(mK), and thus a building with a wall thickness of about 50 to 60 cm can comply with the current *Energieeinsparverordnung* (EnEV) in Germany [3] (Engl.: Energy Saving Ordinance). Expected future requirements can be met with ILC walls including active thermal insulation.

As far as costs are concerned, it is difficult to make clear statements. In Berlin, infra-lightweight concrete as a concrete with specified properties is about 3 times as expensive as normal concrete. The price for an ILC as a concrete with a specified composition is still higher, running to about 4 to 5 times that of normal concrete. The cost is higher because of the more expensive high-performance raw materials and because ILC is not (yet) established. For this reason, concrete plants have to load their processing machines with the raw materials required for each formulation. For *Life Cycle Costing* (LCC) [4], a fair-faced concrete wall made of infra-lightweight concrete is comparable to a load-bearing concrete wall with an external thermal insulation composite system (ETICS), especially when considering the thermal insulation properties as well as the longer life of the monolithic concrete wall. Compared to more complex double-walled walls or claddings with stone, the monolithic light-weight concrete wall certainly provides cost advantages.

A blemish attached to any use of concrete is the "carbon footprint" of cement. Portland cement is made by heating limestone (calcium carbonate) in a process known as calcination, where a molecule of carbon dioxide is liberated from the calcium carbonate to form calcium oxide. To this CO_2 content from chemical decomposition, however, an energy-related content is added from thermal and electrical energy consumption during the heating process. At present (VDZ Environmental Report 2015, Table 5-2 [5]), roughly 0.4 t CO_2 per ton of cement result from chemical decomposition and about 0.16 t from energy. In 2014, the country with the highest cement consumption was China with 2 454 million tons per year (2nd U.S.A, 3rd Europe), whereas Germany ranked sixth with 27 million tons as highest consumption in Europe. In total, cement production accounts for 7% of global CO2 emissions. ILC800 with a cement content of 330 kg/m³ (Table 1) produces 132 kg of CO_2 by chemical decomposition and 53 kg energy-related.

First findings from a *Life Cycle Assessment* (LCA) on sustainability [4] showed that during a life cycle the equivalent CO_2 of an ILC exterior wall is similar to that of a concrete wall with ETICS. The LCA investigations also show that, depending on the parameters selected, very different results can be obtained.

In the German "Assessment System for Sustainable Construction of Multi-Family Houses" [6], the assessment

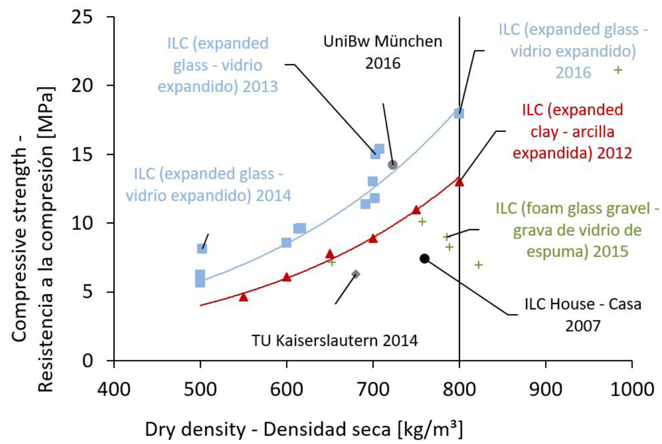

Fig. 2. Research results for various ILC compositions.

approaches do not appear to be applicable to ILC. It is, for example, questionable how the silica fume as a common concrete additive of ILC can be reasonably considered in the LCA because it is a waste product from the silicon industry. What is the service life of an ILC wall? What are realistic time intervals for replacing an ETICS façade? What are the actual maintenance costs of an ILC wall?

As in all other areas mentioned here, there is still a need for research and development. Also, to implement infra-lightweight concrete into standardization, further basics are still to be explored. Nevertheless, today's state of knowledge is advanced enough to tell that ILC exterior walls - produced in-situ or delivered as precast elements to the construction site - can be considered a serious alternative to the conventional wall systems. The results of previous research at the TU Berlin as well as current and planned research projects will be presented in the next section.

2.
STATE OF RESEARCH

2.1. General

According to Eurocode EC2 [7], the dry density of lightweight concrete is between 800 and 2000 kg/m³. Whereas very light porous and aerated concrete has been used for decades for masonry which must be plastered/protected after brick laying, structural lightweight concrete with a dry density of less than 800 kg/m³ has not been used for large-scale monolithic structural elements. We refer to such lightweight concrete as infra-lightweight concrete [1] because its dry density is below (Latin = infra) the limits of lightweight concrete.

Infra-lightweight concrete is achieved by replacing the usual (heavy) aggregates with very light ones, such as expanded clay, (recycled) expanded glass, foam glass gravel, pumice or tuff. By adding air-entraining agents, the dry density can be further reduced by means of an additional air inlet into the cement matrix. Similar effects can also be obtained using stabilizers and an increased water/cement (w/c) ratio, whereby excess water is first enclosed and subsequently air pores are created after drying. Although the air content of ILC is > 20%, the porous matrix is closed. The porosity even enables a good performance in freeze-thaw resistance (see section 3.3.2). There are many ways to reach the goal. Table 1 shows various compositions of ILC (dry densities ρ_{dry} <800 kg/m³): the ILC with expanded clay as lightweight aggregate (LWA), which was used in 2007 [1] for the detached house shown in Fig. 1 (at that time with the professional advice of Prof. HILLEMEIER, TU Berlin, and Prof. THIENEL, UniBw München) and its further development [8] into several ILC grades with dry densities between 600 and 800 kg/m³. Those ILC grades were investigated in a comprehensive study on the structural behaviour of different beam configurations subjected to bending, resulting in a calculation method to design ILC beams [2].

