Self-Compacting Lightweight Aggregate Concrete for Composite Slabs

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This is an original scientific paper published in Concrete Beton, journal of the Concrete Society of Southern Africa, in Volume 130, pp 9-13 March 2012.

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ABSTRACT: In the construction of high-rise buildings, very often lightweight structures are used in order to minimise costs. The application of composite slabs can be an economically advantageous construction method because of the placement of trapezoidal steel sheets, independently of the crane, and because of their simultaneous function as formwork, working platform, reinforcement and horizontal stiffeners.

This applies to the construction of new buildings and refurbishment of existing buildings that require lightweight structures. Composite slabs of lightweight concrete combine the advantages of rapid construction and extensive industrial prefabrication.

This paper describes the development of a pumpable, self-compacting, lightweight aggregate concrete (SCLC), which has optimised properties for use in composite slabs. In the first step, a few variations of SCLC with a bulk density class D1.6 were developed. These materials varied in their mechanical properties, e.g. compressive strength, tensile strength, and Young's modulus. Furthermore, different shrinkage reducing admixtures (SRA) were added to the mix of one chosen SCLC, which accordingly showed favourable mechanical properties. With the addition of SRA, shrinkage deformations in the concrete could be reduced considerably. In the next step SCLC compositions for the bulk density classes D1.4 and D1.8, respectively, were developed.

Finally, the mechanical performance of composite slabs made with the developed SCLC compositions was studied by means of four-point bend tests. Particular attention was directed at interactions between the concrete and sheet steel as well as at the failure mechanisms inherent in the slab system. The test results clearly demonstrated the relevance of concrete properties to the improvement of the performance of the composite slabs.

1. INTRODUCTION

Composite structures represent one of the most economic solutions for flooring in structural engineering. The advantages of crane-independent, rapid installation of steel decking sheets combined simultaneously with their formability, making a ready working platform available, and reinforcement and stiffening elements for horizontal loads are responsible for the success of this technology. To achieve minimal dead weight in such structures, the use of lightweight concrete is necessary. In particular, self-compacting, pumpable lightweight aggregate concrete can simplify the construction process and optimise quality as well as minimise noise generation and erection time.

The aim of the ongoing project is to develop a self-compacting lightweight concrete well suited to use in composite floors and to investigate the load-bearing behaviour of the composite slabs. Since the complex interaction of the composite members (SCLC and steel) in the adhesion, friction, sheet deformation, and clamping effect, is influenced by profile geometry and the particular properties of the SCLC, several parameter combinations have been investigated experimentally and by means of finite element analysis.

2. DEVELOPMENT OF SELF-COMPACTING LIGHTWEIGHT CONCRETE

The first SCLC compositions with commercially produced lightweight aggregates (LWA) were developed approximately 10 years ago (Mueller and Mechtcherine 2000). In the following years intensive research was undertaken in order to improve the rheological behaviour of SCLC and make it pumpable, (Mechtcherine et al. 2003; Haist et al. 2003). Although some research was also directed toward improving the ductility of SCLC by the addition of short fibres, (Mechtcherine et al. 2003), generally speaking the optimisation of the properties of this new material in its hardened state with regard to particular applications has so far never been a topic of investigation. In the framework of this project, a purposeful further development of SCLC technology has begun to take into account the special demands of construction using light composite slabs. Apart from excellent flowability and robust pumpability, such application demands high tensile strength, high stiffness, low brittleness of the concrete, and low shrinkage and also low creep deformations. Four of the SCLC compositions developed, belonging to the bulk densities classes from D1.4 to D1.8 are presented in this paper (see Table 1).

Table 1. SCLC compositions developed

Concrete Density class	SCLC-1 D1.6	SCLC-4 D1.4	SCLC-6 D1.8	SCLC-7 D1.6
Cement*	10.3	10.9	10.3	10.7
Fly-Ash	9.5	9.9	5.0	9.9
Silica Fume (solid)	-	-	0.6	0.7
Water**	15.9	16.5	17.7	15.4
SP***	0.95	0.64	0.8	1.0
VA****	0.15	0.30	-	-
LSP*****	-		5.1	-
Sand 0/2	23.7	-	-	21.5
Split 5/8	-	-	22.3	-
LWA 2/10	37.4	33.0	-	39.2
LWA 0/4	-	26.2	36.3	-

All components are given in % by volume, except SP and VA.