For an experimental building constructed in 2014 at the University of Kaiserslautern [9], infra-lightweight concrete with a dry density of < 700 kg/m³ with an LWA made of expanded glass was used. The composition and the results of the construction monitoring were published in 2016 in *Beton- und Stahlbetonbau* by SCHULZE AND BREIT [10]. For exterior walls of a detached house, CALLSEN AND THIENEL [11] developed a composition based on a mixture of expanded clay and expanded glass. Fig. 2 shows the performance (compressive strength versus dry density) of the compositions developed at the TU Berlin depending on the type of aggregate as well as the results from Munich and Kaiserslautern.

In the course of several research projects, which brought about two doctoral theses and a large number of diploma, master and bachelor theses at the Chair of Conceptual and Structural Design, TU Berlin, a considerable level of knowledge about this new material has been achieved [12]. Results on production, concrete properties and the behaviour of the reinforced infra-lightweight concrete are shown in section 3.

2.2. Current research projects at TU Berlin

2.2.1 Multi-functional lightweight concrete elements (MultiLC)

In the course of the research project funded by the German Federal Ministry of Education and Research (BMBF)

"MultiLC - Multifunctional Lightweight Concrete Elements with Inhomogeneous Properties" [13], exterior components which heat, cool, are, vapour-permeable and decompose airborne pollutants are being developed in cooperation with various partners from the industry (HeidelbergCement, Sika Germany, Transsolar, schlaich bergermann partner). The project goes for a holistic solution for a construction which is functional, aesthetic, resource-efficient, environmentally friendly, and recyclable.

Part of the project is the investigation of inhomogeneous components composed of layers with ILC800 (shell) and ILC600 (core). After successful structural investigations on small and medium-sized beams and walls (1:2), 1:1 prototypes with inhomogeneous cross-sections (Fig. 3) were produced in a precast plant (Heidelberger Betonelemente Laußnitz) and examined for their building physical aspects at the TU Berlin. With "fresh-in-fresh" production, a sufficient bond between the layers was achieved so that in the preliminary tests delamination occurred neither by shrinkage nor by external loads. Depending on the effect of temperature cycles between -20°C and +50°C, besides assessing the durability, an "effective" thermal transmittance coefficient (U value) is experimentally determined, which results from active thermal insulation. Water flows through capillary tube mats under the surface of the component with flow temperatures of 5°C, 10°C and 15°C. The expected "effective" U value was calculated to be between $U_{eff,15°C}$ = 0.12 W/(m² K) and $U_{eff,\ 5°C}$ = 0.24 W/(m² K) instead of the static U value of U_{bem} = 0.38 W/(m² K). The reference value of the EnEV for exterior walls was reached already at U = 0.24 W / (m² K). Grey-water and/or groundwater can be used as the heat source in the real building, with the flow temperature depending on the depth below ground level and the region. For example, at a depth of 20 m the groundwater temperature in Berlin is around 12°C and in the countryside barely below 9°C [14]. The pump power consumption for active thermal insulation is less than 0.1 kWh/(m²a).

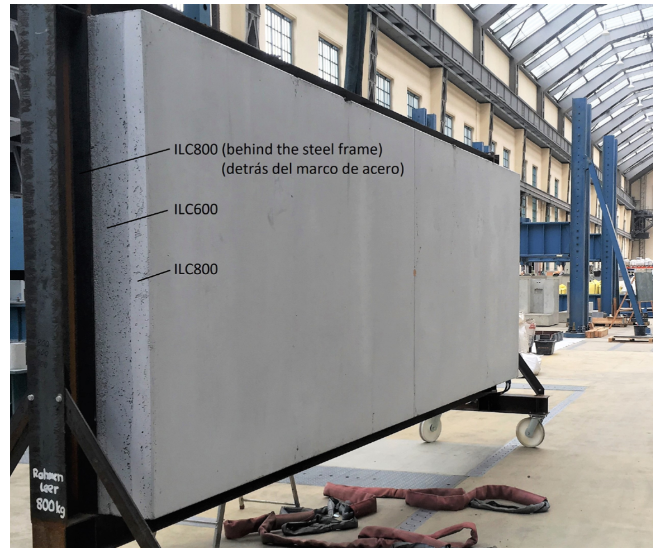

Fig. 3. Test wall (2 m x 6 m) made of layered ILC800 (shell) and ILC600 (core).

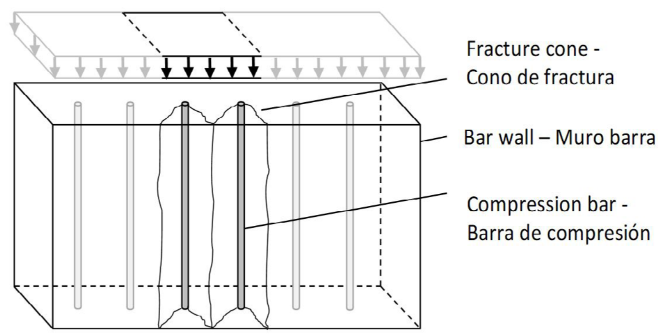

Fig. 4. Strut walls with load-bearing core made of UHPC and fracture cone in ILC [15].

2.2.2. *Strut walls*

The vertical load transfer of "strut walls" (Fig. 4) is primarily ensured by slender cores made of Ultra-High Performance Concrete (UHPC) or the reinforcement itself. With this novel structural approach, the ILC stabilizes the load-bearing core against buckling perpendicular to the component axis. This results in a design that takes into account and optimally utilizes the advantages and disadvantages of each material.

The aim is to develop an energy-efficient design concept for vertical construction elements. With this monolithic construction method, the ILC still fulfils its heat-insulating and weather-protecting function, but is involved in the vertical load transfer only to a limited extent. In particular, far higher buildings, strut walls can bear the high vertical loads in the lower floors.

2.2.3. *Prefabrication of ILC components (ILVO)*

In the context of the present high demand for housing space in Germany, prefabricated construction offers a number of advantages for new residential buildings as a time-saving, economical and low-emission construction method. Large-size precast elements, which have a ready-to-use surface on both sides, can bring about durable and sustainable buildings in combination with existing precast slab systems, such as wood-concrete composite or wooden panel construction.