* CEM II/A-LL 32.5 R

** Without pre-wetting Water

*** Super plasticizer (SP) in % by mass of cement

**** Viscosity agent (VA) in % by mass of cement

***** Limestone powder (LSP)

For all compositions, expanded clay was used as LWA. The coarse LWA had a grain size of 2 mm to 10 mm. The grain size of lightweight sand ranged from 0 mm to 4 mm. Since the porous expanded clay can absorb high amounts of mixing water, which may considerably affect the consistency of fresh concrete, the expanded clay aggregates were pre-wetted with water (18.5% by mass of coarse LWA and 21% by mass of lightweight sand). This additional water did not influence the strength of SCLC negatively. However, it may have had an effect on its shrinkage behaviour.

An ELBA laboratory mixer with a capacity of 60 litres was used at the TU Dresden for the concrete development. The mixture SCLC-1 (cf. Table 1) was developed in an earlier project, (Mechtcherine et al. 2003), and used in this study as reference concrete and the basis for a further optimisation.

The total mixing time was three minutes in the preliminary tests. The reference concrete SCLC-1 showed a slump flow of 680 mm, a flow time t_{500} of 3.8 s and the V-funnel flow time of 6.3 s. During first mixings of SCLC-1 it was observed that a part of the coarse lightweight aggregates was ground, or ruptured, due to the intensive mixing process. To minimise this, the mixing intensity was reduced, but the total mixing time was still limited to three minutes. Since the super plasticiser on the polycarboxylate ether basis could not develop its full effect during this short time period, at the applied low mixing intensity, the consistency of the fresh concrete mixture became stiffer when tested directly after mixing: the slump flow decreased to 610 mm.

However, in the process of the subsequent 'post-mixing' with very low intensity, which simulated the post-mixing in a ready-mix concrete lorry, the SCLC became more workable. Figure 1 shows the change of the concrete consistency over time, which is appropriate to the application of this material as ready-mix concrete in the production of composite slabs at the construction site.

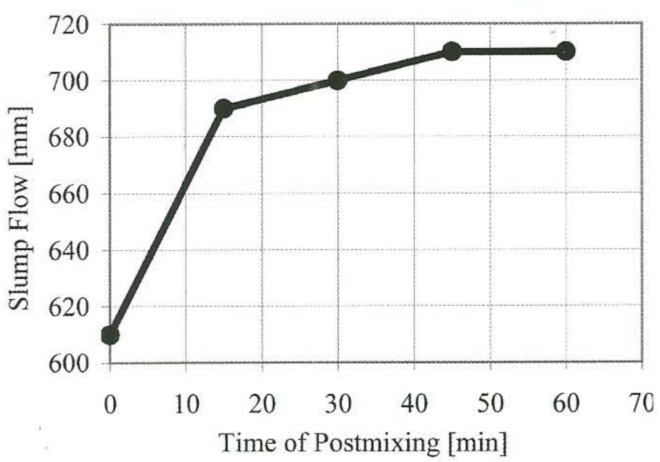

Figure 1. Change of the slump flow during the low-intensity post-mixing.

SCLC-1 was used for the production of a first series of slabs at the TU Kaiserslautern using a concrete plant mixer with a volume of 1 m^3. Testing of characteristic concrete properties in the fresh and hardened state provided nearly the same values of the characteristic properties as those obtained at the TU Dresden.