The conditions for prefabricated constructions with ILC have not yet been fully explored and are the subject of a two-year research project funded by the German Federal Environmental Foundation (*Deutsche Bundesstiftung Umwelt*, DBU). The project, which will start in autumn 2018, is intended to apply the experience gained so far at the TU Berlin to multi-storey housing in cooperation with HOWOGE housing association in Berlin. Architects and engineers work with the housing association, precast manufacturer Tinglev and engineering firm Transsolar to develop marketable precast elements for a residential project.

3. INFRA-LIGHTWEIGHT CONCRETE TECHNOLOGY

3.1. *Composition and production*

The production of infra-lightweight concrete is –similar to usual normal concrete and lightweight concrete– not restricted to certain raw materials or a particular composition.

The compositions developed by TU Berlin (Table 1) consist of cement, water, LWA, silica fume, superplasticizer and stabilizer. Whether expanded clay, expanded glass (Fig. 5) or other lightweight aggregate eventually yields the best result, cannot yet be finally stated. Our team at TU Berlin has the most experience with expanded clay mixtures. However, expanded-glass mixtures promise higher strengths.

When using a compulsory mixer, the blades should have plastic coating to avoid crushing the LWA. Otherwise the fine grain content increases with increased mixing time, which negatively affects the concrete properties. In addition, as for lightweight concrete, the absorption water of the LWA must be taken into account [16]. Depending on the material and grain size, light-weight aggregates absorb different amounts of water, which is then no longer available in the cement paste during the hydration process and must, therefore, be added to the mix. In general, this amount of absorption water is added to the mixing water, and the mixing time has to be adapted until the desired consistency is achieved after the water absorption of the LWA. A determination of the amount of absorption water is often difficult because the lightweight aggregates cannot be supplied with a constant moisture content, which leads to undesirable variations in the concrete properties. If the LWA is saturated, the excess water creates an increased moisture content of the hardened concrete, which can result in higher thermal conductivity and lower freeze-thaw resistance. The water absorbed inside the LWAs causes internal curing [16], because excess water is available for hydration for a longer period of time. The rather closed surface of expanded glass grains requires a

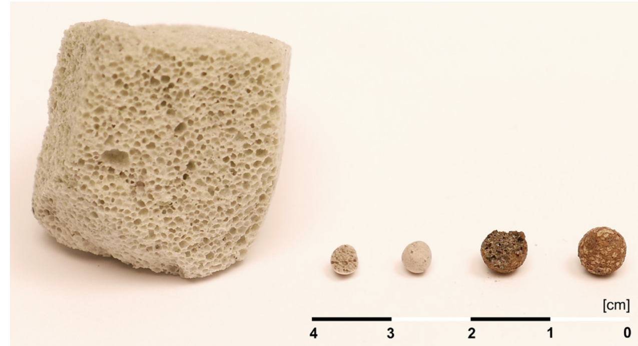

Fig. 5. Lightweight aggregates: foam glass gravel, expanded glass, expanded clay (left to right).

TABLA 1
Comparación de la composición y propiedades de los materiales de diferentes ILCs.

	TU Berlín					TU Kaiserslautern	UniBw München
	2007 [1] cf. ILC800	2012 [8] cf. ILC800	ILC800	ILC750 2016 [17] 1)	ILC700	2016 [10] cf. ILC700	2016 [11] cf. ILC750
	Composición [kg/m³]						
Cemento	330	322	333	295	260	370	350
Agua	165	157	185	175	164	136	149
Humo de sílice							
- UniBw Múnich, proporción de cenizas volantes	-	57	66	68	70	-	118 *(Distribución desconocida)*
Áridos ligeros		Arcilla expandida (seca)				*vidrio expandido*	*vidrio expandido 1/2, 2/4 y Arcilla expandida (seca)2/6*
	0/2-200 1/4-25 2/8-170	0/4-135 1/4-78 2/8-190	0/2-73 1/4-97 2/6-147	0/2-59 1/4-103 2/6-160	0/2-46 1/4-108 2/6-173	*0,25/0,5-74* *1/2-74* *4/8-62*	*215 (Distribución desconocida)*
Agentes aireantes	2,0	-	-	-	-	-	
Plastificante	-	4,8	3,52	3,36	3,19	5,8	
Estabilizador	-	0,46	0,63	0,53	0,45	0,5	***Mezcla de aditivos fluidificantes/ plastificantes, aireantes y retardantes***
Impermeabilizante	-	-	-	-	-	1,3	
Retracción	-	-	-	-	-	9,2	
Agentes espumantes	-	-	-	-	-	7,4	
	Propiedades determinadas experimentalmente						
Den. aparente fresca/seca $\rho_{fr/tr}$ [kg/m³]	1000/760	1050/780	1075/809	1009/766	947/711	720 740/650-700	749/723
Resistencia cúbica, $f_{ilcm,150}$ [MPa]	7,0	13,0	13,4	11,4	9,6	6,3	14,2
Resist. a tracción, f_{ilctm} [MPa]	0,66	1,02	0,87	0,76	0,65	0,48	0,71
Módulo de elasticidad E_{ilcm} [MPa]	4000	5500	3900	3500	3100	3500	5273
Conductividad térmica, $\lambda_{tr,10}$ [W/(mK)]	0,181	0,193	0,193	0,178	0,166	0,15	0,185
Condiciones de almacenamiento	Baño de agua		4 días en encofrado, seguido de 20°C y 35% humedad rel.			*22°C y 55% humedad rel.*	*ca. 95% humedad rel.*

1) ILC600 and ILC650 ver [2]
2) Calculado de acuerdo al ensayo de flexión [26] $f_{lctm} = 0{,}9\ f_{lctm,fl,40} / 1{,}7$

lower portion of absorption water during mixing, but, on the other hand, less internal curing is to be expected. According to the current state of knowledge, it is not recommended to pump either expanded clay or expanded glass mixtures because the pump pressure forces water into the lightweight aggregates, which stiffens the mixture and can clog the pipes. In addition, the desired air pores deaerate out of the cement paste, which leads to an increase in density. Infra-lightweight concrete should not be compacted with internal vibrators, as the air deaerates from the cement paste, which results in too high a density and can even cause segregation. Optionally, compaction (e.g. external vibrators, poking) can be helpful for visual reasons, for instance to improve the surface quality.

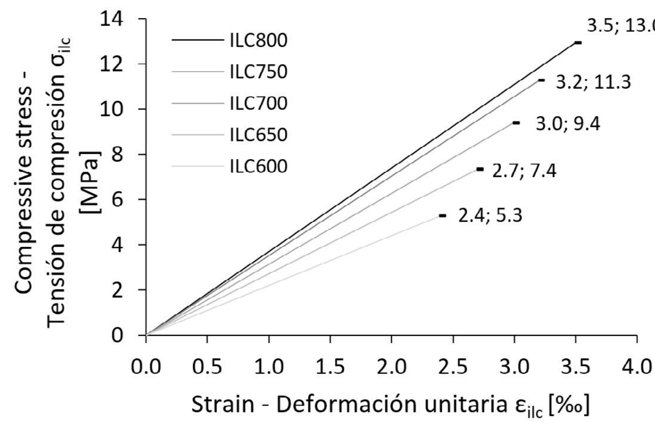

Fig. 6. Idealized stress-strain-relationship of ILC under compression.

3.2. *Properties*

3.2.1. *Fresh concrete properties*

The ILC properties described below refer to the investigated compositions ILC600 to ILC800 from [17] which are in part listed in Tab. 1. In lightweight concrete technology, density and strength are the most important properties. Fresh density is an important property to be quality checked during production, as it can be used to estimate the target dry density. The fresh density of ILC is about 190 to 230 kg/m³ (ILC600 to ILC800) above the dry density. Since compaction with internal vibrators can adversely affect the properties (density and strength), the ILC described here was developed as a self-compacting concrete. That means the concrete is rather self-levelling and thus fills all voids (e.g. between reinforcement and formwork) but does not deaerate, as the increased air entrainment ensures the thermal insulation property. A self-levelling consistency of the ILC can be assumed if the slump flow exceeds a value of approx. 600 mm.

3.2.2. *Hardened concrete properties*

At the mesoscopic level (in the millimetre range), where concrete can be simplified as an inhomogeneous binary system of matrix and aggregates, ILC behaves like common lightweight concrete [2]. The load-bearing behaviour of ILC or LC under compression is determined by the matrix and not, as in NC, by the aggregates. ILC has an almost linear-elastical behaviour, because microcracks develop just before the sample strength is reached. The mean ultimate strains vary between ε_{ilcm1} = 2.4 ‰ and 3.5 ‰ at average compressive strengths between f_{ilcm} = 6 MPa and 13 MPa. This variation in ultimate strains still needs to be investigated. Because of the linear-elastic stress-strain relationship, a constant modulus of elasticity (E_{ilcm} = 2300 to 3900 MPa for ILC600 to ILC800) can be assumed up to the ultimate load (Fig. 6).

According to standards [18], the specimen must be stored in water or, according to the German National Annex (NA) [19] for 6 days at 95% relative humidity and afterwards in a standard climate at 20°C and 65% relative humidity. In practice, however, lightweight concrete samples are usually stored at 95% relative humidity after stripping and until testing. The hardened concrete properties of the ILC600 to ILC800 from [17] were determined on test specimens stored under the same conditions as the corresponding test beams, with about 4 days in the formwork and then under "dry" climatic conditions of 20°C and 35% relative humidity until a concrete age of 28 days. It was found that the moisture content, depending on the storage of the test specimens, has a significant effect on the structural behaviour and deformation behaviour (strength and modulus of elasticity). A test series with different storage conditions resulted in an average increase of the elasticity modulus by 32% and of the cylinder compressive strength by 15% when ILC was stored in water.

For the long-term behaviour of ILC with and without loads, i.e. creep and shrinkage, different results are available. There is no German standard that regulates the testing of concrete for creep and shrinkage. Standards exist for testing "products and systems for the protection and repair of concrete structures", part 4 (DIN EN 12617-4 [20]) describing shrinkage and swelling of test specimens measuring 40 mm x 40 mm x 160 mm. In 2007, measurements performed at TU Berlin on such test specimens showed a shortening by 0.9 mm/m from shrinkage and 5.0 mm/m from creep (including elastic portion and shrinkage) at a compressive stress of $0.5 \cdot f_{ck}$ after 180 days [1]. However, it is doubtful whether results obtained on such small specimens can be transferred to real-structure dimensions.

At Kaiserlautern University, shrinkage measurements on three beams with 150 mm x 150 mm x 700 mm were conducted in the context of investigations regarding an experimental building made of ILC (completion 2014). With shrinkage reducing agents (see Table 1), after 180 days a shrinkage of 0.7 mm/m was measured, and without shrinkage reducing agents it was about 1.4 mm/m to 1.6 mm/m [10]. Both in the journal *DAfStb-Heft 422* [21] of the German Committee for Reinforced Concrete and in the recommendations by RILEM [22], cylinders with a diameter of 150 mm and a height of 600 mm are recommended for creep and shrinkage tests. Based on this, creep and shrinkage tests were conducted to achieve an "approval in an individual case" (*Zustimmung im Einzelfall*, ZiE) for a single-family house in *Aiterbach* (completion 2015). The selected test specimens were standard cylinders with a diameter of 150 mm and a height of 300 mm. The samples were monitored for 428 days. After 180 days, 0.8 mm/m shrinkage and 1.8 mm/m creep (including elasticity and shrinkage) were documented [11].