Primarily based on the results of the first four-point bend tests (cf. Chapter 4), a few material parameters of SHCC were subsequently selected to be improved, in order to enhance the mechanical performance of the composite slabs. The following changes were the objective:

- extension of the range of bulk densities classes to D1.4 and D1.8,
- increase in the tensile strength,
- increase in the Young's modulus,
- reduction of creep and shrinkage deformations

To reduce the bulk density of SCLC to the density class D1.4 (mixture SCLC-4), the normal-weight quartz sand utilised in the reference mixture was substituted by lightweight sand (cf. Table 1). The mixture SCLC-6 was designed to meet the bulk density class D1.8 and simultaneously to increase the Young's modulus and the tensile strength in comparison to the reference composition. It was attained by replacing the coarse LWA by basalt split and by adding silica fume, while the quartz sand was replaced by lightweight sand (cf. mixture SCLC-6 in Table 1). The silica fume was used in the form of a colloid suspension with 50% by mass of solid material. To improve the grain size distribution, which was disturbed by the introduction of the split aggregates, some limestone powder was used additionally in the mixture SCLC-6. Finally, mixture SCLC-7 was developed with the goal of reducing the bulk density by a small amount (in order to be more secure in reaching the density class D1.6) and to increase the tensile strength. The first goal was achieved by increasing the content of LWA slightly and simultaneously by lowering the portion of quartz sand slightly. An increase in the tensile strength should be attained, similar to the SCLC-6 composition, by adding silica fume suspension (cf. Table 1).

The properties of the hardened SCLC were tested at a concrete age of 28 days according to the German standard DIN 1048. Table 2 gives the results of the mechanical tests performed. As expected, SCLC-4 (bulk density class D1.4) showed lower strength and stiffness in comparison to the reference SCLC-1 (bulk density class D1.6).

The reduction of the compressive strength was moderate; however, as a result of using LWA for all aggregate grain fractions, there was a pronounced decrease in the values of the most relevant parameters, Young's modulus and the splitting tensile strength. In contrast, the testing of the mixture SCLC-6 (bulk density class D1.8) revealed a considerable increase in tensile strength, leaving the perceptual increase in the compressive strength and Young's modulus well behind. Finally, SCLC-7 showed, again in comparison to the reference SCLC-1, a slightly lower dry density, while comparing better to the bulk density class D1.6.

The compressive strength and Young's modulus of this mixture were somewhat below the reference values, but a significant perceptual increase in the splitting tensile strength could be attained.

Table 2. Mechanical properties for different SCLC mixtures

Concrete Bulk Density Class	SCLC-1 D1.6	SCLC-4 D1.4	SCLC-6 D1.8	SCLC-7 D1.6
Dry density*	1630	1390	1765	1543
Compression strength**	40/43	34/36	46/48	39/41
Young's modulus	20000	14000	21000	18700
Splitting tensile strength	2.4	1.4	3.4	2.8

* The dry density is given in kg/m^3, all mechanical properties are given in MPa.
** Compressive strength measured on cylinder/cube

Since the SLCL compositions developed have a high proportion of fines and increased total water content due to the pre-wetting of LWA, high shrinkage deformation can be expected. In the composite slab, concrete shrinkage deformations are constrained by the profiled steel sheet, which leads to tensile stresses in concrete. This effect is particularly pronounced at the upper chord of the profiled sheet, a region where stress concentrations from mechanical loading occur as well. To decrease the shrinkage deformations and therefore to counteract early cracking, two different shrinkage reducing admixtures (SRA) and one concrete sealant agent (SA) were used as concrete additives. Their effect on shrinkage behaviour was tested on prisms made of the reference concrete SCLC-1 using the Graf-Kaufmann method (cf. Figure 2).

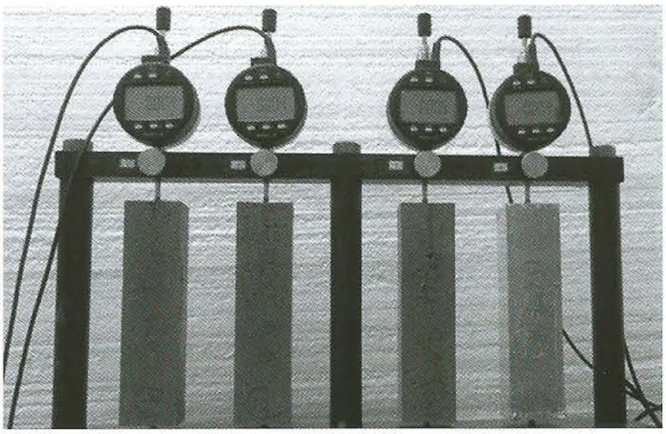

Figure 2. Equipment used for shrinkage measurements.