3.3. *Durability*

3.3.1. *Concrete cover*

In concrete, the steel reinforcement is protected from corrosion by an alkaline environment (pH value between 12.5 and 13.5), this is the so-called passivation process. Water and carbon dioxide cause carbonation in the concrete, which voids the passivation and which progresses at different rates, depending on the type of concrete and environmental influences (exposure class). The carbonation depth is calculated as follows [23].

$$y = k\sqrt{t} \tag{1}$$

with: y Carbonation depth [mm]
k Carbonation coefficient [$mm/a^{0,5}$]
t Age of concrete [a]
a Anno/year

The carbonation coefficient k describes the carbonation progress of concrete and is $k = 3\ mm/a^{0.5}$ for normal concrete [23]. That is, after 100 years, carbonation has progressed by 30 mm. Measurements at TU Berlin showed for ILC $20 < k < 30\ mm/a^{0.5}$, which leads to a carbonation depth of 200 to 300 mm at the same age of concrete! With a silane-based water-repellent agent on the surface, k was reduced to about 15 to 20 $mm/a^{0.5}$. The risk of reinforcement corrosion is thus not averted, but the surface is protected from weather conditions, and reticular surface cracks are prevented. On the single-family house of 2007 (Fig. 1), such water-repellent agents were used. Since then, the concrete surface has retained its good condition. The reinforcement chosen for the ILC exterior walls consisted of fibre-reinforced polymer (FRP). More cost-effective than FRP and closer to the mechanical properties of a common reinforcement (and also bendable, optionally) is galvanized reinforcement. This is used in a current construction project in Berlin-Lichtenberg, the *Betonoase* (Fig. 12), in the ILC building skin. The more costly alternative would have been stainless steel reinforcement. For non-corrosive reinforcement, the bond is decisive for determining the concrete cover. According to EC2 [7], for lightweight concrete, the minimum concrete cover to ensure the bond must be increased by 5 mm due to the reduced concrete tensile strength. This also applies to ILC. The minimum values for protection from corrosion apply to normal and lightweight concrete alike, although it was shown that - at least for lightweight concrete with 800 kg/m³ - the carbonation rate and thus the risk of corrosion is very high. A positive effect of the rapid carbonation of ILC is that a concrete element fully carbonates within its lifetime and extracts about 55 kg CO_2/m^3 from the environment (example calculation on concrete with a cement content of 360 kg/m³ [23]). This corresponds to about 1/3 of the CO_2 from the calcination (see Section 1).

3.3.2. Freeze-thaw resistance

Regarding the freeze-thaw resistance of infra-lightweight concrete, tests were carried out on ILC800 and ILC600 in accordance with DIN CEN/TS 12390-9: 2006 [24] as part of a research project ("INBIG – Infra-lightweight Concrete in Multi-Storey Housing" [4]). The composition of ILC800 according to Tab. 1 meets the requirements of exposure classes XF1 and XF3 under direct weathering, i.e. without surface coating (water repelling agents). ILC600 cannot be used for XF3 without surface treatment; an evaluation for XF1 is not possible due to a criterion not available.

3.3.3. Fire Protection

The "fire protection standard" [25] lists non-flammable building materials (building material class A1). These include primarily concretes according to EC2 [7]. Although ILC is not included due to its lower dry density and strength, the general description applies to "building materials containing no more than 1% (percentage by mass) of homogeneously distributed organic ingredients" [25]. ILC is therefore classified as non-flammable.

ILC elements can be designed according to EC2-1-2 [26]. The minimum concrete cover ensures that the reinforcement is protected from high temperatures. Since ILC has better heat-insulating properties, this design method delivers conservative results. The hazard of spalling, however, still needs to be investigated even this risk rather adheres to High Performance Concrete (HPC).

4.
CALCULATION BASIS FOR STRUCTURAL DESIGN

4.1. Method

Infra-lightweight concrete is intended primarily for exterior walls of buildings and these wall panels usually take, in addition to their selfweight, the loads of floors and the roof as well. If such loads are evenly distributed over the entire length of the wall section and centrically applied, there are B-sections (B for BERNOULLI), and the wall can be designed for pure compression. Reinforcement is then only necessary to avoid shrinkage cracks. However, geometrical or static discontinuities, such as windows, recesses, or concentrated or eccentric load applications, almost always occur, and –as in the case of normal concrete– such D-sections are best dimensioned using the strut-and-tie-models. In the area of the ties, additional reinforcement is then inserted into the infra-lightweight concrete wall.

Slender lintels, balconies or other cantilevered elements can be made of infra-lightweight concrete as long as the spans are not too large. These bending elements can be dimensioned according to the method presented below.

The calculation approaches for bending as well as the bonding, cracking and deformation behaviours presented here are based on the results of a DFG research project (SCHL 1901/7-1), which were published in [17] and [2]. In the following, only the particularities of the ILC in relation to common calculation approaches are summarized. The calculation approaches were successfully applied already for an approval in the individual case in question.

4.2. Bond

The bond properties between concrete and reinforcement affect various calculation approaches:

- A full bond between concrete and reinforcement is one of the basic assumptions for the beam theory for calculating the resistance moment.
- The type of bond failure (pull-out or splitting failure) affects bond-stress-slip relationship and bond strength, and thus the required concrete coverage.
- The bond-stress-slip-relationship influences the degree of

tensile stiffening (bond coefficient β_t) and thus indirectly affects the calculations for crack width and deformation.

- The anchorage length and lap length of the reinforcement in the element can be calculated from the bond strength (maximum bond stress) and its design value, respectively.

In principle, two types of bond failure are defined: the pull-out failure (shearing-off of the concrete brackets between the reinforcement ribs due to low concrete compressive strength) and splitting failure (longitudinal cracking from circumferential tensile stress due to low concrete cover or tensile strength). Splitting failure in lightweight concrete is more likely to occur [27], since the ratio of tensile to compressive strength is lower compared to normal concrete (considered by the coefficient $\eta 1$ according to EC2, Section 11.1.2 (1) [7]). Basically, the design value of the bond stress f_{bd} is determined according to equation (8.2) EC2, section 8.4.2 (2) [7] as a function of the tensile strength. It is smaller for lightweight concrete compared to normal concrete, resulting in greater bond lengths. In addition, the required concrete cover must be increased by +5mm for lightweight concrete (see 3.3.1).