Figure 3 shows the test results for total shrinkage, including the autogenous and drying components. The addition of SRA resulted in a clear decrease in shrinkage deformations in comparison to the reference mixture without such additive. In contrast, the use of concrete sealant agent was not only not beneficial, but even caused some increase in shrinkage.

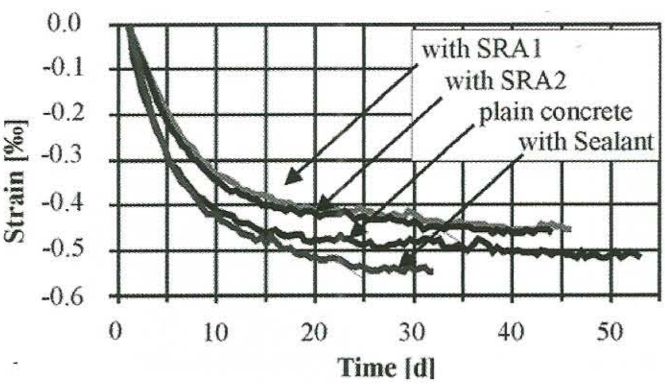

Figure 3. Development of total shrinkage strain over time for SCLC without and with shrinkage reducing additives (SRA) and sealant agent (SA), respectively.

To estimate the effect of the additives on cracking behaviour of SCLC, instrumented ring tests were performed. The setup of this test is shown in Figure 4. It consists of two steel rings of different diameter. Fresh SLCL was placed between the rings. At a concrete age of one day, the outer steel ring was removed and the circumference of the concrete annulus was exposed to desiccation at the standard laboratory climate (20 °C, 65% RH). The inner steel ring was equipped with strain gauges for measuring deformations of this ring induced by the shrinkage of the concrete annulus. From the deformation

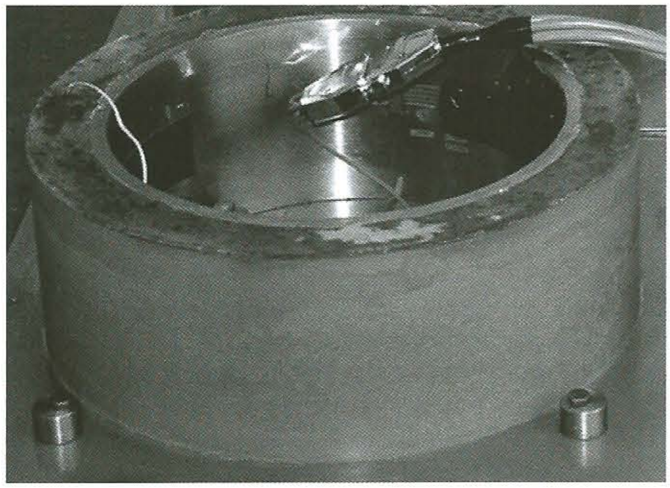

Figure 4. Instrumented ring test for estimating concrete cracking due to restraint of shrinkage deformations.

values measured, the stress in the SCLC annulus could be estimated using formula by Hossain & Weiss (2004).

Figure 5 shows typical cracks as observed in the ring test right after the crack formation in SCLC. In their tendency, the test results agree well with the findings of the shrinkage measurements. However, in the ring tests the differences were much more pronounced: while the reference concrete cracked at the age of 15 days and showed a crack width of 0.8 mm, the mixes with the additives SRA1 and SRA2 displayed considerably smaller crack openings of 0.2 mm and 0.3 mm, respectively. The cracking occurred also considerably later in SCLC-1 with SRA, at a concrete age of 27 days (SRA1) and 39 days (SRA2), respectively. The largest crack width was registered for concrete with the sealant: it was 0.9 mm right after crack formation at a concrete age of 19 days.