Tests on ILC samples according to RILEM [28] lead to pull-out failure and thus confirmed the relationship between bond strength and concrete compressive strength. Calculations according to fib Model Code 1990/Bulletin 8 [29] for lightweight concrete and "poor" bond conditions, which only consider compressive strength, provided good conformity with the test results [17]. Nevertheless, as a conservative approach for ILC for the calculation of the bond stress the above mentioned equation (8.2) from EC2, Section 8.4.2 (2) [7] is recommended, as a splitting failure is also possible for ILC elements with insufficient concrete cover.

4.3. Deformations

Reinforced concrete elements subject to compression or tension shorten or lengthen accordingly to their compressive or tensile load, where, as a rule, cracks normally occur at a right angle to the direction of load. In the cracked state, although the reinforcement dominates the load-bearing and deformation behaviours, the concrete carries loads between the cracks (tension stiffening). The degree of tension stiffening between the cracks can be expressed by means of the bond factor β_t (corresponding to k_t for crack width calculation). For ILC, a value of β_t = 0.8 was determined for short-term loading (0.6 is to be used according to EC2 [7]). ILC therefore carries a higher load between the cracks, resulting in lower deformation. Thus, a simplified calculation method according to equation (7.18) EC2, Section 7.4.3 (3) [7] provides conservative results for elements under flexural stress. Deformations can thus be estimated by calculating the deformations for state I and state II and subsequent interpolation with a distribution coefficient ζ. For the distribution coefficient, there are several approaches [30]. A deformation model that provides realistic results was documented in detail by the second author [17].

4.4. Crack width

The calculation of the crack width according to EC2 [7] by using the equation (7.8), Section 7.3.4 (1) is based on simplifications and empirical assumptions. It also depends on parameters of the reinforcement, the effective concrete tensile strength, the Young's moduli and the tension stiffening effect. As with the deformation calculation (see previous Section 4.2), the tension stiffening between the cracks for standardized concretes according to EC2 [7] is taken into account for short-term loading with k_t = 0.6 (corresponding to the bond factor β_t). In terms of long-term behaviour, it is reduced to kt = 0.4 due to bond creep (equivalent to 70% of bond strength) (see comment to EC2 [31].

Test results on ILC-deformation samples and ILC beams confirmed the calculations of crack width for steel reinforcement (or for FRP bars according to manufacturer SCHÖCK [32]), taking into account the specific concrete properties of the ILC according to Tab. 1 and a bond factor β_t = 0.8 under short-term loading.

4.5. Bending

The calculation in accordance with EC2 [7] in the limit state of the load-carrying capacity of bending beams (B section) is made by restricting the strains, i. e. strain limits of the concrete and the reinforcement. The required reinforcement is calculated by means of the internal equilibrium of forces that results from the corresponding stress-strain relationship of the materials (Fig. 7). This approach is also applicable to ILC after the following adjustments. Due to the linear elastic and brittle material behaviour under compressive stress (Fig. 6), a triangular distribution of the stress-block should be assumed in the bending compression zone of an ILC beam instead of a parabola-rectangle block. The position of the concrete compression force F_c is therefore at $a = 1/3 \cdot x$ and the coefficient $\alpha_R = 0.5 \cdot \varepsilon_{c2}/\varepsilon_{cu}$ (Fig. 7). Experimental results of beam tests confirmed this theory. The calculation diagram (Fig. 8) delivers for the related moment defined as

$$\mu_{Eds} = \frac{M_{Eds}}{b\, d^2 f_{cd}} = \alpha_R\, \xi\, (1 - k_a\, \xi) \tag{2}$$

with the dimensionless ratios ζ = z / d. and ξ = x / d. After rearranging Eq. 2 follows

$$0 = \left[1 - k_a - \frac{M_{Eds}}{\alpha_R}\right] \varepsilon_{c2}^2 + \varepsilon_{s1}\left[2\,\frac{\mu_{Eds}}{\alpha_R} - 1\right] \varepsilon_{c2}^2 + \varepsilon_{s1}^2\, \frac{\mu_{Eds}}{\alpha_R} \tag{3}$$

The solution of Eq. (3) provides a calculation diagram (Fig. 8) to determine the required reinforcement without iteration. Finally, the required reinforcement section area is

$$A_{s1,f1} = \frac{1}{\sigma_{s1,f1}} \left[\frac{M_{Eds}}{z = \xi\, d}\right] \tag{3}$$

with the reinforcement stress $\sigma_{s1,f1}$. The calculation diagram for a structural design of ILC beams is applicable to reinforcing bars made of steel (index s) and FRP (index *f*) [2].

The determination of the design value of the concrete compressive strength fcd of infra-lightweight concrete must be set for every project within an *ZiE* (see Section 6) and is calculated according to EC2 [7] from the characteristic

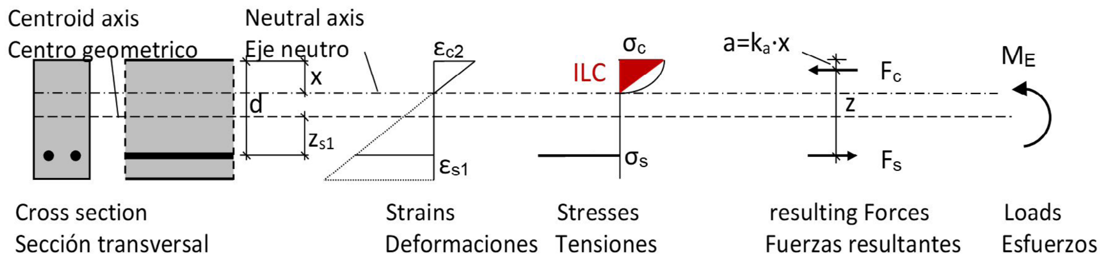

Fig. 7. Strains, stresses, and internal forces in crack section of a flexure ILC beam.