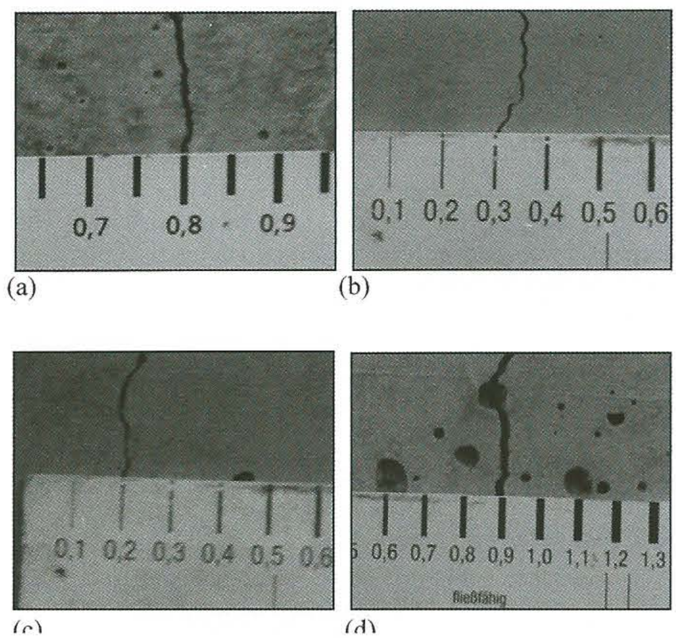

Figure 5. Crack widths observed in ring tests right after crack formation:

a) Reference composition SCLC-1, cracking age 15 days
b) SCLC-1 with SRA1, cracking age 27 days
c) SCLC-1 with SRA2, cracking age 39 days
d) SCLC-1 with sealant, cracking age 19 days.

3. TESTING THE PUMPABILITY OF SCLC

One of the key properties required for an efficient application of SLCL for the production of the composite floors is robust pumpability. This property was tested by producing 1 m³ of fresh SCLC in a regular concrete plant and pumping it in a circle for a while and subsequently casting of composite slabs with the pumped concrete. Here is one experiment, in which SCLC-7 with addition of SRA1 was pumped and will be described.

The lightweight aggregates were pre-wetted in the 1m³ mixer. Subsequently, the concrete was mixed with the same mixer. The slump flow of fresh SLCL right after mixing was 650 mm.

A truck-mounted concrete pump M28-4 from Putzmeister was used in the test. The walls of the pipe system were first lubricated by pumping an amount of a premix made of cement, sand and water. Subsequently, the pump started to deliver SCLC. After the premix and the very first portion of SCLC were pumped into the waste, the pumping process was changed to the cycle regime.

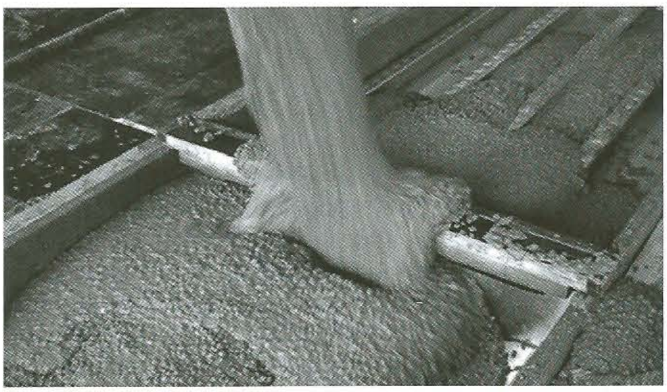

Figure 6. Casting a composite slab with pumped SCLC.

The velocity of pumping was set to 8-10 m³/h. After 10 minutes of pumping it was interrupted for a further 10 minutes to investigate the condition of the mix, then the pumping process continued. The velocity was increased to 70m³/h. The testing of the mix during the interruption showed that no segregation occurred. A significant decrease in slump flow to 490 mm was observed indicating some loss in the workability of the material. This could likely be traced back to the surplus of water absorption by LWA due to the high pumping pressure. With an addition of super plasticiser (0.2 % by mass of cement) and some water (approximately three litres) the desired consistency was reached again. The pumping test was continued for another five minutes and then finished by casting composite slabs with the pumped SCLC (cf. Figure 6).

4. TESTS WITH COMPOSITE SLABS

4.1 *Test setup and main results*

Preliminary tests with two composite slab specimens (denoted here as specimen A and specimen B) were performed, in order to obtain initial references, regarding their applicability to and behaviour of self-compacting lightweight in composite floors. The experiment setup was designed similar to previous tests on composite slabs with lightweight concrete by Faust at Leipzig University, (Faust 2002), and Kessler at the TU Kaiserslautern (Kurz & Kessler, unpubl.). According to Koenig & Faust (1997) and Kurz & Kessler (2007), the composite slabs showed ductile bearing behaviour with longitudinal shear failure in 4-point-bend tests. The specimens were approximately the same size; the tests were carried out according to Eurocode 4.

The specimens were made using a profiled sheet steel type Super-Holorib SHR51 with a nominal thickness of 1.00 mm. They had a width of 70 cm and a height of 14 cm. The length of the one specimen type was 3.40 m ('long' shear length of 90 cm) and that of the other specimen type was 2.20 m ('short' shear length of 60 cm). At the points of load application, crack-initiating sheets were installed. The same dimensions were chosen for the new specimens A and B, to be tested in this project with SCLC. The concrete composition SCLC-1 was used (cf. Chapter 2).

During the testing of specimen A (with a 'long' shear length of 90cm), the first slip appeared at the load of 58.8 kN (25.8 kNm). The maximum load was 87.2 kN (37.2 kNm), which was 48% above the load of the first slip. Thus, the load bearing behaviour can be classified as 'ductile'. Specimen B (with a 'short' shear length of 60 cm) reached a peak load of 112.3 kN (29.1kNm), while the first slip, appeared at 71.4kN (18.9 kNm). With a load increase of 57% after the first slip, the load bearing behaviour can also be classified as well as 'ductile'. The abort criterion of mid-span deflection of L/50 was insignificant for both tests.

From these maximum loads, shear strengths of 525.2 kN/m² and 512.3 kN/m², respectively, could be obtained for A and B. The calculation was done according to the regulations of Eurocode 4, without taking into account the support pressure, and under assumption of a triangular compression stress distribution (Faust 2002). The primary test results are given in Table 3.

Table 3. Test results for composite slab specimens with SCLC Specimen

Specimen		A	B
f_{yp}	[MPa]	337.8	337.8
$0.9_{fcm,cube}$	[MPa]	38.43	38.43
Length	[m]	3.4	2.2
Width	[m]	0.70	0.695
M_u	[kNm]	37.2	29.1
η	[%]	79	54
τ	[kN/m²]	512.3	525.2

4.2 Deformation and failure behaviour of the composite slabs

While the maximum loads achieved were within the expected range, the failure mode and crack pattern in part showed unusual features, which were significantly different to the well-known behaviour of normal weight concrete specimens. First cracks appeared, as expected, at the crack-initiating sheets and on the longitudinal edges of the specimen (cf. Figure 7). These horizontal, longitudinal cracks split the concrete cover at the height of the composite sheet's upper chord. In contrast to composite slabs made of ordinary concrete, an additional crack appeared with further load increases and opened within a distance of approximately 20 cm from the crack-initiating sheet, while the initial crack at the crack-initiating sheet was closed.

For specimen A this crack was vertical in the beginning and split later. One branch headed towards the load application area and the other grew between the load application and the support. With further increases in load, another crack formed in the same way at a distance from the first, equal approximately to the height of the slab. This crack ran along the compression trajectories toward load application as well. Specimen B showed only one considerably curved crack heading toward load application (see Figure 8).

Figure 7. Specimen A at the ultimate limit state.

The more the cracks opened, the more their edges shifted against each other. For Specimen B a vertical displacement of the crack edges could be recognised and local buckling of the composite sheet was observed. After cutting specimen B it could be observed that the curved crack ran through the entire width. The concrete at the lower crack edge was clearly damaged. Burls of the composite sheet left abrasion marks on the concrete, and the angle of the concrete rib was sheared off. These marks have gone undetected in tests of ordinary concretes of normal weight.