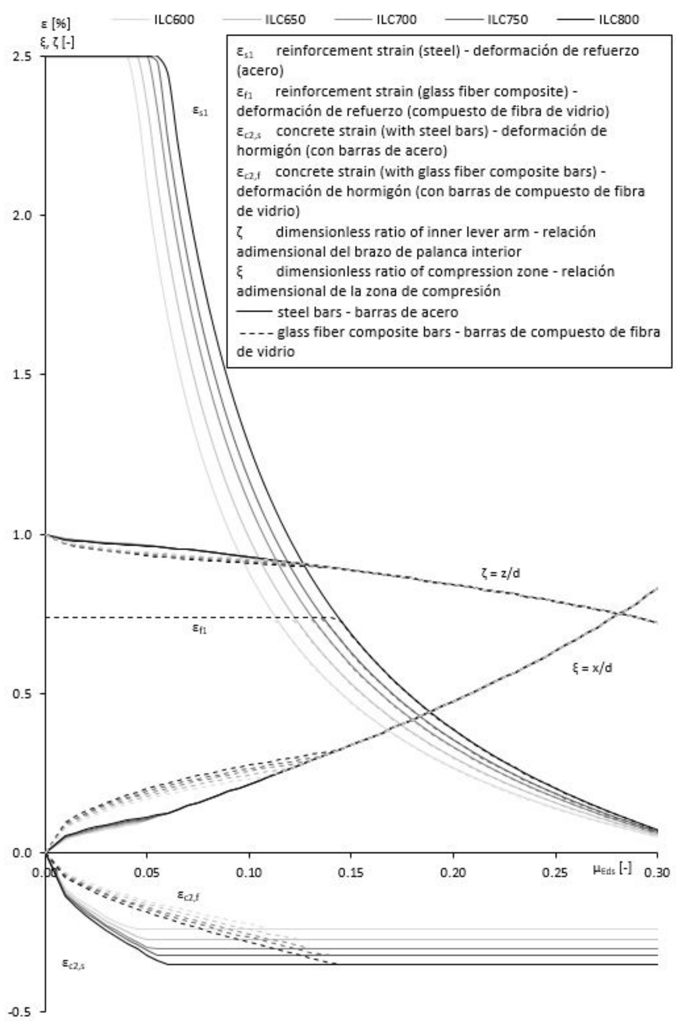

Fig. 8. Calculation diagram for ILC [2].

compressive strength f_{ck} times the long-term factor α_{cc} and divided by the material safety factor γ_c. Lightweight concrete has a lower long-term factor than normal concrete and is taken into account in EC2 [7] by a reduction to 0.75 or 0.80 instead of 0.85 for normal concrete. First tests on ILC confirmed this reduction. The material safety factor γ_c, which includes coefficients of variation from model uncertainties, geometry and material strength, is identical for normal and lightweight concrete. For ILC, no significantly higher coefficients of variation for material strength are to be expected. The characteristic compressive strength f_{ck} must be calculated [17] or every project within an ZiE and results from the targeted mean compressive strengths f_{cm} and their expected scatter.

5.
STRUCTURAL DETAILING

Infra-lightweight concrete, when used in accordance with the material characteristics, simplifies the structural detailing of many areas of the structure. The architect breaks new ground in fair-faced concrete construction. The research project INBIG [4] was conducted together with Prof REGINE LEIBINGER from the Chair of Construction and Design, TU Berlin. At the University as well, design cooperation of engineers and architects is important. Various types of buildings, such as infills, linear blocks and point blocks were examined. Material-appropriate window, ceiling and balcony details were developed and produced as prototypes. Fig. 9 shows an example of a floor slab made of normal concrete, which is connected directly to the ILC balcony. Thermal investigations [4] showed that a thermal barrier is not required.

Investigations with regard to mounting windows and door frames, attachments and shelves on ILC walls were carried out with dowels for aerated concrete. The results revealed a typical failure for lightweight concrete, characterized by larger breakout cones compared to normal concrete. In a test series, injection and long-shaft anchors with anchoring lengths of 100 mm or 140 mm were pulled out of an ILC sample wall. The permissible loads were exceeded by more than 20% when compared to lightweight concrete masonry blocks with the same strength.

6.
APPROVAL IN EACH INDIVIDUAL CASE

For buildings made of infra-lightweight concrete, an approval in each individual case (*Zustimmung im Einzelfall, ZiE*) must presently be obtained. This is regulated in Germany by the "Model Building Code" [33]. The certificate can be provided with the approval of the highest construction control authority

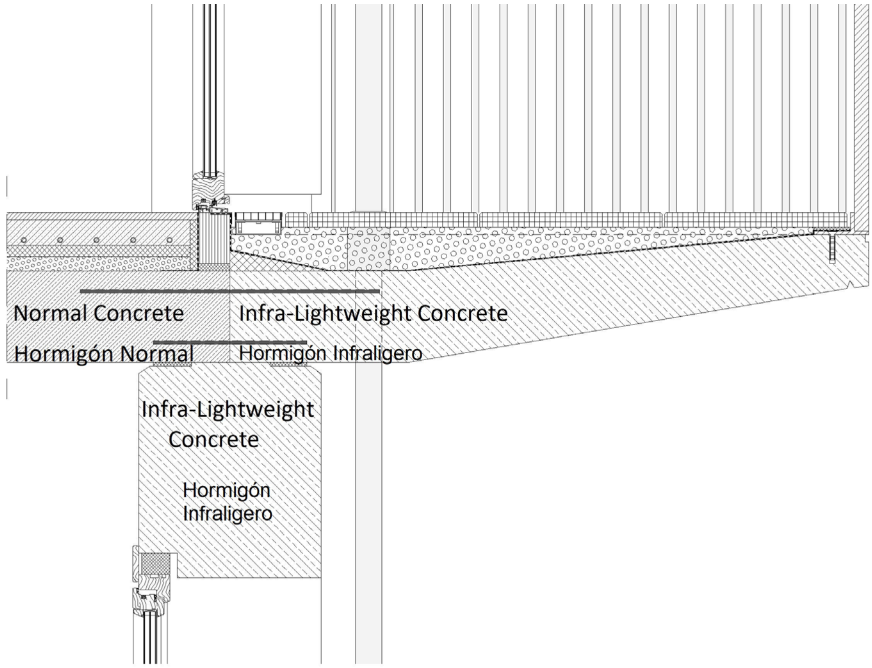

Fig. 9. Connection slap-wall balcony (drawing and photo) without thermal barrier [4].

for construction products for which no technical code and no general technical rule exist or which deviate substantially from a technical building code. The approval may also be waived by the highest construction control authority, if no risks are to be expected.

As an example, the bulletin for the Federal State of Berlin on *ZiE* [34] is given below:

- In general, the applicant can be a party to the project, e.g. the client, the planner, the manufacturer or the executing company.
- The informal request including the required documents must be submitted to the highest construction control authority of the respective federal state (Berlin in this case).
- A request for a *ZiE* can only be made for the use or application of one particular non-regulated construction product or one specific non-regulated construction type in one specific construction project. For all other cases separate requests must be submitted.
- The required request documents include a description of the subject of the request, construction documentation and information on the type and size of the demands.
- In general, the request must be accompanied by documents relating to structural design, test reports, expert opinions and any *ZiE* already issued.
- The fee is between € 500 and € 15 000, depending on the scope and difficulty of processing, the relevance of the subject of the request and the economic situation of the applicant and the benefits for the parties involved. Institutions such as public authorities, public corporations, churches, charities and similar are exempted from the fee.

It is advisable to initiate the procedure at an early stage of planning by means of an informal request so that required documents can be produced and submitted in time. In particular, expert opinions and possibly required experimental tests take time. Testing laboratories and consultants are assigned by a party (usually by the applicant), who accordingly has to bear the costs. The *ZiE* cannot take the place of the necessary constructional inspection by a test engineer.

Fig. 10. Experimental building made of Infra-Lightweight Concrete (2014) [10].

7. BUILDINGS WITH INFRA-LIGHTWEIGHT CONCRETE

Especially in Switzerland, fair-faced concrete buildings made of lightweight concrete without any additional thermal insulation have been constructed for some time. A book by FILIPAJ gives a good overview [35]. The book by FAUST [27] or, as an English equivalent, that by CLARKE [36] can be named as standard references for lightweight concrete, and also show numerous application examples. With lightweight concrete, however, the requirements of the *EnEV* [3] cannot be met with economic wall thicknesses, here, infra-lightweight concrete is required. The paper will present the small number of examples that have been built so far and two buildings being planned or under construction.

In 2007, the first building (Fig. 1) made of infra-lightweight concrete was constructed [1] in *Berlin-Pankow*. For this purpose, design details were developed that met thermal and structural requirements. The exterior walls of the family house are made of infra-lightweight concrete while the core –ceilings and interior walls– is made of normal concrete. The infra-lightweight concrete used had an average compressive strength of f_{ilcm} = 7.8 *MPa* at a dry density of ρ_{tr} = 760 kg/m³. From the thermal conductivity $\lambda_{10,tr}$ = 0.181 W/ (*mK*) at a wall thickness of 50 cm, a *U* value of 0.34 W/(*m²K*) is calculated, with was sufficient for the *EnEV* 2006 in force at the time.

The construction of an experimental building made of infra-lightweight concrete (Fig. 10) on the campus of the University of Kaiserslautern served as a prototype to prove the reproducibility of research results and to collect long-term data for further research. The aim of the project was to develop a highly heat-insulating self-compacting lightweight concrete composed of recycled components such as expanded glass and ecologically optimized cement in the sense of a "sustainable construction". With a measured thermal conductivity values of approximately λ = 0.15 W/(*mK*), a wall thickness of 50 cm resulted in a heat transfer coefficient of *U* = 0.28 W/(*m² K*) [10].

Client and architect THALMEIR [37] realized an infra-lightweight concrete house in Aiterbach in 2015 (Fig. 11), technically supported by Prof. THIENEL and *Heidelberger Beton GmbH*. The 50 cm exterior walls of the building are made of infra-lightweight concrete with a thermal conductivity of $\lambda_{10°,tr}$ < 0,185 W/(*mK*) and achieve strength class LC8/9. A dry density of 723 kg/m³ was realized by a lightweight aggregate mixture of expanded glass (Liaver) and expanded clay (Liapor) [11].

The youth recreational facility *Betonoase* is a current construction project in Berlin with exterior walls made of infra-lightweight concrete (Fig. 12). In 2016, the design of the architects Gruber+Popp won the assignment over five competitors. In the process of the construction approval, a design concept of the non-standard ILC was submitted and corresponding full-scale tests were carried out for the issuance of a *ZiE*. The structural design of bending elements (lintels and canopies) was based on research results from 2016 [17]. The full-scale tests carried out at the TU Berlin corroborated the calculations and allowed for the *ZiE* being granted. The *Betonoase* was completed at the end of 2017.

The housing association *Wohnungsbaugesellschaft Mitte* (wbm GmbH) is planning the construction of a high-rise building at the corner of *Mollstraße/Barnimstraße* in *Berlin-Friedrichshain*. The project emerged from the ideas competition "urban living" for the redensification of inner-city residential areas. The contribution of Barkow Leibinger Architects with schlaich bergermann partner and Transsolar was recommended for follow-up and for assessing its feasibility. The competition design provided for a 16-storey residential tower with exterior walls made of infra-lightweight concrete (Fig. 13), based on

Fig. 11. Detached house made of Infra-Lightweight Concrete in Aiterbach (2016) [37].

Fig. 12. Youth recreational facility Betonoase made of Infra-Lightweight Concrete (2017).

the concept of strut walls (see Section 2.2.2), located in the competition property at *Karl-Marx-Allee*. In the course of the project follow-up wbm GmbH decided to realize the project with 12 floors at the *Mollstraße* location in *Friedrichshain*.

8. SUMMARY AND OUTLOOK

More than ten years of experience including several funded research projects and completed buildings as well as projects by other researchers show that infra-lightweight concrete is ready for practice for a wide range of buildings. The research results and the strong demand on the part of clients and architects as well as the corresponding increase in successfully realized construction projects proofed the high potential of ILC. In order to present the current state of knowledge on infra-lightweight concrete in a practice-oriented way for potential users, an Infra-Lightweight Concrete Handbook was published [38]. The on-going research will tackle the few open topics to widen the range of application of ILC structures.

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