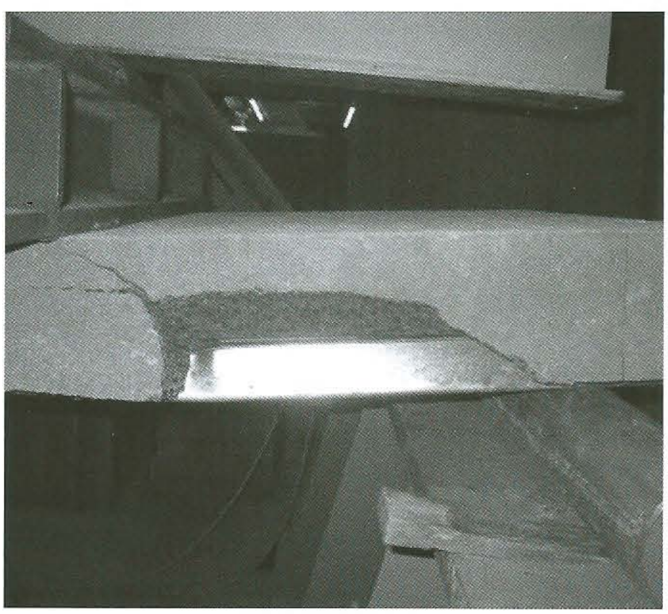

Figure 8. Specimen B at the ultimate limit state

Specimen A with its 'long' shear length and specimen B with its 'short' shear length were both split longitudinally after reaching maximum load. Each crack started at an upper chord angle of the Super-Holorib-sheet and ran inclined through the entire specimen thickness. Specimen A was split at each rib of this undercut profile (see Figure 9). The test results observed by Koenig & Faust (1997) and Kurz & Kessler (2007) with conventional lightweight concrete showed similar behaviour.

5. SUMMARY

Several SCLC compositions suitable for the production of composite slabs were developed in this investigation. The bulk density classes ranged from D1.4 to D1.8. To secure a target workability of SCLC over the delivery and casting time, LWA were pre-wetted by a defined amount of water.

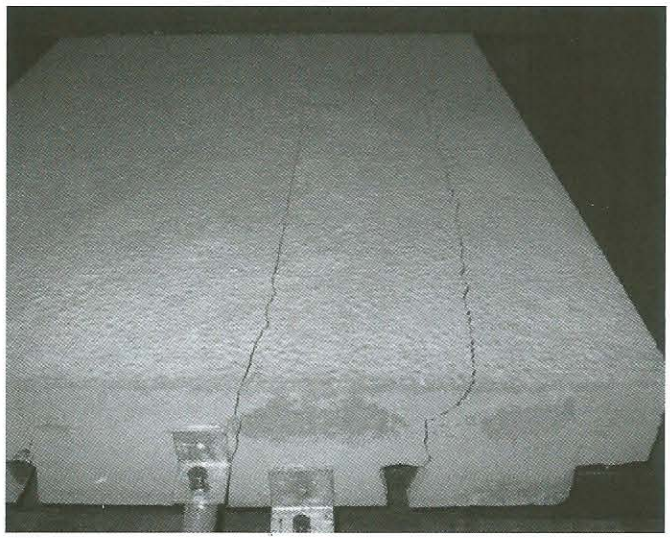

Figure 9. Longitudinal splitting cracks in specimen A.

Furthermore, it was shown that the mixing intensity and duration play a significant role with regard to concrete workability. Shrinkage measurements showed a clear, positive effect of the addition of shrinkage reducing additives, while the addition of a sealing agent led to no improvement.

These results were confirmed in the instrumented ring tests: the cracking of the specimens with SRA occurred at a higher concrete age, and crack widths were considerably lower in comparison to the specimens made without the addition of SRA. Furthermore, the pumpability of SCLC was validated by pumping tests.

Composite slabs made of SCLC showed a ductile failure in the bend tests. The crack pattern was very different to that known in the corresponding tests on composite slabs made with ordinary concrete. The observed failure mode was not only the well known and assumed longitudinal shear failure, but also a combined failure from transverse force and longitudinal shear. Investigations are in progress.

6. ACKNOWLEDGEMENTS

This research has been sponsored by the *Bundesamt für Bauwesen und Raumordnung* with funding from the initiative *'Zukunft Bau'* (reference number Z 6 – 10.08.18.7-07.9/II 2 – F20-07-19). The authors are responsible for the content of this report.